DELFI-1 Project

EDT Experiment onboard Delfi-1

DELFI.1.TW.4122.10-11

Thesis Report
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January 2012
This report is the result of a master thesis project performed at the Faculty of Aerospace Engineering of the Delft University of Technology at the chair Space Systems Engineering. The graduation committee consisted of

- Ir. B.T.C. Zandbergen
- Dr. Ir. M. Kruijff
- Ir. R. Noomen

The objective of the thesis was to design and size an electrodynamic tether experiment for use onboard the Delfi-1 university satellite.

This report consists of the following documents

Publications

Thesis Documents
Part I DELFI.1.TW.4122.10 EDT Experiment onboard Delfi-1, Preliminary Design
Part II DELFI.1.TW.4122.11 EDT Experiment onboard Delfi-1, Operation and Design
DELFI.1.SPC.4122.01/02 EDT System Requirements

The thesis project is roughly divided into two parts, a preliminary design phase consisting of a literature study and the development of a baseline experiment. During this phase the paper entitled “Bare Electrodynamic Tape Tether Experiment onboard the Delfi-1 University Satellite” was written and presented at the 4th ESA international propulsion conference in June 2004. The preliminary design phase was concluded with the “EDT Experiment onboard Delfi-1, Preliminary Design” document. For the second phase the feasibility of the proposed experiment was determined including a more detailed performance analysis and design of experiment systems. The design and development of the deployment system was performed by S. van de Heijning resulting in the thesis report entitled “Design of an Electrodynamic Tether Deployment System”. In this thesis report the main focus is on the design of the electrodynamic tether and the telemetry system of the experiment resulting in the “EDT Experiment onboard Delfi-1, Operation and Design” document.

I would like to take this opportunity to thank everyone who supported me during my thesis work. First I would like to thank my thesis mentor Barry Zandbergen for his support, comments, remarks and his patience. I would also like to thank Michiel Kruijff and Ron Noomen for reading my report and taking place in my graduation committee. And thanks to Michiel for and showing me the YES2 test facility, my first experience with real space hardware. Also many thanks to everyone from Delta-Utec (2004) for proposing the experiment, answering my questions and supporting my thesis work. I am also thankful to all Delfi project members and staff. A special thanks goes out to 2003-2004 members of the Delfi-1 project for the great time we had both at the faculty during ‘office hours’, at the monthly drinks and during the occasional dinners and borrels and not to forget during all the hilarious moments like the tuin kabouter incident, it was a very relaxed and gezellig project team I enjoyed being part of. I would like to thank my family and friends for their encouragement and believe in my ability to finish my thesis work even though at times it seemed an impossible task with me and studying being a contradictio in terminis. Also I would like to thank the (student) support system at and beyond the TU Delft and all the students I met who just understood no questions asked, I couldn’t have done this without you guys! And a special thesis unrelated but a very important thank you to Anna and Lykle for entrusting me with Dasha, there are no words to express my gratitude.

Anne-Marije Wijnans
Delft, January 2012
SUMMARY

Electrodynamic tether propulsion exploits the naturally occurring phenomena when a bare conducting wire moves through a magnetic field. This charges the tether with respect to the plasma environment. Being exposed to the ionospheric plasma environment collection of electrons and ions take place using either a passive or active current collection allowing for a current to run through the tether. A Lorentz force will subsequently act on the tether moving across the magnetic field lines. This force is used to accelerate or naturally decelerate the satellite. The system can also be used to generate power at a cost of orbital energy. The advantage of using an electrodynamic tether for propulsion is that it does not require propellant to provide thrust and can be a very simple system operating completely independent from the main spacecraft. The current development of electrodynamic tethers is focussed on the use of a bare tether anode as an efficient electron collection device and the development of survivable tethers capable of operating for extended periods in the micrometeoroid and orbital debris environment. The aim is to develop a low-cost electrodynamic tether experiment as payload onboard a micro-satellite. The Delfi-1 university satellite is a typical micro-satellite platform designed and developed by students. Using the Delfi-1 satellite as a platform the intention is to demonstrate the use electrodynamic tethers for satellite propulsion and validate current theories on the operation of bare electrodynamic tethers.

The subject of this thesis is

To Design and Size an Electrodynamic Tether Experiment for use onboard the Delfi-1 University Satellite

The main objectives of the experiment are to provide a proof of concept of bare electrodynamic tether propulsion and deploy and operate a tape tether. A tape tether design has been selected having a favourable geometry for current collection and survivability in the micrometeoroid and orbital debris environment in comparison with ‘traditional’ wire tethers. The tape tether also has favourable drag properties allowing for a rapid deorbit when cut from the main satellite decreasing the risk of collision with operational satellites. A secondary objective for the experiment is to determine if the release of a neutral gas can enhance the current of the tether and the deorbit performance. This experiment is fundamental in the development of a fully passive deboost capability for tether equipped systems.

The limited amount of storage and mass, power and data rate available when using a micro-satellite platform for the experiment combined with low complexity and cost requirements inherent to the Delfi-1 project drives the design to a bare minimum required for performing the primary scientific objectives. The baseline design for the experiment is characterised by a passive bare floating electrodynamic tether deployed in nadir direction using a passive deployment mechanism. To estimate the performance of the electrodynamic tether in the Delfi-1 orbit range the environment is modelled and a tether design tool was developed allowing for rapid evaluation of various tether dimensions over the orbit range. The design of the system is driven by deorbit performance requirements and the constraints of operating onboard a micro satellite. The inclination range for the experiment was limited to inclinations below 85° and above 95° to prevent over dimensioning of the experiment, Delfi-1 orbit altitudes of 650 – 1000 km are all feasible for the experiment.

The tether payload consists of a 5.7 kg experiment a bare passive tape tether, the experiments requires no more than 6 W of power and a data rate of 210 bps. The electrodynamic tether consists of an aluminium tape (foil) laminated to a Kapton® substrate providing rip stop protection. Tether length ranges from 500-900 m with a width of 15-20 mm and approximately 26-32 µm thick. The system is deployed using a passive cold gas thruster or a spring ejection system and requires a stabilising end mass of 1.1-1.5 kg. The experiment will achieve a minimum deorbit of approximately 100-320 m in a two week period, for lower altitudes and inclinations this will increase to approximately 1390-3700 m. Up to approximately 720 km aerodynamic drag effects are of a similar order to Lorentz drag forces. A method of filtering both the aerodynamic and solar radiation force perturbations on the orbit will have to be developed. Use can be made of cyclic variations occurring in both these forces this will require multiple updates of the orbital position of the satellite diurnally.
The deorbit will be measured using an onboard GPS receiver, tether bias measurements and data from Delfi-1 attitude and control system including magnetic field measurements and solar angle and intensity data from the electrical power system are required to give an indication of tether performance. Additional tether tension measurements, plasma diagnostics and tether temperature measurements will aid in distinguishing between Lorentz and aerodynamic drag acting on the tether, they will however strain the current budgets for the experiment considerably. A neutral gas cathode is expected to work in the lower inclinations of the Delfi-1 orbit range for tethers exceeding 850 m in length. Neutral gas remaining in the cold gas thrusters after deployment of the tether can be utilised to this end.

A recommendation for further development of the experiment is to design two separate experiments. One version aimed at the lower orbit altitude range where aerodynamic drag is comparable to Lorentz drag. Possibly using a longer wire tether and incorporating an active cathode allowing for direct current measurements. For higher altitudes the passive bare tether is a valid approach for achieving the set experiment objectives as deorbit will be mainly due to the induced Lorentz force acting on the tether. These orbits are however heavily populated with operating satellites. The tape tether design is optimised for surviving the micrometeoroid environment and assures a rapid deorbit when cut being the logical choice for reducing the operating risks for this orbit range. A flight altitude below the international space station is strongly recommended to increase the credibility of the experiment and also the number of flight opportunities. Design tools developed for this thesis can be extended to lower orbit altitudes and incorporate the use of a wire tether. Further development of orbit simulation tools, filtering strategy for estimating Lorentz forces, more research into current collection for short tethers, dynamic stability analysis and tether development is required.
ABSTRACT

The experiment proposed in this paper aims to demonstrate the deployment and operation of a bare electrodynamic (ED) tape tether in a low earth orbit. A bare ED tether does not require a separate current collection device thereby reducing system mass, complexity, etc. A tape tether is used as it is the most efficient geometry for current collection and it reduces the risk of tether severance. This experiment is fundamental in the development of a fully passive deboost capability for tether-equipped systems. The development of the tape tether, deployer and the method of experiment data acquisition are described.

1. INTRODUCTION

Since the 1990’s electrodynamic (ED) tethers are considered for propulsion purposes [1]. Advantage of an ED tether is that it does not require propellant to provide thrust. Studies have shown that for some missions, this can lead to a significant mass reduction. To date, a number of ED tether experiments have flown, but more experiments are needed to fully qualify the technology. However, the number of flight opportunities is limited because of the high cost of flight and the lack of suitable platforms. One way to increase the number of flight opportunities and to decrease the cost of flight, is to develop a low-cost ED tether experiment as payload on board of a micro-satellite. These are satellites typically characterised by low mass, rapid development, and low cost. To this end, ED tether system mass shall be minimised to the bare minimum needed to allow demonstration of the proper working of an ED tether. In this paper, the design of such a tether system is described.

2. OBJECTIVES AND REQUIREMENTS

Purpose of the work is to realise a low-cost ED tether experiment for flight on board of a micro-satellite that is capable of demonstrating tether deployment and its subsequent operation with as aim to achieve de-orbit. In addition, measurements shall be incorporated that allow for the verification of the design models used and the force level(s) attained.

The experiment shall be designed to operate on a micro-satellite. These are satellites with a mass in the range 10-100 kg. To establish more detailed experiment requirements, a number of micro-satellites, including TU-Delft’s own Delfi-1 micro-satellite [2], and their payload capabilities have been studied. The following set of general requirements for the experiment has been derived:

- Orbit altitude 650 - 1000 km (circular)
- Inclination 70° - 110°
- Mass ≤ 5 kg
- Power ≤ 5 W
- Data rate ≤ 200 bps
- Dimensions should not exceed 450 x 450 x 140 mm

The range of orbits (altitude and inclination) indicated is because most micro-spacecraft are launched piggyback and are without a propulsion system. Hence, the orbit of the micro-satellite cannot be selected freely.

3. BASELINE CONCEPT

Except from the tether itself, most tether experiments use a conducting (insulated) wire as tether equipped with a specific electron collector and emitter to produce a current in the tether [1]. However, this leads to a heavy and complex system. Studies [3] have shown that a bare tape ED tether without any special means for electron collection offers a highly mass efficient way to collect current. As such, it does provide a means of reducing system mass and system complexity.

Tape ED tethers are also considered attractive because of their longer lifetime expectancy in orbit and because of their aerodynamic drag. The latter ads to a rapid de-orbit of the satellite. It is also considered an advantage in case the tether is cut as in that case the tether will be capable of a self-standing de-orbit.

It is for the above reasons that the tape ED tether is selected instead of the commonly used wire-type tether.

Finally, to reduce ED tether system mass and cost, it is vital to limit tether length to the barest minimum
needed for demonstrating a proper understanding of the working principles involved. In this study we therefore focus on the minimum length needed to allow for determining a detectable change in orbit altitude.

4. ED TETHER OPERATION

4.1 Lorentz Force

A wire (tether) moving through a geomagnetic field induces an electromotive field (EMF) along the tether.

\[
EMF = \int (\mathbf{v} \times \mathbf{B}) \, dl
\]

where:
- \(EMF\) – orbit induced electromotive field [V]
- \(\mathbf{B}\) – magnetic field strength [T]
- \(\mathbf{v}\) – tether velocity relative to magnetic field [ms\(^{-1}\)]
- \(dl\) – infinitesimal tether length [m]

Assuming a straight tether (no bowing due to ED forces) oriented along the local vertical and using the magnetic dipole approximation for Earth’s geomagnetic field the induced electromotive voltage per unit of length can be approximated using [4]:

\[
E = v \cdot B_{eq} \cos(i)
\]

where:
- \(E\) – electromotive voltage per m [Vm\(^{-1}\)]
- \(B_{eq}\) – magnetic field strength equatorial orbit [T]
- \(i\) – orbit inclination [°]

Typical values for \(E\) are given in Fig. 1.

When the tether ends make contact with the plasma the EMF induces a current through the tether. At the top-end of the tether (point furthest away from Earth) electrons are collected that subsequently flow to the lower-end. At the lower-end ions are collected from the surrounding plasma, which upon impact with the tether are neutralised, thus ensuring a steady flow of current. In case the width of the tether remains below about 4 times the Debye length [5], the magnitude of the current can be calculated using Orbit Motion Limited Langmuir theory (OML). It follows for the maximum OML current for a bare tether [6]:

\[
I_{OML}^{(max)} = \frac{8eE}{\sqrt{9m_e}} dt
\]

where:
- \(I_{OML}\) – OML current [A]
- \(e\) – electron charge [C]
- \(n_e\) – electron density [kgm\(^{-3}\)]
- \(d_t\) – (average) tether diameter [m]
- \(m_e\) – electron mass [kg]
- \(l_e\) – electron collecting tether length [m]

For a tape tether an average tether width is calculated to take into account the twisting of the tether [6]:

\[
d_l = \frac{2(a + b)}{\pi}
\]

Fig. 2 gives some typical maximum OML currents for a specific tether for different orbits.

The results show that current decreases with increasing altitude and inclination. The irregular variation of current with altitude is caused by the electron density distribution [7].
In Fig. 3 the effect of tether length on OML maximum current is given.

![Graph showing predicted current levels (I_{OML}) for various tether lengths (L) in a 650 km 70° inclination orbit.]

Tab. 1 gives calculated values of the Debye length $\lambda_D$ [13] at different altitudes.

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>$4\lambda_D$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>29</td>
</tr>
<tr>
<td>700</td>
<td>33</td>
</tr>
<tr>
<td>750</td>
<td>34</td>
</tr>
<tr>
<td>800</td>
<td>34</td>
</tr>
<tr>
<td>850</td>
<td>39</td>
</tr>
<tr>
<td>900</td>
<td>49</td>
</tr>
<tr>
<td>950</td>
<td>55</td>
</tr>
<tr>
<td>1000</td>
<td>64</td>
</tr>
</tbody>
</table>

From this table, we learn that a tether width of 30 mm ensures that at all altitudes $\geq 650$ km OML theory can be applied to predict tether current.

Assuming that the tether is straight and oriented perpendicular to the magnetic field lines the Lorentz force acting on the tether can be calculated using:

$$F_L = IBL$$  \hfill (5)

$F_L$ – Lorentz force [N]
$I$ – current in tether [A]
$L$ – tether length [m]

This force will act against the motion of the tether. As such, it works in the same direction as the aerodynamic drag.

4.2 Decay Rate

Both the Lorentz force and the air drag acting on the tether dissipate orbital kinetic energy and lower the altitude. The drag force due to air drag for near circular orbits can be approximated by: [1, 8]

$$F_{air\text{drag}} = -\frac{1}{2} \rho C_D A_d v_{rel}^2$$  \hfill (6)

$\rho$ – atmospheric density [kgm$^{-3}$]
$C_D$ – drag coefficient [-]
$A_d$ – drag area [m$^2$]
$v_{rel}$ – satellite velocity relative to atmosphere [ms$^{-1}$]

The mechanical power dissipated is calculated using Eq. 6: (verified using [9])

$$P = F_{\text{drag}} v_{sat}$$  \hfill (7)

$P$ – dissipated power [W]
$F_{\text{drag}}$ – drag force [N]

The amount of power dissipated is proportional to the rate of change of the orbital energy:

$$P = -\frac{dE}{dt} \Rightarrow Pdt = -dE$$  \hfill (8)

$$E = -\frac{1}{2} \frac{\mu M}{a}$$  \hfill (9)

$$E_2 = E_1 - dE$$  \hfill (10)

$\mu$ – gravitational constant [m$^3$s$^{-2}$]
$a$ – semi major axis [m]
$dt$ – change in time [s]
dE – change in orbital energy [J]
$M$ – total mass [kg], see next section

Fig. 4 shows calculated change in SMA for various orbits for a specific tether configuration and a total system mass of 50 kg.

![Graph showing calculated change in semi major axis (ΔSMA) per day for a 30 mm wide and 1 km long tether.]

The Tab. 2 shows the contribution of air drag in the total change of SMA. The drag contribution is
estimated at solar maximum, which generally gives highest drag.

Tab. 2. Contribution (in %) of air drag in total $\Delta SMA$

<table>
<thead>
<tr>
<th>Orbit</th>
<th>650</th>
<th>700</th>
<th>750</th>
<th>800</th>
<th>850</th>
<th>900</th>
<th>950</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>70°</td>
<td>37%</td>
<td>28%</td>
<td>18%</td>
<td>12%</td>
<td>11%</td>
<td>10%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>75°</td>
<td>47%</td>
<td>37%</td>
<td>25%</td>
<td>18%</td>
<td>15%</td>
<td>14%</td>
<td>14%</td>
<td>13%</td>
</tr>
<tr>
<td>80°</td>
<td>63%</td>
<td>52%</td>
<td>39%</td>
<td>28%</td>
<td>25%</td>
<td>23%</td>
<td>23%</td>
<td>22%</td>
</tr>
<tr>
<td>85°</td>
<td>83%</td>
<td>76%</td>
<td>54%</td>
<td>49%</td>
<td>50%</td>
<td>47%</td>
<td>46%</td>
<td>46%</td>
</tr>
<tr>
<td>89°</td>
<td>98%</td>
<td>98%</td>
<td>96%</td>
<td>94%</td>
<td>93%</td>
<td>92%</td>
<td>91%</td>
<td>91%</td>
</tr>
</tbody>
</table>

The results show that the preferable orbits for the experiment are at high altitude and low inclination where Lorentz drag is the predominant force acting on the tether.

4.3 Tether Mass and Tension

The total mass of the system follows from:

$$M = m_{sat} + m_t$$

(11)

With:

- $m_{sat}$ – satellite mass (excluding tether) [kg]
- $m_t$ – deployed tether mass [kg]

Tether mass is determined using:

$$m_t = \rho_t L$$

(12)

$\rho_t$ – specific tether density [kg/m]

Because of the difference in gravity pull (gravity gradient) a tension force results in the tether. This tension force depends on tether mass and ballast mass at the free tether end. Maximum tension (@ moderate Lorentz force) can be approximated using:

$$T = 3m_t L \omega^2$$

(13)

$T$ – tension [Nm$^2$]

$m_A$ – $m_b + \frac{1}{2} m_t$ (equivalent end-mass) [kg]

$m_b$ – ballast mass [kg]

$\omega$ – orbital frequency [rads$^{-1}$]

4.4 Stability

The behaviour of tether and satellite together depends on ED torque, (restoring) gravity gradient (GG) torque, mass distribution and tether length.

Static stability

ED and restoring GG torque always reaches equilibrium in the static case in case the tether has an angle $< 45^\circ$ from the vertical. At larger angles the magnitude of the GG torque decreases and the system may become unstable possibly leading to satellite flip-over (tumbling). The current at which the angle of the tether exceeds $45^\circ$ is described in [8] as:

$$I_{crit} = \frac{3\omega^2}{B} \left( m_b + \frac{1}{2} m_t \right)$$

(14)

Tab. 3 gives critical current in comparison with maximum OML current. It shows that the currents remain well below critical levels.

Tab. 3. Critical current for various tether lengths

<table>
<thead>
<tr>
<th>Tether length [km]</th>
<th>Stable Current levels [A]</th>
<th>Maximum $I_{OML}$ [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.026</td>
<td>0.004</td>
</tr>
<tr>
<td>1</td>
<td>0.052</td>
<td>0.014</td>
</tr>
<tr>
<td>1.5</td>
<td>0.076</td>
<td>0.026</td>
</tr>
<tr>
<td>2</td>
<td>0.100</td>
<td>0.040</td>
</tr>
<tr>
<td>2.5</td>
<td>0.126</td>
<td>0.056</td>
</tr>
</tbody>
</table>

Dynamic stability

Dynamic analysis shows that resonance between tether librations and environmental variations (magnetic field, plasma density) affect the out-of-plane stability and eventually due to coupling the in-plane stability [10]. Eventually libration amplitude reaches a level resulting in tumbling of the system. A passive bare tether operates in both nadir and zenith direction so the system is still capable of de-orbit when tumbling.

The following linearised equations of motion of the tether system in a circular orbit have been generated following the work of [8, 11-12]:

$$\dot{\theta} + 2 \frac{L}{L^*} \left( \theta + 1 \right) + 3 \omega = \frac{Q_\theta}{L^* m^* \omega^2}$$

$$\dot{\phi} + 2 \frac{L}{L^*} \phi + 4 \Phi = \frac{Q_\phi}{L^* m^* \omega^2}$$

$$\dot{L} - 2 \omega - 3 = \frac{Q_l}{L^* m^* \omega^2}$$

$\theta$ – in plane angle

$\phi$ – out of plane angle

$Q$ – generalised force

$m^*$ – reduced system mass

$$m^* = \frac{m_{sat}}{M} \left( m_b + \frac{1}{2} m_t \right)$$

(16)
For $m_b = 0$ and $M \gg m_t$

$$M = \frac{1}{2} m_t = m_A$$  \hspace{1cm} (17)

The most critical phase for the experiment is the deployment. For a vertically oriented tether energy dissipation during or after deployment is required for stabilisation. The amount of energy to be dissipated equals [13].

$$E_{diss} = \frac{1}{2} L T_{equi} = \frac{3}{2} m_A \omega^2 L^2$$  \hspace{1cm} (18)

An ED tether operating without current control system eventually becomes unstable due to current variations and changing geomagnetic strength and direction especially at high inclinations. However, at low current levels, this is a relatively slow process [14] and therefore is not expected to be critical for deployment and operation.

5. DESIGN

To limit the cost of the ED tether experiment, we aim to minimise system mass and volume, and to reduce complexity while ensuring proper operation of the tether and the deployment mechanism. System mass is minimised by selecting minimum tether length required.

An advantage of flying on a micro-satellite like Delfi-1 is that a relatively small drag force is sufficient to obtain a measurable change in SMA within a short time. Because of this a completely passive tether design has been selected. This gives a lower current than when including a cathode, but limits complexity, power usage and mass.

5.1 Tether

Aluminium is selected as tether material. In [15] it is shown that aluminium offers low cost and high specific conductivity. To ensure tether integrity it is reinforced with tape. This stops ripping of the aluminium foil when damaged by debris or during deployment. The aluminium is coated to protect the tether against oxidation (e.g. atomic oxygen).

Tether dimensions follow from considerations concerning the Debye length and the minimum force needed to generate a measurable change in SMA. Tether width is selected at 30 mm. Tab. 1 shows that this allows for maximum OML current collection for all possible orbits within range. The length of the tether is selected at 1 km. This gives a change in SMA of minimum 12-298 m/day depending on the orbit, Tab. 4.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>30 mm x 5 µm x 1 km</td>
</tr>
<tr>
<td>Tether mass</td>
<td>0.7 kg</td>
</tr>
<tr>
<td>Specific resistance</td>
<td>$2.74 \times 10^8$ Ωm$^{-1}$</td>
</tr>
<tr>
<td>Reinforcing laminate</td>
<td>8 mm x 12.5 µm</td>
</tr>
<tr>
<td>Tension force</td>
<td>1.36 mN</td>
</tr>
<tr>
<td>ΔSMA</td>
<td>12 - 298 m per day</td>
</tr>
<tr>
<td>Ratio maximum disturbing/stability</td>
<td>0.3</td>
</tr>
<tr>
<td>Ballistic coefficients</td>
<td>Delfi-1 + tether: 1.1 m$^2$kg$^{-1}$</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-100 + 50 °C</td>
</tr>
</tbody>
</table>

5.2 Deployment Mechanism

An open-loop control strategy is chosen for the tether deployment. This reduces the system volume and complexity. Stable deployment is expected because of the low currents in the tether (Eq. 15).

A reel system is selected for storage and deployment of the tether. The tether shall be deployed perpendicular to the reel axis, with the deployer attached to the satellite. Based on the length of the tether we find for the diameter of the reel 135 mm. This is within the required maximum width of the payload bay (140 mm). The width of the reel is taken slightly larger than the tape width at 34 mm. This allows for installing tape guides on the reel, which prevent the tether slipping from the reel.

A motorised reel deployer and an inertia driven reel are considered. For a motorised reel deployer small velocity variations can easily lead to slack build-up, which may cause blockage of the tether deployment. An inertia driven reel, for example by using a spring driven tether deployment, is less susceptible to slack. However, a braking system is needed. Further study is required here.

5.3 Telemetry

Experiment data consists of onboard sensor data and satellite tracking data (altitude).

The onboard sensors consist of:
- Optical turn counter (12 bit data @ 1 Hz)
- Magnetometers (Delfi-1 standard equipment, not part of payload)
- Voltmeter (12 bit data @ 1 Hz)
- Global Positioning System (GPS) receiver (based on SSTL SGR-05, accuracy is 20 m)

The optical turn counter is used to measure the deployed tether length, and to determine the deployment velocity.
The magnetometers measure the magnetic field strength thereby allowing for an estimation of the current in the tether. The voltmeter is needed to measure the induced EMF again allowing for model verification. The GPS receiver is used before and after tether deployment to determine orbit decay rate due to air and Lorentz drag. Because of the accuracy of the GPS receiver used at least two days of operation are considered necessary to get a good indication of the change in SMA, see also Tab. 6. Another way of determining orbit decay is via the Delfi-1 tracking system. However, this has a lower accuracy and information is only obtained at certain time intervals. This then requires a longer operation time for a noticeable change in SMA to occur. To determine the effect of air drag on de-orbit rate two options are considered, an air density measurement device onboard and ground processing using the GPS data and an orbit propagation model. The latter method has been selected for this study.

5.4 Miscellaneous items
The following miscellaneous items have been taken into account:
- DC/DC power converter
- Stepper motor and control board

The power converter is dimensioned for a power level of 4 W taking into account an efficiency of 75%. The converter selected is capable of handling various bus voltages.

The stepper motor is included to allow for braking and or driving the reel.

5.5 Total system and integration with Delfi-1
The mass allocation for the tether system is shown in Tab. 5. Average power used by the experiment is estimated at 4 W.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>Size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployer</td>
<td>2.0</td>
<td>135 x 34</td>
</tr>
<tr>
<td>Telemetry + stepper motor</td>
<td>0.5</td>
<td>100 x 70 x 45</td>
</tr>
<tr>
<td>Power converter</td>
<td>0.7</td>
<td>15 x 10 x 89</td>
</tr>
<tr>
<td>Tether</td>
<td>0.7</td>
<td>1 km x 30 mm x 5 µm</td>
</tr>
<tr>
<td>Total system</td>
<td>3.9</td>
<td></td>
</tr>
</tbody>
</table>

Magnetometers are not included in the table because they part of the attitude control system of Delfi-1. We only use the data.

Development time of the tether system is estimated at 4 years and development cost at € 200,000.

Fig. 5 shows a schematic drawing of the Delfi-1 satellite and the tether system. The tether system is installed onto the payload platform and is deployed in nadir direction. The opposite side is occupied by the satellite’s gravity gradient boom (pointing accuracy of ±5°).

Fig. 5. Delfi-1 satellite

The cost of flying the experiment onboard Delfi-1 is estimated at M€ 0.65 including launch and 3 months of operations.

6. OPERATION

The experiment is activated in the last phase of the Delfi mission to allow other payloads to operate at constant altitude. During the deployment of the tether the optical turn-counter records the deployed length. Following deployment the GPS and voltmeter are activated. The magnetometer is already active as part of Delfi-1 attitude control.

6.1 Operating Time
The operational life of the experiment is limited by tether lifetime in the micrometeoroid and orbital debris (M/OD) environment and by tether instability. The operational time of the experiment needed to obtain a measurable change in SMA is given in Tab. 6:

<table>
<thead>
<tr>
<th>De-orbit measuring system</th>
<th>Required Δ SMA [m]</th>
<th>Minimum operating time [days]</th>
<th>Maximum operating time [days]</th>
<th>M/OD Survival probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>20</td>
<td>0.055</td>
<td>1.4</td>
<td>99.9%</td>
</tr>
<tr>
<td>GS tracking</td>
<td>4000</td>
<td>11</td>
<td>228</td>
<td>89.4%</td>
</tr>
</tbody>
</table>

Minimum operating time is for lowest altitude and inclination, maximum for highest.

Tether survival probability is calculated using orbital debris flux model [7,16] for maximum operating time only. Results are also given in Tab. 6. Whether
instability problems occur within the 3 months of operation time is still to be investigated.

6.2 Risks during Operation
As most important risks have been identified:
- Tether severance
- Non functional fully or partially deployed tether

When the tape tether is severed it is highly susceptible to air drag as it has a high ballistic coefficient, see Tab. 4. As a result, the tether performs a fast de-orbit, thereby minimising the collision risk with other orbiting objects. In case the tether does not produce a (sufficiently high) Lorentz force the satellite’s altitude is reduced by air drag only. This will give a higher collision risk, but the satellite is still removed from orbit.

7. CONCLUSIONS & RECOMMENDATIONS
A passive ED tether experiment is designed fit for use on Delfi-1. The system is capable of changing the altitude of Delfi-1 with 10-300 m/day depending on the initial orbit and time of launch (solar max or min.). A mission at high altitude and low inclination is preferred because of the reduced disturbing effect of air drag on de-orbit rate. However a low altitude orbit reduces the risk of collision, see Tab. 6. Since endangering other satellites should be remote, further work is considered necessary to reduce this risk to the barest minimum.

To reduce the risk of collision, two options may be considered. The first option is to use a cathode to enhance de-orbit capability. Thereby reducing time in orbit. The second, more promising, option is to avoid the heavily populated orbits by flying below 600 km or even lower to also avoid the International Space Station. For this option a cathode and direct current measurement need to be incorporated to allow determining tether performance. Both options lead to an increase in system mass, and complexity, and limit the number of flight opportunities.

8. REFERENCES
5. Gilchrist B.E., Bilen S.G., Gallimore A.D., et al., Current Collection to Long Conductors with Wide Geometries for Bare Electrodynamic Tether Applications: A Laboratory Update, AIAA 2002-1123, 40th Aerospace Sciences Meeting and Exhibit, 2002
7. SPENVIS- Space Environment Information System & Space Engineering
DELFI-1 Project

EDT Experiment onboard Delfi-1

Preliminary Design

DELFI.1.TW.4122.10

10-01-12

Thesis Report
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NOTATIONS, SYMBOLS & ACRONYMS

\begin{align*}
a & \quad \text{semi major axis} \\
a_{\text{ad}} & \quad \text{aerodynamic drag acceleration} \\
A_c & \quad \text{cross sectional area tether} \\
A_{\text{coll}} & \quad \text{effective current collection area tether} \\
A_d & \quad \text{drag area} \\
B & \quad \text{magnetic field strength} \\
B_{\text{all}} & \quad \text{ballistic coefficient} \\
C_D & \quad \text{drag coefficient} \\
d_e & \quad \text{effective tether diameter} \\
dl & \quad \text{increment of tether length} \\
dt & \quad \text{time increment} \\
D_0 & \quad \text{normalizing diameter of 1 mm} \\
E & \quad \text{electromotive voltage per m} \\
E & \quad \text{orbital energy} \\
f & \quad \text{3.46 empirical parameter} \\
F_{\text{ad}} & \quad \text{aerodynamic drag force} \\
F_L & \quad \text{Lorentz force} \\
h & \quad \text{orbit altitude} \\
i & \quad \text{orbit inclination} \\
l & \quad \text{current in tether} \\
l_{\text{OML}} & \quad \text{current in tether} \\
l_e & \quad \text{electron collecting tether length} \\
l_i & \quad \text{ion collection tether length} \\
l_{\text{sp}} & \quad \text{specific impulse} \\
L_t & \quad \text{total deployed tether length} \\
m & \quad \text{total system mass} \\
m_b & \quad \text{end mass} \\
m_{i,\text{eq}} & \quad \text{equivalent ion mass} \\
m_t & \quad \text{mass of the deployed tether} \\
n_e & \quad \text{electron density} \\
P & \quad \text{power} \\
r & \quad \text{geocentric orbital radius} \\
t & \quad \text{tether thickness} \\
T & \quad \text{tension force} \\
T_t & \quad \text{tether temperature} \\
v & \quad \text{tether velocity relative to magnetic field} \\
v_{\text{rel}} & \quad \text{satellite velocity relative to atmosphere} \\
v_{\text{orb}} & \quad \text{orbital velocity} \\
\Delta v & \quad \text{orbital velocity change} \\
V & \quad \text{voltage} \\
w & \quad \text{tether width} \\
\theta & \quad \text{geomagnetic latitude} \\
\rho & \quad \text{atmospheric density} \\
\rho & \quad \text{material density} \\
\rho_t & \quad \text{specific tether density} \\
\sigma & \quad +9.58\text{E}-9 \text{ craters/s·m}^2 \text{ is the empirical debris flux} \\
\omega_0 & \quad \text{orbital frequency}
\end{align*}

\textbf{Symbols}

\begin{itemize}
  \item[$\theta$] geomagnetic latitude \quad \text{[°]}
  \item[$\rho$] atmospheric density \quad \text{[kgm}^{-3}] \\
  \item[$\rho$] material density \quad \text{[kgm}^{-3}] \\
  \item[$\rho_t$] specific tether density \quad \text{[kgm}^{-1}] \\
  \item[$\sigma$] +9.58E-9 \text{ craters/s·m}^2 \text{ is the empirical debris flux} \\
  \item[$\omega_0$] orbital frequency \quad \text{[rads}^{-1}] 
\end{itemize}

\textbf{Sub and superscripts}

\begin{itemize}
  \item[$e$] electron \\
  \item[$i$] ion \\
  \item[$t$] tether
\end{itemize}
Acronyms

bps  bits per second
AC   Alternating Current
ACS  Attitude Control System
ADCS Attitude Determination & Control System
ASI  Agenzia Spaziale Italiana
ATEx Advanced Tether Payload
CDHS Delfi-1 Command and Data Handling System
COMM Delfi-1 Communications System
DEP  EDT Deployment System
DCS  Deployment Control System
DoD  Department of Defence
DTU  Technical University of Denmark
ECSS European Cooperation for Space Standardisation
ED   Electrodynamic
EDDE Electrodynamic Delivery Express
EDT  Electrodynamic Tether
ELF  Extremely Low Frequency
EM   End Mass
EMC  Electromagnetic Compatibility
EMF  Electromotive Field
EOL  End of Life
EPS  Electrical Power System
ESA  European Space Agency
ESOC European Space Operations Centre
ETBSim Electrodynamic Tether Bead Simulator
FBD  Functional Breakdown
FEAC Field Emitting Anode Cathode
GAS  EDT Gas storage and release System
GGB  Gravity Gradient Boom
GS   Ground Station
HDRM Hold Down and Release Mechanism
HW   Hardware
ISS  International Space Station
LEO  Low Earth Orbit
MIT  Massachusetts Institute of Technology
M/OD micrometeoroid and orbital debris
MOI  Moments of Inertia
MT   Mechanical Tether
MTBF Mean Time Between Failure
NAL  National Aerospace Laboratory of Japan
NASA National Aeronautics and Space Administration
NRC  National Research Council of Canada
OML  Orbit Motion Limited
PL   Payload
ProSEDS Propulsive Small Expendable Deployer System
PUID Project Unique Identifier
RAMS Reliability Availability and Safety Requirements
RTM  Requirements Traceability Matrix
SATAJ Self Accelerating Tethers around Jupiter
SC   Spacecraft
SEDS Small Expendable Deployer System
SLR  Standard List of References
SMA  Semi Major Axis
SS   Delfi-1 structure subsystem
SSI  Subsystem Interface
STS  EDT Structural System
Physical Constants

<table>
<thead>
<tr>
<th>Physical Constant</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geocentric Earth mass</td>
<td>$M_E$</td>
<td>$5.974 \times 10^{24}$</td>
<td>$\text{kg}$</td>
</tr>
<tr>
<td>Universal gravitational constant</td>
<td>$G$</td>
<td>$6.673 \times 10^{-11}$</td>
<td>$\text{m}^3\text{kg}^{-1}\text{s}^{-2}$</td>
</tr>
<tr>
<td>Earths gravitational constant</td>
<td>$\mu$</td>
<td>$3.986 \times 10^{14}$</td>
<td>$\text{m}^3\text{s}^{-2}$</td>
</tr>
<tr>
<td>Magnetic field strength @magnetic equator</td>
<td>$B_{eq}$</td>
<td>$3.012 \times 10^{-5}$</td>
<td>$\text{T}$</td>
</tr>
<tr>
<td>Elementary electron charge</td>
<td>$e$</td>
<td>$1.602 \times 10^{-19}$</td>
<td>$\text{C}$</td>
</tr>
<tr>
<td>Electron mass</td>
<td>$m_e$</td>
<td>$9.109 \times 10^{-31}$</td>
<td>$\text{kg}$</td>
</tr>
</tbody>
</table>
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1 INTRODUCTION

This document [DELF.1.TW.4122.10] is the first part of a thesis having the goal to design and size an electrodynamic tether experiment capable of demonstrating the operation of a bare passive tether onboard the Delfi-1 micro satellite. It intends to provide an overview of critical aspects concerning the design and use of tethers as follows from literature and to present an initial (baseline) design of the electrodynamic tether experiment which shall serve as a starting point for more detailed studies presented in the second part of this thesis.

The thesis is carried out as part of the student-led Delfi-1 project, which aims to design and develop a university micro satellite capable of operating advanced technology test payloads. The Delfi-1 project in a broader sense provides students with an opportunity to gain hands-on experience in the various aspects of the design, development, launch and operation of a small technology test satellite.

The Delfi-1 satellite will be designed to operate multiple payloads during a one year mission launching the satellite using a piggy back launch. Some Delfi-1 characteristics are [Annes]

- Mass < 50 kg
- Dimensions 450 x 450 x 450 mm
- Power 39 W
- Gravity Gradient stabilised
- Orbit altitude range h 650-1000 km
- Orbit inclinations range i 70º-110º
- Payload Mass \( \leq 5 \text{ kg} \)
- Payload Power \( \leq 5 \text{ W} \)
- Payload Data rate \( \leq 200 \text{ bps} \)
- Payload Dimensions should not exceed 450 x 450 x 140 mm

One of the proposed payloads is an electrodynamic tether experiment. The aim of this experiment is to demonstrate the use of tethers for satellite propulsion and validate current theories on the operation of bare electrodynamic tethers. The experiment was proposed by Delta-Utec (Leiden) and it is intended to demonstrate part of the operation of the proposed Self Accelerating Tethers around Jupiter (SATAJ) concept [LeBreton] and the use of a passive tether as a method of deorbiting satellites and spent rocket stages limiting space debris.

This document provides an overview of various aspects related to tether experiment design, experiment objectives and an initial design of the electrodynamic tether experiment. In the chapter 2 a short introduction on the working of an electrodynamic tether system is given and a number of potential uses of electrodynamic tethers are listed. The current technology status of electrodynamic tethers is also described in this chapter. In chapter 3 a mission analysis is performed to determine the main objectives of the electrodynamic tether experiment. Previous electrodynamic tether experiments and proposals including two for the Delfi-1 satellite have been studied and based on current electrodynamic tether technology status and in concurrence with user needs the mission objectives are determined. In chapter 4 some general guidelines for the design of the electrodynamic tether experiment onboard the Delfi-1 satellite are introduced. In chapter 5 a baseline design for the payload is selected and the system requirements are derived. A workpackage description for the subsequent design phases is also generated.

---

1 Delfi.1 refers to the Delfi-1 project. TW refers to thesis work, and the number 4122 refers to the EDT payload on board of Delfi-1. Higher system level documents all bear the numbering 4120. In subsequent sections the prefix DELFI.1. is omitted from references to internal documents.
2 ELECTRODYNAMIC TETHER PRINCIPLES

In this section the basic operation of an electrodynamic tether (EDT) system is briefly explained and a number of potential uses for electrodynamic tethers are listed. Also an overview of the current technology status is given.

2.1 Electrodynamic Tether Basics

An EDT is a conducting wire that interacts with Earth’s magnetic field and generates a force that influences the orbit of the satellite converting kinetic energy into electrical energy or vice versa, either dissipating or increasing the system’s orbital energy. A conducting wire moving through a geomagnetic field induces an electro motive force field (EMF) along the tether due to induction of the second kind resulting in a voltage drop of the plasma with respect to the tether.

\[ EMF = \int (v \times B) \, dl \]  

\( v \) – tether velocity relative to magnetic field [ms\(^{-1}\)]
\( dl \) – increment of tether length [m]
\( B \) – magnetic field strength [T]

A tether moving in a pro-grade orbit will charge to a positive bias with respect to the ionospheric plasma at the upper end oriented away from the Earth and negatively at the nadir pointing end. The biased tether collects electrons from the plasma at the positively charged end and ions (emits electrons) at the negatively biased end closing the current loop. Space charging effects will balance these currents biasing the tether to floating potential resulting in a current flow in the tether.

![Figure 1: EDT in drag operation mode](image)

The electrons emitted by the tether travel along magnetic field lines bouncing between ionospheric boundary layers disappearing into the background plasma and not returning to the tether [Heide]. With a current flowing through the moving tether a Lorentz force is exerted on the tether by Earth’s geomagnetic field

\[ F_L = \int (I \cdot dL) \times B = I \int dL \times B \]

\( F_L \) – Lorentz force [N]
\( I \) – current in tether [A]
For an electrodynamic tether in a Low Earth Orbit (LEO) the induced Lorentz force for a passive tether acts on average as a drag force dissipating the orbital kinetic energy reducing the orbit altitude of the system. This is the configuration that can also be used for power generation, if an up-boost is required the direction of the current needs to be reversed with the tether operating in thrust mode. To reverse the current a power source is required to actively bias the tether with respect to the surrounding plasma. The electrical power generated by an EDT is assumed to be equal to the work done by the Lorentz drag force acting in the opposite direction of the satellite velocity [Vannaroni]

\[ P = F_L V_{orb} = VI \]  
(2-3)

- \( P \) – power [W]
- \( V \) – voltage [V]
- \( V_{orb} \) – orbital velocity \([\text{ms}^{-1}]\)

Assuming the amount of power generated by the tether is proportional to the rate of change of the orbital energy \( E \) of the spacecraft (SC) the resulting orbital change can be calculated as

\[ P \sim \frac{dE}{dt} \]  
(2-4)

- \( dt \) – time increment [s]
- \( E \) – orbital energy [J]

With orbital energy \( E \) given as

\[ E = \frac{-1}{2} \frac{GM_E m}{a} \]  
(2-5)

- \( G \) – universal gravitational constant \( 6.673 \times 10^{-11} \, \text{[m}^3\text{kg}^{-1}\text{s}^{-2}] \)
- \( M_E \) – geocentric Earth mass \( 5.974 \times 10^{24} \, \text{[kg]} \)
- \( m \) – total system mass [kg]
- \( a \) – semi major axis [m]

### 2.2 Potential Applications for Electrodynamic Tethers

Electrodynamic tethers operating in either generator (drag) or thrust mode have various applications

- Deorbit of spent upper stages and LEO satellites with the system capable of operating autonomously on defect satellites reducing space debris [less; Hoyt]
- Orbit maintenance and manoeuvres of for example the International Space Station (ISS) [Jainandunsing; Cosmo]
- Reduce weight of upper-stage rockets
- Generating electrical power
  - Peak power generation useful for providing high-power energy bursts to short-duration experiments
  - Eclipse power source
  - The main power source for example ISS [Estes]
- Use on planetary missions to Jupiter, Saturn or any planet with a significant magnetosphere as a power source and/or orbit control device with Jupiter’s environment ideal for the use of short electrodynamic tethers due to the strong magnetic field and high plasma density. EDT’s can be used both as propulsion device and power source in the Jovian environment [Gallagher]
- Sensor line: Sanmartin [3] proposed the use of a tether as a sensor line for in-situ ionospheric measurements to study Earth’s atmosphere below 200 km
- Communication antenna ULF/ELF/VLF: Use tethers to provide world wide communications capability; VLF capability was shown by Charge-2, see appendix 1
- Combination of moment exchange mechanical tether (MT) and ED tether
Two applications mentioned above, deorbiting and power generation, have been examined in more detail in [TN.4122.22] as part of the current work and will be shortly summarised below.

Various studies have been performed focussing on EDT’s as a power generator for the International Space Station [Cosmo; Estes]. The EDT can be used for power generation, but may be required to operate with thrusters to compensate for the Lorentz force decelerating the spacecraft. This can be more efficient than conventional power sources depending on the mission type; according to [Lorenzini] 5-10 day use of a combination of EDT and rocket propulsion is more efficient than using fuel cells as a power source.

Advantages using an EDT as a power source are
- Efficient power converter of orbital energy to electrical power
- High specific power for longer tethers (20 km) [TN.4122.26]
- Simple system
- Works during eclipse

Disadvantages using an EDT as a power source are
- Unwanted deorbit of the satellite
- Decreased performance at high altitudes and inclinations
- Technical Readiness Level (TRL) lower than conventional systems

An EDT can also be used for deorbiting purposes. Space debris (all non functional man made objects in orbit) is an increasing problem requiring an active approach by all parties involved in the launching and operating of spacecraft and rockets. One of the main methods for reducing the amount of space debris is deorbiting satellites and spent rocket stages at end of life (EOL) to limit their remaining orbital lifetime to less than 25 years [ESA 1999; NASA 1995]. The use of conventional propulsion systems for deorbit purposes is currently limited to chemical propulsion systems using either cold gas (low specific impulse ($I_{sp}$), high propellant mass and volume) or monopropellant hydrazine thrusters (operational flexibility) [less; TN.4122.22]. Cold gas systems are generally too heavy due to the high propellant mass required with the specific impulse being the lowest of all propulsion systems. Using a rocket system for deorbit purposes requires a significant amount of propellant mass depending on the initial orbit altitude. The average orbital velocity change ($\Delta V$) for a deorbit in LEO is roughly $400 \text{ms}^{-1}$ requiring on average a propellant mass fraction of $1/5^{th}$ of the spacecraft mass at the start of the manoeuvre [less]. For nano- and micro-satellites adding a deorbit system based on conventional propulsion can double the SC mass as these satellites usually do not require an onboard propulsion system for their mission [Janovsky]. Also the requirements put on the propulsion system design are more stringent when used for deorbit purposes. The thrusters need to have increased life and the system also needs to be functional when the satellite is not operating. This could require the system to provide its own power, attitude control and orbit determination for it to be able to operate.

Various studies have proposed the use of EDT systems for deorbiting spacecraft or rocket stages at End of Life (EOL). The main advantage of an EDT over conventional propulsion systems is that it does not require any propellant, only the tether system itself and a power source depending on the operation mode (thrust or drag mode) are needed. For LEO orbits the EDT system can deorbit a spacecraft by operating in a passive drag mode independent of the spacecraft increasing the reliability of the deorbit system. Deorbit using a tether will result in a spiral transfer to the final orbit similar to applying a constant low thrust burn making it comparable to high $I_{sp}$, low thrust electric propulsion manoeuvres. The Terminator Tether (TT) study by [Hoyt] showed that an EDT with total mass of 2% of the spacecraft mass is capable of transferring typical constellation satellites in a 1300 km circular Earth orbit within months to a re-entry orbit of 200 km. A study done by [less] obtained similar results deorbiting a 500 kg satellite at 1300 km to an altitude of 240 km within 20-100 days for a range of inclinations. According to [less; Hoyt] an EDT system with a mass of up to 30-50 kg is capable of deorbiting most LEO satellites within months. To deboost satellites with a mass below 100 kg [Carroll] showed that using an optimised chemical propulsion systems results in a lower mass than for an EDT system, however a tether system is considered simpler, safer and cheaper.

---

2 Delfi document overview is given in the list of references at the end of this document.
In the current work a small investigation has been performed aiming to determine the potential benefits of an EDT system. The detailed results are reported in [TN.4122.22]. The main results show that using an EDT system of mass up to 30-50 kg on a 500 kg spacecraft in a 1500 km initial orbit is beneficial compared to rocket propulsion for ΔV requirements in excess of 150-250 ms⁻¹. Deorbit strategies where the orbit altitude is reduced to 200-250 km allowing aerodynamic drag to take over requires an even larger ΔV, which makes the use of an EDT system even more attractive. Using a mission specific tether system with a 15%-2.5% mass ratio distribution (mₜ/mₛ) to estimate the mass of the tether system for mₛ ranging from 10 to 2000 kg the EDT deorbit becomes the favourable system for satellites of 100-150 kg when compared to a chemical propulsion system with Iₚₜ = 300 s, shown in figure 2.

The simplest EDT deorbit system conceivable is an entirely passive system using a bare tether to collect current. Active current control would allow for more precise orbit control manoeuvres, deorbiting by changing the orbit eccentricity lowering perigee altitude requiring less ΔV, or inclination changes to lower orbit inclinations where tether drag operation is more favourable.

Advantages when using an EDT for deorbit purposes are
- Low mass system for satellites m > 250 kg range for tether system mass (30-50 kg)
- Mass ratio mₜ/mₛ ranges from 2.5%-15%
- No propellant (increased storage - lifetime; lower mass)
- Reliable, operates independent of satellite; does not require power for passive operation
- Low cost mainly due to mass advantage
- Simple system
- One off the shelf design applicable for different applications and SC mass
- Passive tether is inherently non explosive reducing space debris risk

Disadvantages using an EDT for deorbit purposes are
- Orbit altitude h<1500 km
- Passive operation optimal for lower inclination orbits i<75º, for near polar orbits deorbit capabilities decrease drastically due to orientation of magnetic field
- Technical Readiness Level TLR 6-7 [NASA/DoD Janovsky]
- Longer deorbit times for short EDT passive operation mode
- Increased area of spacecraft with higher risk of debris impact

For spacecraft and rocket stages not having a propulsion system the use of an EDT as a deorbit system will have advantages. For spacecraft already equipped with a propulsion system the use of an EDT can be preferable in certain cases depending on the spacecraft mass, the deorbit capabilities of the propulsion system onboard, the initial orbit and required deorbit ΔV-Δt and subsequent propellant mass.

![Figure 2: Propulsion system mass (mₚ) versus tether mass (mₜsys) as function of spacecraft mass (mₛ) [TN.4122.22]](image-url)
2.3 Technology Status

The technology of mechanical and electrodynamic tethers has been developed over the past 30 years. To date a number of tether experiments have been flown, not all successfully but they have shown the capabilities of space tethers. In appendix 1 previously flown tether missions, planned missions and future mission proposals are collected in a table with some missions described in more detail. In appendix 2 an overview of parties involved in the development of tethers is given. Below various aspects of EDT systems design and the current areas of research are listed.

The main components of an EDT system shown in figure 3 are the tether, the deployment mechanism, a stabilising end mass also known as the sub-satellite, plasma contactor device, electronics, instruments and data handling systems.

Figure 3: General EDT system breakdown

Of these elements the tether, deployer and plasma contactors are found to be most critical.

Tether
Research areas consist of tether materials, degradation in space and survivability of the tether in the micrometeoroid and debris environment. For high voltage and current systems the tether will have to be protected from the effects of the high electrical potential between the tether and ionosphere when insulated. A study performed by [Anselmo] concluded that for single wire tethers in LEO survivability in the micrometeoroid and orbital debris (M/OD) environment is an issue and also states different tether geometries and designs can mitigate the risk. The 20 km SEDS-2 wire tether was expected to survive 12 days but was cut after 4 indicating the importance of new tether designs having an increased survivability. Concepts include multi-strand braided tethers as used for the TiPS mission surviving 10 yrs in orbit and enforced tape tethers used by ATEx. The ATEx mission failed during deployment most likely due to tether heating and its effects on tether properties indicating a need for thermal modelling of the tether especially during mission critical phases like deployment. The design of 'deployable' survivable tethers taking friction, stiction and shape memory into account is also of interest. Tether heating especially for low orbit altitudes and atmospheric probes can be a critical factor during operation.

Bare Tether Current Collection
The demonstration of using a bare tether to efficiently collect current both being a more effective anode than a passive spherical current collection device [Sanmartin] and being less complex than active plasma contactors. For comparison, the TSS-1R sphere used for passive current collection has a surface area of an 8 m$^2$ [Cosmo], $d_{\text{sphere}} = 1.6$ m, $l_{\text{sphere}} = 1$ mm. Assuming aluminium is used as the material for the sphere this gives a mass of approximately 21 kg. In contrast a 5 km wire tether, diameter $d_t$ of 0.85 mm has a collection area of 13.35 m$^2$ and a mass of only 7.6 kg. The small cross-sectional area of a tether also enables the tether to collect current within the orbit motion limited (OML) regime theoretically inducing the largest possible current density [Sanmartin; Ahedo].
An in orbit demonstration of orbit motion limited (OML) current collection using a bare tether is a priority for further development of this concept validating the current theoretical models predicting OML current collection theory. Entirely passive operation of a tether generating both orbit induced EMF (verified by the PMG mission) and collecting current is potentially a very simple passive deorbit system. The current levels and drag force an EDT system can theoretically induce is currently limited by plasma contactor capacity and dynamic stability more than by electron collection if the proposed bare tether anode principle [Sanmartin] does indeed work.

**Deployer and tether control**
The development of deployment mechanisms capable of deploying various tether designs (multi-braid; tape tethers) is required. The ATEx tape tether failed to deploy during due to a lack of robustness in deployer design [appendix 1]. TiPS successfully deployed a multi-braid tether however the deployment of tape tether has yet to be demonstrated. Also development of deployment systems that can both deploy and retract a tether using tether retraction for dynamic control and to initiate rotation of the system allowing for stabilisation of the tether [LeBreton] is a challenge.

Electrodynamic tethers need to be able to operate for extended periods, months to years, depending on function and orbit. Dynamics induced by out-of-plane forces tend to destabilise the tether. Also variations of day-night ionospheric density, temperature and magnetic field strength can induce long term instabilities of the system. A control system increasing the stability of the tether allowing for higher current levels, either by active current control or mechanical stabilisation required for long term operation of EDT's. The stability of tether during deployment and in deployed state and verification of expected dynamics of the tether need to be researched further.

The SEDS-2 mission has shown that tethers can be deployed to a stable vertical configuration using a simple feedback system during deployment [appendix 1]. Research is being done on self rotating and self balancing EDT’s [LeBreton; Peláez]. Tether stability during operation can also be increased by using a part mechanical part ED tether limiting the required stabilising end mass and complexity of an active current control device [Kruijff].

**Plasma contactors**
For high power and short ED tethers plasma contactors (anodes/cathodes) are required to generate sufficient current. Current-voltage characteristics of cathodes and anodes and temperature analysis of hollow-cathodes and effects on surrounding electronics and systems need to be researched. As of yet only complex and high power requirement contactors have been used. Simple systems such as field emitting anode cathode (FEAC) or heated filament methods are being developed. Focus on low power and mass and robust simple systems. Use of the bare tether as a current collection device and plasma contactor is inherently the simplest system available.
3 EDT EXPERIMENT OBJECTIVES

In this chapter potential scientific objectives for the EDT experiment are listed. The electrodynamic tether experiment is intended to demonstrate the use of electrodynamic tethers for satellite propulsion and in part the operation of the proposed Self Accelerating Tethers around Jupiter (SATAJ) concept [LeBreton; TN.4122.05].

3.1 Primary Experiment Objectives

The main goal of the experiment is to validate the current theoretical models of (anode) current collection using a bare electrodynamic tether. To increase both the current collection efficiency and the survivability the tether will be made of a tape design. The LEO demonstration mission for the EDT experiment has the following main objectives [SLR 08-09; TN.4122.05]

- Demonstration of current collection capability of a bare electrodynamic tether
- Demonstration of tape tether deployment and operation
- Design and development by students

3.1.1 Demonstration of Tether Current Collection

The study and application of bare tether current collection being an efficient anode, see section 2.3, is also of significant interest due to its capability for deboost. This deboost automatically works in case of satellite and cathode failure and when a tether gets cut loose from its cathode, increasing the safety and thus applicability range of tether systems for boost, power generation and deboost. As of yet only insulated ED tethers have been tested in orbit the first bare tether (5 km EDT + 10 km MT) was scheduled to fly in August 2002 for the ProSEDS mission, see appendix 1, but was eventually cancelled in 2003 (see chapter 4), the use of bare tethers in space is still an untried concept [Lorenzini].

3.1.2 Demonstration of a Tape Tether

For EDT experiment onboard Delfi-1 the design of a tape (foil) tether has been selected to be developed and tested having the following advantages when compared to a wire tether

- Larger current collection capability within orbit motion limited (OML) regime per unit of tether length being a very lightweight solution
- Favourable drag properties when cut allowing for rapid disposal
- Increased survivability

Current Collection Area and Tether Density

The amount of current the bare tether collects is a function of the conductive area exposed to the ionospheric plasma. For a tape tether the effective diameter is used to calculate the current collection area $A_c$ taking into account twisting of the tether in space [Tomlin]. A tape tether has the same current collection and drag area as an equivalent wire tether with a diameter equal to the tape tether effective diameter $d_t$ [LeBreton]

$$d_t = \frac{2(w + t)}{\pi} \quad (3-1)$$

$d_t$ – effective tether diameter [m]

$w$ – tether width [m]

$t$ – tether thickness [m]

The mass of a tether having a constant cross-sectional area is

$$m_t = \rho_t L_t = \rho A_t L_t \quad (3-2)$$

$m_t$ – mass of the deployed tether [kg]

$\rho_t$ – specific tether density [kgm$^{-1}$]

$L_t$ – total deployed tether length [m]
with the tether cross-sectional area \( A_c \)

\[
A_c = wt
\]  

(3-3)

Comparing wire and tape tethers with an equal current collection area a thin tape has a smaller cross-sectional area and subsequently a lower specific tether density. Tapes provide a definite advantage when designing for a large current collection area and low mass system with the advantages of tape tethers become more apparent at larger widths as can be seen in appendix 12 showing a comparison between tape – round wire tethers including an equal mass round wire tether. When optimising for current collection area and low tether densities the tether to be as wide and thin as possible.

**Drag Properties**

The same principle applies for the aerodynamic drag properties of a tape tether again having a lower tether density when compared to an equivalent drag wire tether. The susceptibility to aerodynamic drag forces is determined by its ballistic drag coefficient

\[
B_{\text{eff}} = \frac{C_D A_d}{m}
\]  

(3-4)

\[
B_{\text{eff}} \quad \text{ballistic coefficient \([m^2kg^{-1}]\)}
\]

\[
C_D \quad \text{drag coefficient assumed 2.2 [-] [Beletsky]}
\]

\[
A_d \quad \text{drag area; projected area normal to velocity vector SC \([m^2]\)}
\]

\[
A_j = d_jL_j
\]  

(3-5)

The drag force and resulting deceleration due to air drag for near circular orbits can be approximated as [Wakker]

\[
F_{\text{ad}} = -\frac{1}{2} \rho C_D A_j v_{\text{rel}}^2 \quad a_{\text{ad}} = \frac{\rho C_D A_j v_{\text{rel}}^2}{2m}
\]  

(3-6)

\[
a_{\text{ad}} \quad \text{aerodynamic drag acceleration \([m/s^2]\)}
\]

\[
F_{\text{ad}} \quad \text{aerodynamic drag force \([N]\)}
\]

\[
v_{\text{rel}} \quad \text{satellite velocity relative to the rotating atmosphere \([m/s]\)}
\]

\[
\rho \quad \text{atmospheric density \([kg/m^3]\)}
\]

The change in semi major axis (SMA) for circular orbits due to atmospheric drag is [Sidi]

\[
\frac{da}{dt}_{\text{circ}} = -\rho \frac{C_D A_d}{m} (\mu a)^{1/2}
\]  

(3-7)

\[
\mu \quad \text{Earth’s gravitational constant \(3.986x10^{14} [m^3s^{-2}]\)}
\]

In the table below characteristic data is given for a 30 mm wide tape tether of thickness 0.02 mm and length 1 km.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>tape</th>
<th>wire eq. mass</th>
<th>wire eq. drag</th>
<th>SC Body + stored EDT</th>
<th>SC Body + tape tether</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_d ) drag area [m(^2)]</td>
<td>19.1</td>
<td>0.87</td>
<td>19.1</td>
<td>0.28</td>
<td>19.3</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>1.62</td>
<td>1.62</td>
<td>775</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>( B_{\text{eff}} ) [m(^2/kg)]</td>
<td>26</td>
<td>1.19</td>
<td>0.05</td>
<td>0.01</td>
<td>0.9</td>
</tr>
<tr>
<td>( F_{\text{ad}} ) [N] @650 km</td>
<td>-6.1E-5</td>
<td>-2.8E-6</td>
<td>-6.1E-5</td>
<td>-9.20E-07</td>
<td>-6.2E-05</td>
</tr>
<tr>
<td>( a_{\text{ad}} ) [m/s(^2)] @650 km</td>
<td>-3.8E-5</td>
<td>-1.7E-6</td>
<td>-7.9E-8</td>
<td>-2.04E-08</td>
<td>-1.4E-06</td>
</tr>
<tr>
<td>( \frac{da}{dt} ) [ms(^{-1})] @650 km</td>
<td>-4.4E-2</td>
<td>-2.0E-3</td>
<td>-1.9E-7</td>
<td>-3.4E-6</td>
<td>-5.7E-5</td>
</tr>
<tr>
<td>( F_{\text{ad}} ) [N] @1000 km</td>
<td>-3.2E-6</td>
<td>-1.5E-7</td>
<td>-3.2E-6</td>
<td>-4.75E-08</td>
<td>-3.2E-06</td>
</tr>
<tr>
<td>( a_{\text{ad}} ) [m/s(^2)] @1000 km</td>
<td>-2.0E-6</td>
<td>-8.9E-8</td>
<td>-4.1E-9</td>
<td>-1.1E-09</td>
<td>-7.1E-08</td>
</tr>
<tr>
<td>( \frac{da}{dt} ) [ms(^{-1})] @1000 km</td>
<td>-2.4E-3</td>
<td>-1.1E-4</td>
<td>-1.1E-8</td>
<td>-1.9E-7</td>
<td>-3.2E-6</td>
</tr>
</tbody>
</table>

\(^3\) Using mean atmospheric density \( \rho = 5.15e-14 \) @ 650km and \( \rho = 2.79e-15 \) @ 1000km [Wertz]
As can be seen in table 1 a tape tether has a higher area over mass ratio when compared to an equal mass and length wire tether. A high area over mass ratio is an advantage when the tether is cut, the tether will be very susceptible to aerodynamic drag and deorbit faster than a wire tether of equivalent mass and length reducing the area time product of the tether and with it the collision risk of the tether with other orbiting spacecraft.

Tether M/OD Survivability

To be a viable system for deorbiting spacecraft and rocket stages the tether lifetime in orbit needs to exceed the required time to deorbit. The tether’s lifetime depends on it surviving micrometeoroid impacts and avoiding collisions with larger space debris and operational spacecraft. Survivable tether designs are a necessity for missions with longer durations also to prevent the debris a tether break-up event will cause. There are currently two general options in survivable tether design, see section 2.3, a multi-strand tether using two or more strands like the Hoytether [Heide; Forward] or the use of tape tethers. Multi-strand tether design for conductive tethers is more complex than a tape tether design, two strands of wire tether carrying current will attract each other the strands need to be separated being failure sensitive.

Three separate methods for calculating tether mean time between failure (MTBF) based on empirical data estimated from previously flown missions among which the SEDS missions have been found in the literature. A flight based conservative estimate for the MTBF determined using SEDS-2 data by [Carroll] with tether diameter \(d_t\) in mm and length \(L_t\) in km is

\[
MTBF = \frac{(d_t + 0.3)^3}{L_t} \quad (3-8)
\]

MTBF – Mean Time Between Failure [years]

Based on a tether cut occurring when collision occurs with a M/OD particle of 1/3 tether diameter or width [Beletsky] calculates the MTBF in years as follows again with \(d_t\) in mm and \(L_t\) in km

\[
MTBF = \frac{4d_t^{1.5}}{L_t} \quad (3-9)
\]

For a single strand tether with a diameter > 1 mm Hoyt estimates MTBF as [Kruijff]

\[
MTBF = \frac{1}{\pi \sigma D_0 L_t} \left( \frac{d_t}{D_0} \right)^{f-1} = \frac{385 \text{ km} \cdot \text{days} \left( \frac{d_t}{1 \text{ mm}} \right)^{2.46}}{L_t} \quad (3-10)
\]

with \(d_t\) in mm and \(L_t\) in km

\(D_0\) – normalizing diameter of 1 mm
\(f\) – 3.46 empirical parameter
\(\sigma\) – \(\approx\) 9.58E-9 craters/s\(\cdot\)m\(^2\) is the empirical debris flux

The three methods have been used to calculate tether lifetime as a function of tether length and width, see [TN.4122.10]. As suggested by [Beletsky] the tether diameter was replaced by the width of the tether. The results are shown in table 2 and figure 4.

Figure 4: Three methods of calculating the MTBF time [TN.4122.10]
Table 2: Three months survival probability 1000 m 30 mm EDT

<table>
<thead>
<tr>
<th></th>
<th>Carroll</th>
<th>Hoyt</th>
<th>Beletsky</th>
</tr>
</thead>
<tbody>
<tr>
<td># hits per 3 months</td>
<td>3.44E-05</td>
<td>1.68E-04</td>
<td>2.94E-05</td>
</tr>
<tr>
<td>P&lt;sub&gt;sev&lt;/sub&gt;</td>
<td>0.0034%</td>
<td>0.017%</td>
<td>0.0029%</td>
</tr>
<tr>
<td>P&lt;sub&gt;surv&lt;/sub&gt;</td>
<td>99.997%</td>
<td>99.983%</td>
<td>99.997%</td>
</tr>
</tbody>
</table>

The results show that the Hoyt method is most conservative, but all methods result in (unbelievably) long lifetimes.

Replacing the tether diameter by the width \( w \) in the Carroll and Hoyt formulas, as suggested by [Beletsky], leads to 26-33% longer MTBF times for the 1 km tether. For equivalent drag wire tethers the tether density will increase and if a similar mass and length wire tether is used instead of a tape tether the \( d \) will be smaller and MTBF decreases see equation (3-8). Generally speaking increasing the width will increase the MTBF of the tether; longer tethers are more susceptible to damage by debris.

Data derived analytically for a 20 km tether calculating the risk of a close approach (distance less than 500 m) occurring between the tether and trackable space debris (> 10 cm) and operational satellites by [Cooke has been extrapolated for a tether length of 1000 m shown below.

Table 3: Expected encounters with catalogued objects for a 1 km tether

<table>
<thead>
<tr>
<th>Tether Altitude [km]</th>
<th>Inclination</th>
<th>Encounters per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>28.5°</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>51.6°</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>88°</td>
<td>0.8</td>
</tr>
<tr>
<td>800</td>
<td>28.5°</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>51.6°</td>
<td>9.35</td>
</tr>
<tr>
<td></td>
<td>88°</td>
<td>14.8</td>
</tr>
</tbody>
</table>

These indicate a realistic chance of a close approach and collision occurring for high altitudes and inclination orbits being undesirable as these orbits are heavily populated by operating satellites. Preferable orbits for flying tether experiments are low orbit altitudes avoiding most operational spacecraft and a significant amount of space debris also allowing for a fast deorbit at EOL of the tether experiment due to increased aerodynamic and Lorentz drag forces.

![Figure 5: Expected encounters with catalogued objects for 1 year period](image)

The chance of collision with catalogued objects is a linear function of the tether length \( L_t \) as shown in figure 5, decreasing the risk would imply flying the shortest tether required for the mission and avoiding densely populated orbits. In section 4 and 5.5.2 the operational risks and risk mitigation strategies are discussed further.
3.2 Secondary Experiment Objectives

Possible secondary objectives for the EDT experiment that may be realised include:

- Current enhancement due to neutral gas release
- Demonstration of self-accelerating rotating tether concept
- Scientific study of the Auroral effects produced by a conducting tether probe

Current Enhancement by Neutral Gas Release

When the TSS-1R tether was cut an unexpected phenomenon occurred, at the broken end of the tether trapped air inside the insulating Teflon sheath was leaking from the tether and this escaping ionisable gas flow allowed for electrical contact between tether and plasma closing the current loop. This gas ‘cathode’ was able to sustain the highest amount of current in the tether of 1.1 A during the experiment and lasted for 75 s [Gilchrist], see appendix 1. This unexpected result of the TSS mission could lead to the design of a lightweight passive cathode system used for temporary increase in tether current levels and Lorentz drag. To demonstrate current enhancement by gas release a neutral gas will have to be released and the effects on the tether current levels determined.

Self-Accelerating Rotation

A short passive bare EDT stabilised by rotation instead of gravity gradient forces can be used to deorbit a low-mass atmospheric entry probe in the Jovian atmosphere [LeBreton]. The stability of the tether is achieved by rotation instead of the gravity gradient force; this will allow for the use of shorter ED tethers, longer operational times combined with higher current levels despite the long term destabilising dynamics of an ED tether mentioned in section 2.3. The torque’s acting on the tether due to the Lorentz force will enable the tether to self-accelerate after an initial rotation using either the satellites attitude control system (ACS) or by partly retracting the tether at a certain velocity, stabilising the tether during its operation [LeBreton]. If the initial rotation is initiated by retraction of the tether the complexity of the deployment mechanism is increased. For the Delfi-1 satellite the possibility of rotating the entire system depends on the other payloads and the satellites attitude and control system capabilities.

Auroral Observations

Another possible secondary goal is a scientific study of the auroral effects produced by a conducting tether probe in Earth’s atmosphere as performed on the Oedipus C mission and proposed by [Sanmartin]. Analysis of the auroral emissions produced by a conducting tether can provide density profiles of the dominant neutral species in the E layer of the ionosphere. The ability to research the induced auroras requires a bare tether to operating at a floating bias. Low inclination orbits are preferred for high induced EMF and altitudes within the F1 layer of the ionosphere produce maximum e-beam intensity [Sanmartin]. Observation of the aurora produced by the floating bare tether will have to be performed from the spacecraft, the e-beam produced by the tether will have a weak energy flux and the beam would be too thin to allow for ground observation across the propagating beam [Sanmartin]. This would enable continuous measurements to be performed. Research needs to be performed if the EDT operating onboard Delfi-1 can produce an observable auroral effect, depending on the orbit and tether dimensions and if data rate, power and mass budgets allow for instruments capable of observing the auroral effects.

Potential Scientific Results

Using and studying bare tether current collection in orbit has not been done, so of significant scientific interest. The results of this experiment will be used to validate the theoretical models (OML theory) and the flight data can provide information on the system dynamics and the plasma environment that each tether mission will encounter. The use of a neutral gas cathode is of interest for other tether design applications due to the de-boost capability generated by this potentially very simple and low mass (temporary) cathode. Long term this experiment can lead to the development of a small low mass system to be used on spacecraft and rocket stages as a deorbiting device to adhere to the orbital lifetime limitation < 25 yrs of objects in space advised in [ESA 1999; Nasa 1995].
4 GUIDELINES FOR DEVELOPMENT

The main driver for any tether demonstration mission operating in LEO is safety with respect to other operational satellites. The ProSEDS mission was cancelled in 2003 because of the perceived risk to other satellites (see appendix 1); also the YES 1 and SEDSAT missions were cancelled due to unfavourable orbits. It is of paramount importance for the success and credibility of the experiment to operate in an orbit situated below the ISS ensuring the space station does not have to perform a collision avoidance manoeuvre also avoiding densely populated orbits, see section 3.1.2, resulting in a killer user requirement [TN.4122.23].

REQ.4122.UR.01  Experiment Orbit Altitude
The tether experiment shall be performed at an altitude below the ISS orbit h < 350 km

The Delfi-1 satellite in its current configuration cannot operate below 650 km [TN.4122.23] requiring a redesign of the attitude control system, it is unsure if the EDT experiment will be able to operate onboard the planned Delfi-1 satellite. There is still the possibility of integrating the tether experiment into the Delfi project with one of the main goals of the Delfi project being to give students the opportunity to gain experience with spacecraft hardware. The EDT payload is suited for student development, some of the work required is development and testing of a deployment system, properties of flat tape tethers need to be tested allowing for hands-on experience. The Delta-Utec program electrodynamic tether bead simulator (ETBSim) also needs to be developed further to simulate tethers using ion collection and flying at high inclinations [TN.4122.05]. Developing the EDT experiment for the Delfi-1 satellite also has the advantage of an existing satellite baseline with design constraints and requirements of the system and interaction with the satellite design team available. To increase the number of flight opportunities and decrease the cost and development time of EDT experiments developing low cost, simple experiments suited for use onboard micro-satellites and sounding rockets is desirable. Taking this into account has been decided to continue developing the EDT experiment for the Delfi-1 satellite having typical constraints for a micro-satellite platform. There will always be a developmental overlap between alternative mission platforms and the experiment onboard Delfi-1 so the work done for this project can be translated to a more suitable flight opportunity. To enable rapid analysis of the system for different flight opportunities the design tools will allow for variable orbital inputs.

Mission Success Criteria
The EDT experiment has a number of potential objectives that will determine if the experiment operation is considered a success each adding to the scientific value of the experiment with execution of the first two objectives being minimum required steps required to regard the experiment as an innovative development in tether design.

1. Prove de-boost capability of a bare electrodynamic tether
2. Deployment and operation of an electrodynamic tape tether
3. Demonstrate effect of gas release on current in tether
4. Demonstrate self-accelerating rotating tether concept
5. Observe the auroral effects

Critical Design Path
Mission critical is the current flight altitude of the Delfi-1 satellite as to a go or no go of Delfi-1 and the development of the Delfi-1 project itself. DTUSat did manage to launch with a 450 m tether onboard a CubeSat, see appendix 1 and [DTUSat]. Also the orbital inclination of the Delfi-1 will affect the ability of the tether to induce a (measurable) bias and Lorentz force, lower inclinations are preferred. The development of the tape tether and the deployment mechanism are considered the critical design paths in the hardware development. It also needs to be determined if generic micro-satellite platforms can provide the required rotation for the self-accelerating rotating tether concept. Assuming that the satellite cannot initiate the rotation of the system a partly retractable tether system will have to be designed to meet this experiment objective increasing the complexity of the experiment.
Costs and Development Time

Using a parametric cost model and scaling cost data of previously flown missions initial cost estimates for the experiment have been performed. Flying the payload on the Delfi-1 satellite is estimated to cost €1.4 - €2 M, with the payload mass set at 6 kg. With the development costs of the payload estimated at €236,000 the payload on the Delfi-1 satellite is estimated to cost a total of €1.6 to €2.2 M [Appendix 15]. For the Delfi-1 mission an existing satellite bus design will be used resulting in a shorter development time when compared to a dedicated mission with a one of a kind satellite bus being designed for the mission. Finding suitable flight opportunities can become a problem (if Delfi-1 is not an option) and delay the experiment, it is advisable to research alternative flight opportunities parallel to the development of the experiment for Delfi-1, see [DES.4122.01;03]. In appendix 6 the project development timeline for the EDT experiment is shown [dated 2003] adhering to Delfi-1 mission requiring the payload to be available for integration on the payload platform in 2007.

Student Development

Implications for design and development within the Delfi-1 project are that continuity of the project must be maintained with multiple students working on the project and discontinuities in the development occurring. This emphasises the need for consistent documentation of design and analysis methods and traceability and verification of results obtained.
5 EDT EXPERIMENT DESIGN CONCEPTS

The EDT experiment will be developed for the Delfi-1 satellite as it is a typical micro-satellite. The design and generated design tools will be applicable to incorporate other micro-satellites or sounding rocket platforms if another flight opportunity is deemed more suitable for the experiment. The payload design for the Delfi-1 bus is characterised as

- Low cost, low mass; limited volume
- Simple mission concept (robust design)
- Fast realisation possibility
- Student development

Designing for a low cost, low mass and short development timeline will require the EDT system to be reduced to the bare minimum necessary to meet the experiment objectives.

5.1 System Design Approach

The design approach of the EDT experiment is visualised and described in appendix 4. This document describing the preliminary design will focus on phase 0-A. Phase B will in part be documented in the subsequent EDT Operation and Design document [TW.4122.11]. An overview of tether knowledge at the TU Delft was used to make an initial list of available design methods and tools for the design [TN.4122.01], the results are summarised in appendix 5. Based on the experiment objectives, design phases, required outputs and an initial functional analysis of the experiment a work break down structure (WBS) is used to identify tasks and outputs that need to be generated during the preliminary and final design phases, see appendix 6. Also an initial development timeline meeting Delfi-1 project timeline requirements is shown [TW.4122.01].

Approach to Uncertainties

The approach to uncertainties in models and physical parameters resulting in uncertainties in performance and design of the EDT are based on ECSS methods. Design margins for budgets are derived from [SLR 156]. Development of alternate designs for the experiment systems, subsystems and mission alternatives is initiated as a contingency plan to mitigate the development and operational risks. Failure modes and there impact and severity on mission performance will be analysed for the EDT experiment during the entire design process to identify mission critical components.

5.2 Functional Specification

The functions the payload needs to perform are derived from the experiments scientific objectives and operating onboard the Delfi-1 bus. The functional specification derived will be translated into the system requirements of the EDT experiment. The functions during each mission phase are determined using a functional flow diagram shown in appendix 7. The functions are allocated to bus, EDT and ground station (GS) systems and are broken down into sub functions by method of functional breakdown (FBD); see figure a 7 and figure a 8 of appendix 7. The functions are gathered in the EDT Functional Specification document [SPC.4122.03], partially shown in table 4 this document will be available for updating and maturing as the project develops.
Table 4: Excerpt from functional specification EDT experiment [SPC.4122.03]

<table>
<thead>
<tr>
<th>ID</th>
<th>Function</th>
<th>Timeline</th>
<th>System</th>
<th>HW</th>
<th>SW</th>
<th>Status</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0</td>
<td>Onboard storage EDT in orbit</td>
<td>365 days</td>
<td>DEP+STS</td>
<td>Reel + structure PL</td>
<td>SLR 114</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>Off Mode to Safety Mode</td>
<td>275 days</td>
<td>TLM, EPS CDHS</td>
<td>data connection command</td>
<td>SLR 123</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.2</td>
<td>Experiment checkout (health)</td>
<td>275+ days</td>
<td>DEP GAS</td>
<td>deployer safety</td>
<td>FBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.3</td>
<td>Listen for (Activation) Commands</td>
<td>weeks</td>
<td>TLM CDHS</td>
<td>Sensors power; data connection</td>
<td>FBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td>Keep EDT in operational condition</td>
<td>365 days</td>
<td>TET + DEP</td>
<td>Tether Storage Device</td>
<td>FBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>Experiment data 1</td>
<td>weeks</td>
<td>TLM</td>
<td>Sensors power; data connection</td>
<td>FBD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.1 System Definition & Boundaries

Based on previous experiments and the two proposals [SLR 09-09] listed in appendix 3 the system breakdown given in figure 3 is adapted and expanded for the EDT experiment using the functional flow diagram for the EDT experiment given in appendix 7 and shown below.

![Diagram of EDT experiment system breakdown](image)

Figure 6: EDT experiment system breakdown

The systems of the EDT experiment are defined as follows:

**Tether (TET):** consists of the ED tether

**Deployment Mechanism (DEP):** consists of tether storage system, ejection mechanism, a deployment control device. This system will also provide for tether retraction and or release mechanism if required.

**Telemetry System (TLM):** All required sensors and data interfaces to and from the CDHS of Delfi-1 bus

**Electrical Power System (EPS):** will enable the payload systems to receive power to receive power from the bus via the payload platform interface

**Structure and Harnessing (STS):** all structure and harnessing required for mounting and connecting EDT to the payload platform not taken into account in the other systems

**Gas Release Mechanism (GAS):** gas storage and release device

**End Mass (EM):** consists of the total mass at tether end mₚ including GAS system, (part of) the DEP system and any additional ballast mass required for stability.
System Interfaces
The EDT experiment shall interface with the Delfi-1 satellite systems via the payload platform (PL), see appendix 8, and shall consist of a structural, electrical and data interfaces (software) with the Delfi-1 Command and Data Handling System (CDHS), Electrical Power System (EPS), Attitude and Control System (ADCS) and the PL platform structure.

Power System Interface
Main function of the EPS system is to convert power from bus voltage 28 V (15 V) to the required voltage for instrumentation and deployment mechanism.

Structure & Harnessing System Interface
Structural Interface consists of the following
- Envelope (EDT)
- Mounting PL and/or Delfi-1 structure subsystem (SS)
- Thermal Control System (TCS) Thermal interface (SS)
- Mass properties (EDT)
- Connectors (PL-SS)
Harnessing consists of
- Power and data interfaces of the EDT electronics with PL bay assuming ground checkout is done via the PL bay interface
- Grounding connectors
- Telemetry interfaces

CDHS Interface
The Command and Data Handling System shall receive, store and send data to the Communication System (COMM) and is capable of autonomous payload control for a minimum time of 15 hrs [SLR 114], data interfaces with the payload consist of
- Command data
- House Keeping data
- Science data

The EDT experiment will interface with the ADCS during deployment and operational phase by inducing a disturbance force and torque on the satellite. The deployed tether will also change the Moments of Inertia (MOI) of the system. No direct interface exists between the EDT and the GS or COMM system. The EDT must also be capable of interfacing with Delfi-1 test and checkout equipment (ground systems) as integrated tests are a payload requirement. Interface requirements are listed in the EDT System Requirements Specification provided as an annex to this thesis report. Interfaces with the operating environment will be discussed in the EDT Operations and Design document.

5.3 System Requirements & Design Drivers
The approach to generating the system, subsystem and component requirements is visualised in appendix 9. The EDT experiments are generated from the scientific objectives and the requirements and constraints originating from operating the experiment onboard the Delfi-1 satellite. Using the functional flow and functional breakdown of the experiment [appendix 7] the functions are translated into system requirements and developed further by method of requirement flow down from mission to system to subsystem and eventually component requirements. Use is made of an excel document, EDT System Requirements Specification [SPC.4122.01], for requirement documentation, flow down and the requirement traceability matrices (RTM). External sources for requirements are previous flown tether experiments and proposals and the NASA tether requirements listing based on the TSS and SEDS missions [Tomlin].
All requirements are to adhere to the ‘requirements on requirements’ as stated within the Delfi-1 project and [Hamann] and are listed below.

- Traceability & Rationale and justification (RTM) and analysis documentation, use of Delfi-1 system of Project Unique Identifiers (PUID) and Standard List of References (SLR)
- Described in quantifiable terms
- Completeness and self contained not referring to another requirement
- Severity-impact of failure to meet requirement on mission
- Maturity: TBD; TBC; in Analysis
- Verification plan [TBW 1] input; for each requirement determine if verification will be done by Inspection, Analysis, Demonstration, Test, Review of Design or Similarity to other systems

In table 5 an example of Delfi-1 requirements on the operation of the payload is shown [SPC.4122.01]. The EDT experiment has a PUID of 4122.

Table 5: Requirements Specification, RTM and verification sheet setup

<table>
<thead>
<tr>
<th>PUID</th>
<th>Title</th>
<th>Description</th>
<th>Source</th>
<th>System</th>
<th>TBD TBC Analysis</th>
<th>Quantifiable check</th>
<th>Work</th>
<th>Severity-impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.xx</td>
<td></td>
<td></td>
<td>RTM, F or</td>
<td>EDT or</td>
<td>Status</td>
<td>Yes - No</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>document</td>
<td>Delfi-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.EDT.21</td>
<td>Operating Inclination</td>
<td>70 – 110</td>
<td>4000-5000.xx</td>
<td>EDT</td>
<td>go</td>
<td>Yes</td>
<td>Perform</td>
<td>Complexity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Orbit</td>
<td></td>
<td></td>
<td></td>
<td>ance</td>
<td>design</td>
</tr>
<tr>
<td>4122.EDT.32</td>
<td>EDT Control</td>
<td>The EDT shall be controlled and operated by the bus</td>
<td>4120.32</td>
<td>TLM</td>
<td>go</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.TLM.16</td>
<td>Health Check</td>
<td>During each operational mode except for the Off Mode the TLM will perform system health checks</td>
<td>4120.61</td>
<td>TLM</td>
<td>go</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.STS.04</td>
<td>Thermal Interface</td>
<td>The STS shall be conductive with structure</td>
<td>4111.0-4120.20</td>
<td>STS</td>
<td>go</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Requirement Traceability Matrix (RTM)

<table>
<thead>
<tr>
<th>Title</th>
<th>Requirement</th>
<th>PUID</th>
<th>PUID</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>inclination &gt;70°</td>
<td>4000-5000.xx</td>
<td>4122.EDT.21</td>
<td>Operating Inclination</td>
</tr>
<tr>
<td>Payload</td>
<td>The payload shall be controlled and operated by the bus</td>
<td>4120.32</td>
<td>4122.EDT.32</td>
<td>Payload Control</td>
</tr>
<tr>
<td>Health</td>
<td>It shall be possible to check the payload’s health during all satellite operations</td>
<td>4120.61</td>
<td>4122.TLM.16</td>
<td>Health Check</td>
</tr>
<tr>
<td>Thermal</td>
<td>Conductive with structure)</td>
<td>4111.0-4120.20</td>
<td>4122.STS.04</td>
<td>Thermal Interface</td>
</tr>
</tbody>
</table>

Verification

<table>
<thead>
<tr>
<th>PUID</th>
<th>Keyword</th>
<th>STATUS</th>
<th>I</th>
<th>A</th>
<th>D</th>
<th>T</th>
<th>RoD</th>
<th>S</th>
<th>Rationale</th>
<th>Verification Control Document</th>
<th>Severity-impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.EDT.21</td>
<td>Orbit inclination</td>
<td>go</td>
<td>A</td>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>EDT shall be designed to operate on Delfi-1 bus</td>
<td>Complexity Design</td>
<td></td>
</tr>
<tr>
<td>4122.EDT.32</td>
<td>EDT Control</td>
<td>go</td>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Breadboard &amp; Integrated Tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.STS.04</td>
<td>Thermal</td>
<td>go</td>
<td>I</td>
<td>D</td>
<td>T</td>
<td>RoD</td>
<td></td>
<td></td>
<td>Integrated Tests</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3.1 Imposed by Delfi-1 Mission & Spacecraft

Delfi-1 is a standardised bus designed for operating multiple payloads. The tether payload will be deployed during the end of the mission so its effects do not interfere with the operation of other payloads requiring onboard storage for at least 9-12 months before deployment. In table 6 a short overview of the Delfi-1 satellite is given.

Table 6: Delfi-1 main characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass $m_{sc}$</td>
<td>45 kg</td>
<td>[SLR 114:89]</td>
</tr>
<tr>
<td>Dimensions</td>
<td>450x450x450</td>
<td>[SLR 114:89]</td>
</tr>
<tr>
<td>Gravity gradient boom (GGB) stabilised</td>
<td>$L_{ggb}$ 7.735 m $m_{ggb}$ 2.5 kg</td>
<td>[144]</td>
</tr>
<tr>
<td></td>
<td>2 kg tip mass deployed to Nadir</td>
<td></td>
</tr>
<tr>
<td>Pointing accuracy</td>
<td>$\pm 5^\circ$ Nadir</td>
<td>[SLR 114]</td>
</tr>
<tr>
<td>Orbit range</td>
<td>650 km - 1000 km circular</td>
<td>[SLR 70]</td>
</tr>
<tr>
<td></td>
<td>70° – 110°</td>
<td></td>
</tr>
<tr>
<td>max time between GS contacts</td>
<td>247 min</td>
<td>[SLR 112]</td>
</tr>
<tr>
<td>maximum eclipse time</td>
<td>35.4 min.</td>
<td>[SLR 133]</td>
</tr>
<tr>
<td>Operating lifetime</td>
<td>1 year</td>
<td>[SLR 70]</td>
</tr>
</tbody>
</table>

Requirements from Delfi-1 to the EDT originating from [SLR 70-114-122-123] are translated to EDT requirements using the RTM by method of parent child allocation shown in table 5 located in [SPC. 4122.03].

Interface Requirements

Interfacing with the Delfi-1 payload platform (PL) imposes mass and dimension restrictions on the EDT experiment. Interfacing with the CDHS software protocol results in telemetry requirements and interfacing with the PL platform structure imposes requirements on the mechanical connections, see table 7. The payload platform has the dimensions of 450 x 450 x 140 mm, divided into a maximum of 20 payload modules of 100 x 160 x 20 mm [SLR 124]. There is a possibility of deviating from the standard payload platform and modules by using a special payload module adapted to a mission specific design. This is to be used for (parts of) experiments with special requirements with regard to placement in the satellite and dimensions. This would however increase development time and costs and will have to be decided on at an early stage in the development process as other payloads might have to be reconfigured. The use of multiple modules is not a problem. If the EDT tether is located on the payload platform, see figure 7, the EDT will be deployed in the zenith direction as the GGB is deployed to nadir [SLR 114: REQ.4111.DEP.07].

![Figure 7: Delfi-1 standard bus design](image)
There is also an optional external (antenna or special payload module) payload volume available, the exact dimensions are \[\text{TBD 1}\]; it will have to fit within the launcher volume constraints for the secondary payload ring. The payload (antenna) modules [SLR 117] shall use no more than 25% of one side - 506.25 cm² of the total outside surface area of the spacecraft. The connection with the corresponding standard payload modules or Delfi-1 data bus will be customised for each antenna module. Payload platform resources and constraints onboard the Delfi-1 payload platform are summarised in table 7. Requirements as to the allowable payload disturbance torque and duration are currently unknown \[\text{TBD 2}\]; analysis will have to be done as to an allowable range of torques. Also the mass distribution of the EDT during operation and placement onboard will affect the satellites MOI. Research into the influence the EDT will have on the ADCS system of the Delfi-1 is required. The Delfi-1 ADCS system is required to maintain a nadir pointing direction \[\text{REQ.4100.11}\] with an absolute pointing error of \(\pm 5^\circ\) \[\text{REQ.4120.24}\] to ensure communications capabilities with the ground station. During storage, deployment and operational phase of the EDT experiment the EDT is required to not compromise the ADCS system as it is essential that the bus remains operational and has communication abilities during the EDT experiment.

EDT Influence on SC Stability: during the EDT storage, deployment and operational phase nominal tether operations will have to ensure the SC bus ADCS is able to maintain a nadir pointing direction \((\pm 5^\circ\) pointing error) keeping the bus operational \[\text{REQ.4122.EDT.16}\].

Table 7: Resources & constraints Payload (PL) platform

<table>
<thead>
<tr>
<th>Resource</th>
<th>Allocation</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (average)</td>
<td>10 W [eclipse 1W]</td>
<td>SLR 122</td>
</tr>
<tr>
<td>Total Payload Platform Mass</td>
<td>11.5 kg</td>
<td>SLR 122</td>
</tr>
<tr>
<td>Payload Platform Outer</td>
<td>450 x 450 x 140 mm</td>
<td>SLR 122</td>
</tr>
<tr>
<td>Experiment time payload</td>
<td>3 Months [EOL Delfi-1]</td>
<td>SLR 117</td>
</tr>
<tr>
<td>Delfi-1 PL modules</td>
<td>Data rate: 20 bps</td>
<td>SLR 123</td>
</tr>
<tr>
<td></td>
<td>Power: 1 W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Connectors data/power: 2 RS-485/2</td>
<td></td>
</tr>
<tr>
<td>1 module</td>
<td>100 x 160 x 20 mm</td>
<td>SLR 123</td>
</tr>
<tr>
<td></td>
<td>0.4 kg</td>
<td></td>
</tr>
<tr>
<td>GGB tip PL platform</td>
<td>130 x 270 x 75 mm</td>
<td>SLR 123</td>
</tr>
<tr>
<td>Antenna PL Module</td>
<td>Surface area 50625 mm²</td>
<td>SLR 117-123</td>
</tr>
<tr>
<td></td>
<td>Volume unknown, 0.1 kg</td>
<td></td>
</tr>
<tr>
<td>Special PL Module</td>
<td>variable dimensions</td>
<td>SLR 117</td>
</tr>
<tr>
<td></td>
<td>volume 1 module (3.2 \times 10^5) mm³, 0.4 kg</td>
<td></td>
</tr>
</tbody>
</table>

The EDT by its very nature will be designed to generate a bias with respect to the surrounding ionospheric plasma environment, Delfi-1 bus and PL requirements state that the design and materials selected shall be such as to ensure that no parts of the spacecraft are charged to high potentials. Differential charging potential shall not exceed 10 V as a design goal \[\text{REQ.4122.EDT.12}\]. There is also an EMC compatibility requirement \[\text{TBW 2}\] the payload will have to adhere to. This requirement will influence the mounting (STS), grounding and design configuration of the EDT.

The Delfi-1 mission requires 6 months of integrated tests to be performed with the payload. To validate requirements a number of them are to be demonstrated or tested some requiring integrated tests with the Delfi-1 bus. By design the EDT will be integrated with the Delfi-1 so compatible software and telemetry interfaces will be available by design.

Other Requirements

Other requirements the EDT must take into account when operating onboard Delfi-1 are related to reliability availability and safety requirements (RAMS), failure effects of the payload on the satellite, operational modes of the payload, payload control, outgassing requirements for materials etc. These are all generated by flow down from Delfi-1 requirements using the RTM shown in table 5.
5.3.2 EDT Specific Requirements

For the Delfi-1 mission the total payload mass is set at a maximum of 11.5 kg. As the EDT is not the only payload, the EDT mass is set to a maximum of 6 kg. The EDT experiment will operate during the final phase of Delfi-1 as not to interfere with other payloads. If [REQ.4122.EDT.56] stating that payload equipment failure shall not have a mission critical effect on spacecraft operations is not met it will only result in loss of the EDT experiment limiting the severity. It is conceivable that the experiment will have access to the full payload resources available on Delfi-1 in terms of power and data rate. As this is not confirmed however a 6 W power budget based on PL mass fraction of 6 kg and data rate allocation of 210 bps [SLR 123] has been used for the EDT Technical Budgets [TN.4122.08] adhering to payload requirements.

Table 8: EDT design budgets

<table>
<thead>
<tr>
<th>Resource</th>
<th>Design Budget</th>
<th>Target incl. 23% margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (average)</td>
<td>6 W</td>
<td>4.5 W</td>
</tr>
<tr>
<td>Mass</td>
<td>6 kg</td>
<td>4.66 kg</td>
</tr>
<tr>
<td>Average data rate</td>
<td>210 bps</td>
<td>162 bps</td>
</tr>
<tr>
<td>Volume</td>
<td>50%-35% of 410 x 410 x 140</td>
<td></td>
</tr>
</tbody>
</table>

Volumetric constrains will be the dimensions of the PL platform with a design effort recommendation to integrate experiment on multiple standard. A mass budget for the EDT payload onboard the Delfi-1 satellite is derived using a number of tether missions and proposals in appendix 10, the initial mass distribution of the EDT systems is shown below. The design margins used for the EDT experiment are consistent with the design margins for the Delfi-1 satellite [SLR 156], using a 23% contingency margin during the conceptual design phase.

Table 9: EDT Experiment mass budget

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Coding</th>
<th>Specification [kg]</th>
<th>Target [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT Payload</td>
<td>EDT</td>
<td>6.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Deployer</td>
<td>DEP</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Telemetry</td>
<td>TLM</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Power</td>
<td>EPS</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Structure and Harnessing</td>
<td>STS</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Tether</td>
<td>TET</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Gas bottles</td>
<td>GAS</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

The mass of the tether is budgeted at 1.6 kg (25%) instead of the 20% specified when using the average mass distribution from other designs, see appendix 10. The percentage derived from other experiments and proposals is expected to be too low for the survivable tape tether design. The mass distribution percentage is biased towards mechanical and wire ED tethers; wire EDT and mechanical tethers (MT) are generally a smaller fraction of the total payload having lower specific tether density $\rho_t \text{kgm}^{-1}$. The terminator tether a survivable EDT for example was 90% of the total system mass. An initial estimate is made of a foil tether 30 mm - 0.015 mm thick (household foil) enforced with a 7.6 $\mu$m thick Kapton tape, commercially available [McInnes] over 25% of its width resulting in an initial estimate of $\rho_t = 1.3 \text{kgkm}^{-1}$ specific tether density, see equation (3-2).

Tether experiments with mass distributions including the entire structure for the payload drive the STS system to a high 18% whereas for the EDT onboard Delfi-1 only various mounting, support structure components and harnessing is considered part of the STS. The terminator tether only allocated 6% as a stand alone tether system comparable to the EDT experiment set up. For the EDT experiment a 10% allocation to STS seems adequate for an initial budget.

A distinction is made between an experiment with or without a (non functional) ballast mass. A stabilising end mass could be required for stability of the tether. Ideally other experiments or the deployer, sensors and gas bottles will be located in the tether’s end mass to allow for more stability without significantly affecting the total mass budget.
If sufficient end mass cannot be provided by EDT systems or other experiments the tether experiment will have to include for additional ballast either by reducing mass of other subsystems or increasing the mass budget and subsequently cost of the experiment. More analysis is required into the stability and dynamics of the tether however with the low currents inherent to passive short EDT operations it is not expected that a stabilising end mass is required and the initial mass budget will not take this into account. An alternative mass budget including an end mass based on the mass distribution of other tether experiments is shown in appendix 10.

In EDT Technical Budgets the mass, power, data rate budgets and volumetric constraints are managed including a bottom-up payload mass, power and data rate distribution is to ensure that the experiment adheres to the set budgets \[TN.4122.08\]. The budgets will evolve to a bottom up distribution as the design matures as is shown in table 10 below.

### Table 10: Example of development of mass budget for tether design

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tether TET incl. design maturity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1km 30 mm 0.015 mm</td>
</tr>
<tr>
<td>Conducting aluminium tether</td>
<td>1.22</td>
<td>20%</td>
<td>1.464</td>
<td></td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td>Enforcing Material</td>
<td>0.08</td>
<td>20%</td>
<td>0.096</td>
<td>0.096</td>
<td></td>
<td>7.6 µm</td>
</tr>
<tr>
<td>Adhesive</td>
<td>TBD</td>
<td>23%</td>
<td>TBD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coating</td>
<td>TBD</td>
<td>23%</td>
<td>TBD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.3</td>
<td></td>
<td>1.56</td>
<td>1.6</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

### Functional and Performance Requirements

Functional requirements are derived by method of RTM from the EDT Functional Specification document \[SPC.4122.03\]. The main performance requirement is that the EDT experiment must be able to achieve the scientific objectives stated in section 3 for the orbit range of the Delfi-1 mission stated in \[REQ.4122.EDT.24-26\]. As was shown in section 2.1 the performance of an EDT system depending on magnetic field strength and velocity and tether angles with de magnetic field is a function its operational orbit.

The NASA Tether Design Criteria [Tomlin] document consists of a number of requirements that are already in place with some relating to component requirements. Arcing considerations affecting tether design (insulation-materials and configuration) states tethers which contain electrical conductors have to take special design considerations into account to prevent arcing or discharge of electricity from the tether [Tomlin], this correlates to the electrostatic charging requirement \[REQ.4122.EDT.12\] but is added as a separate requirement \[REQ.4122.EDT.12b\] as the previous requirement only incorporates bias and other design aspects can be used to mitigate the risk of arcing.

The nominal tether range will have to be defined for each experiment operational phase with the tether in plane and out of plane pendular motions required to be within a certain amount of degrees from nadir during nominal tether operation [TBD 3]; this is listed as requirement [REQ.4122.TET.07] and needs to be analysed. The system should also be capable of remaining within operational range for the time required to perform the experiment objectives [REQ.4122.EDT.37]. The derived requirements for the EDT experiment are listed in the EDT System Requirements Specification [SPC.4122.01] located in the annex of this report.

### 5.3.3 Design Drivers

General tether experiment drivers are that a longer tether, a heavier tip-mass and low orbit and inclination are preferred. The initial baseline design for the EDT experiment will concentrate on the bare minimum required to meet the main experiment objectives. Once a baseline design is available the secondary experiment objectives will be taken into consideration. Design drivers for flying onboard the Delfi-1 satellite are summarised as:

- Low Mass, Power and Limited Storage Volume
- Simple & Robust Design
- Low Cost
- Safety
5.4 Experiment Concept Designs

Using design option trees, literature and some previous TU Delft student EDT experiment proposals listed in appendix 3 various configuration options for the experiment have been derived. The results are given in figure a 11 in appendix 11. In this section the various experiment configurations capable of performing the primary experiment goals are characterised with respect to some important trade off criteria. These trade off criteria are

- Mass
- Stowed Volume
- Complexity
- Development Risk

At this stage cost is assumed to be directly linked to mass and complexity and is not taken as a separate trade off criteria. Trade off is done by method of top down pair wise comparison between options; trade off criteria are given equal weight at this point so a system of + - is sufficient to perform a trade off. The primary experiment objectives require the tether to be bare at the anode end to collect current and be of a tape design. The results are summarised in a trade off table given in appendix 11. Some details are given below.

For missions requiring high drag forces it is necessary to insulate lower end of tether to achieve sufficient current levels using a cathode device to close the current loop. Designing an EDT for maximum deorbit performance will increase the required ballast and tether mass for stability, the additional cathode mass, insulated tether mass and increases the complexity of the experiment. However to achieve the primary experiment objectives it is sufficient to perform a proof of concept of propulsion using a bare EDT, not requiring the EDT to be designed for optimal deorbit performance allowing for the use of a passive and low current system.

![Figure 8: Distribution of bias and current along floating tether](image)

With the tether current entirely driven by the motion induced EMF the tether is charged to floating potentials. The system automatically adjusts for variations in the ionospheric density and the system is always operating at its maximum potential for the local environment. The induced EMF charges the top (anodic) section of the tether to a positive bias and the lower end to a negative bias with respect to the local plasma potential, section 2.1, the resulting bias and current distribution along the tether are figuratively shown above.

For a floating tether a large part of tether length ($l_i$) is required to collect sufficient ion current to close the current loop reducing the current levels significantly. The current at both ends of the tether also goes to zero for floating operation making direct current measurements off the tether impossible.

Designing for an inherently more stable entirely passive, low current EDT will have a mass and volume advantage and be a simplest system conceivable as no insulation or cathode is required making it suitable for operation onboard the Delfi-1 platform but the decreased deorbit performance will also reduce the measurable effects of the tether.
5.5 Preliminary Baseline Design

Following the generation of the trade off table a baseline design for the EDT experiment is selected with the following characteristics

- Entirely passive EDT operating at floating potentials in deboost mode
- Bare foil tether (enforced)
  - No mechanical part
  - No insulated part
- Deployed in zenith direction, located on standard PL platform or external SPL platform [TBD 17]
- System stabilised by method of passive stabilisation; no additional ballast mass [TBC 1] budgeted with the end mass consisting of DEP system and gas canister
- Passive deployment (control) system, inertia driven reel, storage single wound tether
- All sensors located at the SC bus
- Gas cathode(s) [TBD 4], time tagged method for gas release @EM

This baseline allows for the design of a low mass, simple and robust EDT experiment operating at floating potentials not using an active cathode and end mass as with the previous experiment proposals, see appendix 3. Also a design effort will be made to use a passive deployment and stabilisation approach having minimal impact on mass and power and increased reliability. The experiment will operate in the last phase of the Delfi-1 mission; the tether will be deployed after which the payload starts gathering scientific data. The experiment will operate for a maximum of three months or until tether severance by M/OD or tether exceeding stability limits and the satellite is in danger of tumbling due to excessive tether librations. As this leads to a loss in communications with the satellite the tether can be cut before this point [TBD 18] and allowed to deorbit separately reducing the area-time product of the tether as it has a higher ballistic coefficient when cut loose, see table 1 in section 3.1.2.

The secondary objective of testing the self-rotating stabilisation of the system is currently not included in the design taking into consideration the GGB stabilisation and absolute pointing requirement of ±5° of the Delfi-1 bus. Also the deployment system will not be designed for tether retraction as this increases the complexity significantly requiring an actively controlled deployer. This objective can be re-evaluated if the payload is operated on a dedicated platform either micro-satellite or sounding rocket. Observing auroral emissions from the tether is also not taken into consideration at this stage. Research giving an indication as to the observability of this effect and an overview of the required instrumentation onboard the bus required for observing the emissions needs to be performed. At this stage taking the low bias for the short tether at the high Delfi-1 inclinations making it extremely hard to observe the auroral effects [Fuji] combined with the limited power and data rate budget for the payload into account it is considered unlikely this objective can be performed on the Delfi-1 mission. The secondary objective of flying a neutral gas cathode is subject to further analysis.

5.5.1 EDT Floating Performance

In this section an initial estimate is made for the required tether dimensions onboard of Delfi-1 over its orbit range. To this end the following assumptions are made

- Tether straight and oriented along nadir vector
- Circular orbit
- Magnetic field modelled as centred dipole, the dipole axis aligned with spin axis Earth ignoring the diurnal variation as the Earth rotates

As a baseline a 30 mm wide tape tether with a thickness of 15 µm is assumed with the focus being on determining the effect of length and the amount of end mass has on the induced EMF, current levels in the tether and the stable operation of the EDT.
**Induced EMF**

The induced electromotive voltage per meter of tether $E$, see equation (2-1) is calculated using the horizontal magnetic field component $B_H$, normal to the velocity vector of the orbit and the tether 

$$B_H = B_{eq} \left( \frac{R_E}{r} \right)^3 \cos(\theta)$$

(5-1)

$B_{eq}$ – magnetic field strength @magnetic equator $3.012 \times 10^{-5}$ [T]

$\theta$ – geomagnetic latitude [º]

$r$ – geocentric orbital radius [m]

Using equations (5-1) and (2-1) the induced $E$ for a straight tether oriented along the zenith-nadir is

$$E = v B_H$$

(5-2)

$E$ – electromotive voltage per m [Vm$^{-1}$]

Sufficient induced bias by tether is required to provide measurable effects of the bare tether current collection and producing observable auroral effects. In figure 9 the values of the induced $E$ per meter of tether length are given for the Delfi-1 orbit range, the orbital inclination reduces the induced bias dramatically in (near) polar orbits. Having the tether operate at floating potentials will limit the inclination range for which the tether can produce measurable effects.

![Figure 9: Induced E for orbit range Delfi-1][2]

**Current Levels & Static Stability**

Current collection by the bare tether is modelled using the OML theory; see EDT Operation and Design [TW.4122.11] for more information on the OML theory. Assuming tether resistance is negligible due to low current levels the maximum OML current levels are calculated using [Kruijff]

$$I_{OML,max} \cong e n_e d \sqrt{\frac{8eE}{9m_e}} t_e^{1/2}$$

(5-3)

$I_{OML}$ – OML current [A]

$e$ – elementary electron charge $1.602 \times 10^{-19}$ [C]

$n_e$ – electron density [kgm$^{-3}$]

$m_e$ – electron mass $9.109 \times 10^{-31}$ [kg]

$t_e$ – electron collecting tether length [m]
The electron collecting tether length is related to the physical length of the tether \( L_t \) and the mass ratio of the electrons and ions [LeBreton]

\[
\frac{L_t}{L_i} = \left( \frac{m_e}{m_{eq}} \right)^{\frac{1}{3}} = \frac{L_t}{L_i} = \frac{L_i}{L_i} \tag{5-4}
\]

\( L_i \) – ion collection tether length [m]  
\( m_{eq} \) – equivalent ion mass [kg]

Electrodynamic (ED) and the restoring gravity gradient (GG) torque always reach an equilibrium in the static case when the tether has an angle < 45° from the vertical. At larger angles the magnitude of the GG torque decreases and the system may become unstable possibly leading to satellite flip-over and tumbling of the system. The stability of the tether is one of the main design drivers for the tether length and the required ballast mass.

The current at which the angle of the tether exceeds 45° is described as the first critical current [Beletsky]

\[
I_{\text{crit}} = \frac{3\omega_b^2}{B} \left( m_b + \frac{1}{2} m_i \right) \tag{5-5}
\]

\( \omega_b \) – orbital frequency [rads\(^{-1}\)]  
\( m_b \) – end mass [kg]

The critical current levels for 650 km and 1000 km-70° orbit are shown below for 3 end masses \( m_b \), the stabilising effect of the end mass is shown increasing the critical current levels.

**Table 11: Current levels for 30 mm - 15 µm aluminium tether [TN.4122.24]**

<table>
<thead>
<tr>
<th>( m_b ) [kg]</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>650 km -70°</th>
<th>1000km -70°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_i ) [m]</td>
<td></td>
<td></td>
<td></td>
<td>( I_{\text{crit}} ) [A]</td>
<td>( I_{\text{oml max}} ) [A]</td>
</tr>
<tr>
<td>250</td>
<td>0.07</td>
<td>0.16</td>
<td>0.25</td>
<td>0.002</td>
<td>0.0005</td>
</tr>
<tr>
<td>500</td>
<td>0.14</td>
<td>0.23</td>
<td>0.31</td>
<td>0.005</td>
<td>0.0015</td>
</tr>
<tr>
<td>750</td>
<td>0.20</td>
<td>0.29</td>
<td>0.38</td>
<td>0.009</td>
<td>0.0027</td>
</tr>
<tr>
<td>1000</td>
<td>0.27</td>
<td>0.36</td>
<td>0.45</td>
<td>0.013</td>
<td>0.0042</td>
</tr>
<tr>
<td>1250</td>
<td>0.34</td>
<td>0.43</td>
<td>0.52</td>
<td>0.019</td>
<td>0.0059</td>
</tr>
<tr>
<td>1500</td>
<td>0.41</td>
<td>0.50</td>
<td>0.59</td>
<td>0.025</td>
<td>0.0078</td>
</tr>
<tr>
<td>1750</td>
<td>0.48</td>
<td>0.57</td>
<td>0.65</td>
<td>0.031</td>
<td>0.0098</td>
</tr>
<tr>
<td>2000</td>
<td>0.54</td>
<td>0.63</td>
<td>0.72</td>
<td>0.038</td>
<td>0.0120</td>
</tr>
</tbody>
</table>

For the maximum OML current levels of EDT for the Delfi-1 orbital altitude extremes the tether remains stable according to the first critical current criteria without the use of an end mass for 70° inclinations. This is due to the extremely low currents inherent to passive floating bare tether operations. At an 85° inclination the tether \( I_{\text{oml}} \) also remain well below the critical current levels for static stability, these orbits however have a larger out-of-plane magnetic field component destabilising the tether [Kruijff]. However as the current in the tether decreases with increasing inclination the largest instabilities are expected to occur at medium inclinations. The tension occurring in the tether due to the gravity gradient can be approximated for moderate Lorentz forces by [Cosmo]

\[
T = 3 \left( \frac{m_b}{2} + m_i \right) L_i \omega_b^2 \tag{5-6}
\]

Results shown in table 12 for the EDT show the tension is in the order of mN’s when having an end mass of 2 kg. For tether design the operational tension forces are not a critical design issue as a 30 mm wide -15 µm thick tether has a yield strength of approximately 12 N depending on the type of aluminium used. It will have to be determined if tether dynamics, deployment and handling forces will put more stringent requirements on tether material strength.
### Table 12: Tether mass, tension levels & lifetime predictions [TN.4122.24]

<table>
<thead>
<tr>
<th>Lₜ [m]</th>
<th>Mass [kg]</th>
<th>Tension [N] EM 0 kg</th>
<th>Tension [N] EM 2 kg</th>
<th>Lifetime [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>0.30</td>
<td>1.31E-04</td>
<td>1.85E-03</td>
<td>2208577</td>
</tr>
<tr>
<td>500</td>
<td>0.61</td>
<td>5.23E-04</td>
<td>3.97E-03</td>
<td>1104289</td>
</tr>
<tr>
<td>750</td>
<td>0.91</td>
<td>1.18E-03</td>
<td>6.34E-03</td>
<td>736192</td>
</tr>
<tr>
<td>1000</td>
<td>1.22</td>
<td>2.09E-03</td>
<td>8.98E-03</td>
<td>552144</td>
</tr>
<tr>
<td>1250</td>
<td>1.52</td>
<td>3.27E-03</td>
<td>1.19E-02</td>
<td>441715</td>
</tr>
<tr>
<td>1500</td>
<td>1.82</td>
<td>4.71E-03</td>
<td>1.50E-02</td>
<td>368096</td>
</tr>
<tr>
<td>1750</td>
<td>2.13</td>
<td>6.41E-03</td>
<td>1.85E-02</td>
<td>315511</td>
</tr>
<tr>
<td>2000</td>
<td>2.43</td>
<td>8.37E-03</td>
<td>2.21E-02</td>
<td>276072</td>
</tr>
</tbody>
</table>

Table 12 also gives lifetime predictions using conservative MTBF values as follows from equation (3-10). Results indicate that the experiment duration is viable in terms of tether survivability. This needs to be re-evaluated at a later stage taking orbital debris fluxes, size and tether dimensions and geometry into account.

As can be seen in table 12 the tether density of the tape (foil) tether could be too high to remain within the set budget of 1.6 kg for tethers exceeding 1250 m. An additional enforcing material is required to prevent the tether from ripping and a coating protecting the aluminium from cold-welding and oxidation effects maybe required. Tether mass can be reduced by designing a thinner foil and by reducing the width of the tether however this will reduce the amount of current the tether can collect decreasing the performance of the system. Tape tether preliminary design drivers are derived from a comparison of various tape tether dimensions in appendix 12 and section 3.1.2.

- Thinner foils having lower mass and smaller storage volume at an almost constant collection area
- Wider tethers more collection and drag area and higher current levels, possibly shorter length and decreased storage volume as more efficient current collector
- Wider and shorter tethers increased lifetime expectancy according to equations (3-8) to (3-10)

Operating a floating tether will deorbit the satellite as it naturally removes energy from the satellites orbit. In table 13 the performance of a 1000 m long tether is calculated for Delfi-1 orbit extremes using the I_{OML} max current approximation of equation (5-3), equation (2-1) for the induced E and equations (2-3) to (2-5) to calculate the change in orbit due to Lorentz drag force.

### Table 13: Performance bare floating tether orbit [TN.4122.24]

<table>
<thead>
<tr>
<th>1000 m-30mm</th>
<th>650 km</th>
<th>1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70°</td>
<td>85°</td>
</tr>
<tr>
<td>I_{OML} [A]</td>
<td>0.013</td>
<td>0.007</td>
</tr>
<tr>
<td>P_{max} [W]</td>
<td>0.78</td>
<td>0.10</td>
</tr>
<tr>
<td>F_{L} [N]</td>
<td>1.04E-04</td>
<td>1.34E-05</td>
</tr>
<tr>
<td>a [m s⁻¹]</td>
<td>2.31E-06</td>
<td>2.97E-07</td>
</tr>
<tr>
<td>GS contacts</td>
<td>71.8</td>
<td>9.2</td>
</tr>
<tr>
<td>247 min Δr [m]</td>
<td>5856</td>
<td>754</td>
</tr>
<tr>
<td>2 weeks Δr [m]</td>
<td>37459</td>
<td>4841</td>
</tr>
</tbody>
</table>

Results show that orbit altitude is reduced most for the tether operating at lower altitudes and at low inclinations. For a 650 km altitude and a 1000 m tether it takes approximately three months to lower the orbital altitude by roughly 37.5 km. Increasing the length of the tether is expected to increase the rate of orbital decay. This will be studied in more detail in the subsequent phase of this thesis work.

The magnetic field components strength and orientation to the tether and the plasma environment for the Delfi-1 orbit range are required for more accurate performance at high inclinations and stability calculations.
5.5.2 Operational Risks
Operational risks occurring in the following experiment phases potentially have severe implications for both the satellite and the EDT experiment and even for other operational satellites.

The following risks have been identified

**Failure during deployment phase**
- Failed deployment
  - Tether degradation, ripping or tension break, tether jerk (mechanical failure)
  - Due to collision with debris or operating satellites
  - Deployment mechanism failure
- Off nominal tether angles
- Entanglement of tether with bus
- Slack tether resulting in tether jerk

**Failure during operational phase**
- Tether break up event
  - Tether degradation, ripping or tension break (mechanical failure)
  - Due to collision with debris or operating satellites
- Tether deviating from the nominal tether operational range resulting in excessive librations and oscillations resulting in loss of COMMS due to ADCS not meeting required state of nadir pointing, possible flip over or slack tether motion
- EDT generates insufficient bias and or current for measurable effects to occur

**Failures during termination phase**
- Tether break up event
  - Tether degradation, ripping or tension break (mechanical failure)
  - Due to collision with debris or operating satellites
  - Failure releasing tether when desired

Deployment System (DEP)
Previous missions have shown the criticality of the deployment phase, the deployment will have to be designed as robust as possible and risks minimised. The GGB is currently deployed in the nadir direction, the EDT baseline design is not integrated with the GGB as development of the GBB and the ability of data and power connection to be maintained via the GGB is still very uncertain and more research is required if this is a feasible option. The EDT and GGB will not be deployed in the same direction as the risk of the tether becoming entangled with the GGB is too high [REQ.4122.DEP.07], requiring the tether to be deployed in the zenith direction. Based on the ATEx deployment failure [Gates] initial deployment requirements are derived mitigating the risk due to thermal effects. These requirements will hold until deployment system has been validated to deploy a tether with tether temperature ranging from $T_{\text{min}}$ to $T_{\text{max}}$. Also a slack tether (zero tension) during deployment is to be avoided, a slack tether describes an uncontrolled free motion and can cause the deployment system to jam or worst case a tether jerk can occur that can ruptures the tether thereby ending the mission.

- Deployment shall not occur during transition from solar to eclipse or vice versa [REQ.4122.DEP.08]
- Maximum deployment time is 62.3 min solar and 34.9 min in eclipse [SLR 133] excluding contingency factor [TBD 5] [REQ.4122.DEP.09]
- During deployment minimise the amount of slack occurring in the tether [REQ.4122.DEP.10]

**Nominal EDT Operation**
When [REQ.4122.EDT.16]: During the EDT storage, deployment and operational phase nominal EDT operations will ensure the ADCS of Delfi-1 is able to maintain $\pm5^\circ$ absolute pointing requirement keeping the bus operational is met the EDT are considered operational. Nominal tether operation is described as the tether remaining within the stability limits of $\pm30^\circ$ [Heide] [TBC 2] from nadir-zenith [REQ.4122.TET.07] during required operational time of the experiment ensuring [REQ.4122.EDT.16] is met and the EDT can perform the primary scientific objectives.
The NASA Space Tether design criteria [Tomlin] state a tether survivability requirement of 95% for mission duration; this is however a requirement that can never be fully verified as it is dependant on models. Analysis of tether M/OD severance risks will have to be performed to determine the tether survivability and if this is a realistic requirement generating tether dimension constraints. The tether integrity requirement [REQ.4122.TET.08b] states that a 95% chance of tether integrity being maintained is required for the EDT experiment duration. To mitigate the impact of a tether cut occurring within the three month experiment time frame the experiment is required to produce measurable effects within two weeks [TBC 11] of operation to increase the chance of mission success.

Collison Risk

Not increasing the amount of space debris and avoidance of operational satellites is paramount for tethered satellite experiments, see section 4. The total number of avoidance/alert situations for operational spacecraft should ideally be equal or of a lesser order compared to a similar deorbit of a satellite without a deployed tether [REQ.4122.EDT.57]. Break up of the tether resulting in a possibly untrackable tether in orbit increases the risk of collision with an operational satellite, this is extremely undesirable and experiment orbits must not be densely populated with spacecraft [REQ.4122.EDT.58], see section 3.1.1. To minimise the chance of collision avoidance manoeuvres being required during the orbital lifetime of the Delfi-1 satellite a number of steps can be taken [TN.4122.23]

1. Adjust orbit and launch window; user (killer) requirement for a realistic flight achievable experiment is an orbit altitude below the ISS [REQ.4122.UR.01]
2. Increase survivability chances of tether
3. Retract tether; not feasible for current experiment
4. Release tether to deorbit faster applicable for orbits up to 800 km [TBD 18]
5. Design the tether for rapid deorbit when cut [REQ.4122.TET.09]

5.5.3 Requirements not met by Preliminary Design

The bias distribution of the tether at floating potentials for the orbit extremes of Delfi-1 is calculated using equation (5-2), in appendix 13 the bias at anode and cathode end of the tether is shown for Delfi-1 orbit extremes. A zenith deployment direction [REQ.4122.DEP.07] results in the largest tether bias with local plasma to be situated at the SC bus connection assuming the tether is not grounded to the SC bus [TBC 3]. A maximum differential of 25 V - 87 V depending on tether length is induced between payload and SC bus increasing the chance of arcing occurring and not meeting the following requirement

- The differential charging potential shall not exceed 10 V as a design goal [REQ.4122.EDT.12]

Having the anode end located at the SC bus results in a maximum differential potential of 5 V requiring the tether to be deployed to the nadir for [REQ.4122.EDT.12] to be met. Other options are to use the GGB platform for the EDT experiment which is currently considered too complex and the development risk is too large. Insulating the tether to prevent arcing or design part of the tether to be non conductive (mechanical) are both initially not considered due to increased mass and complexity and development risk. A viable option is to negotiate the required deployment direction of the boom. Delfi-1 bus design allows for this change to be possible but will have to be confirmed by ADCS and PL engineer.

- The floating tether shall be deployed in a nadir direction to minimise the differential potential between payload and SC bus to < 10 V [REQ.4122.DEP.07b]

The EDT must be able to induce sufficient bias and current levels to be able to produce measurable effects and a method of measuring tether performance in orbit has to be developed. It is unlikely the EDT will produce significant effects in near polar orbits (see figure 9) and designing the experiment to include orbital inclinations between 85° and 95° will put enormous constraints on the design budget therefore the initial EDT design will not take these inclinations into consideration.

- Operating Orbit Inclination EDT experiment
  70°-110° [REQ.4122.EDT.25] => 70°-85° and 95°-110°
Development Contingency Plan

Design Critical Components

- Conducting foil tether design [dimensions when stored, deployability, manufacture]
- Ability to measure operation of a floating EDT for Delfi-1 orbit range

It has to be determined if enforced tape tether design is suited for the Delfi-1 payload considering that mass and volume are critical design factors for this payload and the development of a tape tether deployer is a critical design path. Alternative for the foil tether is to use a round (possibly slightly flat) wire requiring a significantly smaller storage volume when level wound on a spool or reel also having more deployment experience. Reduced tether lifetime issues and current levels will have to be taken into account. If the floating tether cannot be deployed in a nadir direction developing part of the tether to be non-conductive thereby separating the SC bus from the tether voltage will have to be investigated. This will also complicate the implementation of the gas cathode. The PMG experiment, see appendix 1 already determined that an insulated ED tether can generate sufficient bias to drive a current through the tether. The goal of this experiment is to prove current collection by the bare anodic section of the tether. If floating operation is not viable in terms of producing measurable effects actively biasing the tether, using a cathode to emit electrons, will result in higher current levels compared to floating operation increasing the deorbit performance and inclination range of the experiment and allowing for direct current measurements of the tether. The system will be more complex and be more susceptible to instabilities. Alternative flight opportunities will be generated for the Delfi-1 mission if the mission cannot adjust its operational altitude to below the ISS orbit. The next project phase is to determine the feasibility of the baseline design (phase A-B) [appendix 4] mainly regarding performance at high inclinations and adapt where necessary using design options table in appendix 11. In appendix 14 the work required to determine if the baseline design is feasible is listed.
REFERENCES


[Zandbergen] Zandbergen, B.T.C., **Space Vehicle Engineering & Technology II: Part B: Space Vehicle Engineering, AE2-S02**; Faculty of Aerospace Engineering, Delft University of Technology, September 2008.

[Zedd] Zedd M., **Experiments in Tether Dynamics Planned for ATEX’s Flight**, Naval Research Laboratory, Washington DC.

**Links**


[SSHP] Small Satellites Home Page http://centaur.sstl.co.uk/SSHP
### Internal Documents

<table>
<thead>
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<th>SLR Identifier</th>
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<td>DDTS Requirements Specification</td>
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<td>DELFI.1.SPC.4100.01</td>
<td>Spacecraft System Requirements Specification</td>
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<td>DELFI.1.DES.4120.02</td>
<td>Payload Module Description</td>
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<tr>
<td>DELFI.1.DES.4120.04</td>
<td>Payload Accommodation Requirements</td>
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<td>Payload-Bus Interface Control Document</td>
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<td>Payload Platform Design Description</td>
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<td>Eclipse Times</td>
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<td>DELFI.1.TN.2410.01</td>
<td>Technical Budgets (draft)</td>
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<td>DELFI.1.TN.4122.01</td>
<td>Overview Tether Know How, Technical note EDT Experiment</td>
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<td>DELFI.1.TN.4122.04</td>
<td>EDT WBS</td>
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<td>DELFI.1.TN.4122.05</td>
<td>PI meetings</td>
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<td>DELFI.1.TN.4122.07</td>
<td>DOT Cost Analysis</td>
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<td>DELFI.1.TN.4122.10</td>
<td>DOT MOD Risks</td>
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<td>DELFI.1.TN.4122.22</td>
<td>Potential Applications of EDT Technology</td>
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<td>DELFI.1.TN.4122.23</td>
<td>Altitude Request DOT Payload</td>
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<td>DELFI.1.SPC.4122.01</td>
<td>EDT System Requirements Specification (2.0)</td>
</tr>
<tr>
<td>DELFI.1.SPC.4122.03</td>
<td>EDT Functional Specification (3.0)</td>
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<td>EDT Experiment Mission Concepts</td>
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<td>DELFI.1.DES.4122.03</td>
<td>DOT Implementation Plan</td>
</tr>
<tr>
<td>DELFI.1.TW.4122.01</td>
<td>DOT Thesis Plan</td>
</tr>
</tbody>
</table>

[Vink] Vink, R. Design Drawings Delfi-1 Satellite

### Tools

EDT Technical Budgets: DELFI.1.TN.4122.08 EDT Technical Budgets (2.1) Excel sheet based tool the mass, power and data rate and dimensions budgets are managed.

EDT Preliminary Design: DELFI.1.TN.4122.24 Excel based tool for baseline performance calculations for EDT experiment

Tether Risk Analysis(2.0): DELFI.1.TN.4122.10 Excel based tool for M/OD risk calculations

TN is Technical Note, DES is Design document, SPC is specification document.
## APPENDIX 1 PREVIOUS TETHER MISSIONS

Table a 1: Previous tether missions

<table>
<thead>
<tr>
<th>Mission</th>
<th>Year</th>
<th>Orbit</th>
<th>Length [m]</th>
<th>Type</th>
<th>Developing Parties</th>
<th>Goals</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemini 11</td>
<td>1967</td>
<td>LEO</td>
<td>30</td>
<td>MT Spin stabilised 0.15 rpm</td>
<td>NASA</td>
<td>Induce artificial gravity by rotation</td>
<td>1 mg generated and observation of complicated tether dynamics</td>
</tr>
<tr>
<td>Gemini 12</td>
<td>1967</td>
<td>LEO</td>
<td>30</td>
<td>MT Swinging</td>
<td>NASA</td>
<td>Induce artificial gravity by rotation</td>
<td>Local vertical, stable swing</td>
</tr>
<tr>
<td>H-9M-69</td>
<td>1980</td>
<td>Sub orbital</td>
<td>500</td>
<td></td>
<td>NASA</td>
<td></td>
<td>Partial deployment</td>
</tr>
<tr>
<td>S-520-2</td>
<td>1981</td>
<td>Sub orbital</td>
<td>500</td>
<td>ED</td>
<td>NASA</td>
<td></td>
<td>Partial deployment</td>
</tr>
<tr>
<td>Charge-1</td>
<td>1983</td>
<td>Sub orbital</td>
<td>500</td>
<td></td>
<td>NASA Japanese ISAS</td>
<td></td>
<td>Full deployment</td>
</tr>
<tr>
<td>Charge-2</td>
<td>1984</td>
<td>Sub orbital</td>
<td>500</td>
<td></td>
<td>NASA Japanese ISAS</td>
<td></td>
<td>Full deployment</td>
</tr>
<tr>
<td>ECHO-7</td>
<td>1988</td>
<td>Sub orbital</td>
<td>unknown</td>
<td></td>
<td>NASA</td>
<td></td>
<td>Magnetic field alignment</td>
</tr>
<tr>
<td>Oedipus-A</td>
<td>1989</td>
<td>Sub orbital</td>
<td>960</td>
<td>ED d = 0.85 mm Spin stabilised 0.7 rpm</td>
<td>NASA, CRC, CSA</td>
<td>Measurements of weak electric fields in the plasma of the aurora</td>
<td>Full deployment</td>
</tr>
<tr>
<td>Charge 2B</td>
<td>1992</td>
<td>Sub orbital</td>
<td>500</td>
<td>ED</td>
<td>NASA Japan</td>
<td></td>
<td>230 m deployed upward and retrieval, spool mechanism jammed during retrieval. Proved concept of long gravity gradient stabilised tethers, demonstrated deployment</td>
</tr>
<tr>
<td>TSS-1</td>
<td>1992</td>
<td>LEO</td>
<td>20000</td>
<td>ED 20 km insulated copper wire</td>
<td>ASI NASA</td>
<td>20 km re-entry of 25 kg satellite deployed from Delta II stage</td>
<td>Worked, downward deployment, swing and cut</td>
</tr>
<tr>
<td>SEDS-1</td>
<td>1993</td>
<td>LEO</td>
<td>20000</td>
<td>MT d = 0.75 mm spectra-1000</td>
<td>NASA Tether Applications</td>
<td>20 km wire tether 12 days lifetime expected</td>
<td>Upward deployment, cut at both ends; 100-300 mA daytime and 10-50 mA eclipse; +150 to -90 V EMF Also passive ops only biased EMF; EMF matched to various models. Demonstrated hollow cathodes for current collection and emission</td>
</tr>
<tr>
<td>PMG</td>
<td>1993</td>
<td>LEO</td>
<td>500</td>
<td>ED; 2 plasma motors Hollow Cathode</td>
<td>NASA, DoD</td>
<td>Prove deboost (generator) and upboost ability of Hollow Cathode Assembly (HCA)</td>
<td>Cut after 3.7 days, proved stable deployment to near vertical by feedback control using friction brake. Remaining 7.2 km survived 59 days [Carroll]</td>
</tr>
<tr>
<td>SEDS-2</td>
<td>1994</td>
<td>LEO</td>
<td>20000</td>
<td>MT</td>
<td>NASA</td>
<td>20 km wire tether 12 days lifetime expected</td>
<td></td>
</tr>
<tr>
<td>Oedipus-C</td>
<td>1995</td>
<td>Sub orbital</td>
<td>1174</td>
<td>ED d = 0.85 mm Spin stabilised 0.7 rpm</td>
<td>NRC and NASA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSS-1R</td>
<td>1996</td>
<td>LEO</td>
<td>19600</td>
<td>ED insulated; 8 m² current collection sphere; 2 electron guns</td>
<td>ASI NASA</td>
<td>Tether severed; ( F_{\text{drag}} = 0.4 ) N, ( \text{EMF} = 0-3500 ) V; controlled current: ( P = 1800 ) W electron guns worked as plasma contactors uncontrolled current: ( 1.1 ) A; power: 3850 W</td>
<td></td>
</tr>
<tr>
<td>TIPS</td>
<td>1996</td>
<td>LEO</td>
<td>4000</td>
<td>MT 4 km dt = 2.5mm hollow braid Spectra fibre + yarn</td>
<td>NRL NRO</td>
<td>Multi strand tether survivability and dynamics</td>
<td></td>
</tr>
<tr>
<td>YES-1</td>
<td>1997</td>
<td>GTO</td>
<td>35000</td>
<td>MT</td>
<td>ESA Delta-Utec</td>
<td>Tethered momentum transfer to GTO</td>
<td></td>
</tr>
<tr>
<td>ATEx</td>
<td>1999</td>
<td>LEO</td>
<td>6000</td>
<td>MT Flat tape</td>
<td>NRO</td>
<td>Enforced tape tether survivability</td>
<td></td>
</tr>
<tr>
<td>DTUSat</td>
<td>2003</td>
<td>LEO</td>
<td>450</td>
<td>ED copper wire 0.2 mm ; FEAC</td>
<td>Denmark University Technology</td>
<td>Deorbit using bare wire and FEAC</td>
<td></td>
</tr>
<tr>
<td>MAST</td>
<td>2007</td>
<td>LEO</td>
<td>1000</td>
<td>MT Hoytether</td>
<td>Tethers Unlimited, Stanford University</td>
<td>Tether survivability</td>
<td></td>
</tr>
<tr>
<td>YES2</td>
<td>2007</td>
<td>LEO</td>
<td>31700</td>
<td>MT</td>
<td>Delta-Utec</td>
<td>Space Mail momentum exchange tether</td>
<td></td>
</tr>
<tr>
<td>STARS</td>
<td>2009</td>
<td>LEO</td>
<td>MT</td>
<td>Kagawa University</td>
<td>Tether deployment test</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cancelled</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSE</td>
<td>2002</td>
<td>LEO</td>
<td>35000</td>
<td>MT 0.5 mm</td>
<td>ESA</td>
<td>Space Mail</td>
<td></td>
</tr>
<tr>
<td>ProSEDS</td>
<td>2002</td>
<td>LEO</td>
<td>5000-10000</td>
<td>ED</td>
<td>NASA</td>
<td>Deorbit a Delta II upper stage and produce power</td>
<td></td>
</tr>
<tr>
<td>Terminator Tether™</td>
<td>2000</td>
<td>LEO</td>
<td>ED</td>
<td>Tethers Unlimited</td>
<td>Similar to ProSEDS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Some Future Proposals & Past Studies

**Providence 2** | Sub Orbital | ED | Delta Utec SanMartin; Japan | OML theory and (neutral) density vertical profile in the critical E- |
**APTUS** | | ED | University of Texas CubeSat |
**MXER** | | |
**EDDE** | | ED | STAR Inc. |
**The Mir Electrodynamic Tether System (METS)** | | ED | Energia Ltd. |
**NanoTerminator™** | 2007-2009 | LEO | 30 | ED flat 8 mm thick | Tethers Unlimited | Prototype for deorbit nano and micro-satellites |
Charge 1-2
Japan and NASA sub orbital sounding rocket missions designed to study the electrical charging of spacecraft resulting from standard e-beam emission. Charge results showed that neutral gas discharge enhanced electron current collection of a positively biased platform by ionisation of the gas increasing the local plasma density. Charge 2: insulated conductive wire 456 m in length with 0.5 mA-48 mA at 1 KeV and a voltage of up to 500 V was applied between the two payloads and the electrodynamic effects induced where studied. Measurements of the induced electromotive force and voltage/current characteristics were explained using a model showing the ion current to the negatively-biased payload limited the current. Also two kinds of VLF waves were observed when bias voltage was applied (2-4 kHz up to 15 kHz). [Sasaki]

Oedipus A-C
Two ED sounding rocket missions Canada launched using a Black Brant X, 3-stage sounding rocket. Both missions used a 0.85 mm conductive (insulated) tether attached to two payloads. Oedipus A focused on measurements of weak electric fields in the plasma of the aurora, ionospheric plasma measurements and researching plane and sheath wave RF propagation in plasma using 960 m tether. OEDIPUS C had similar goals as its predecessor, to research the importance of EDT for the propagation of RF waves between the two satellites the tether was cut at both ends. The experiments were also designed to help understand how charged particles associated with the aurora affect satellite transmissions. The OEDIPUS C successfully demonstrated the major axis spinner stabilisation for the tethered system using 1174 m ED tether [Cosmo].

Plasma Motor Generator PMG
The PMG experiment goals were to test the ability of an EDT and hollow cathode assembly (HCA) to operate in deboost (generator) and upboost mode. A 500 m insulated tether was deployed in LEO orbit using 2 plasma motors for anode and cathode. Current levels generated: 100-300 mA (daytime) and 10-50 mA (eclipse). The total voltage biased from +150 to -90 V and only the induced EMF (passive operation) was measured and matched against various models [Cosmo]. PMG demonstrated both power generation and propulsion using an EDT proving current reversal in ED tethers. The HCA’s were also shown to be a low power way to collect and emit electrons from the ionosphere [Cosmo].

Tethered Satellite System TSS-1R
TSS-1R a 19.7 km insulated copper ED tether generated high voltages and extracted currents from the ionosphere proving the feasibility of ED tethers. The current levels generated by the tether during deployment were up to a factor 3 higher than the predicted levels based on the Parker Murphy (PM) theory, see figure a 1. Also when the satellite’s ACS yaw thruster fired a large increase in tether current was observed indicating that the local plasma density was increased by ionisation of the neutral gas emitted by the thrusters. Two electron guns worked as plasma contactors and the 8 m² current collection sphere managed to collect 1.1 A of current. The orbiter was subjected to a drag force of 0.4 N. The system generated 1800 W of power with currents limited. A flaw in the (10 year old) insulation briefly increased current flow to 1.1 A and power levels to 3850 W before the tether was burned through by the high power electric arc between the tether and the deployment boom. The TSS-1R confirmed that a tether can induce large EMF potentials at orbital velocities [Cosmo].

![Figure a 1: TSS-1R current-voltage characteristics compared to predicted Parker Murphy model][Stone]
Conclusions from TSS experiment concerning gas release ACS:
A large increase of the tether current, a precipitous drop of the satellite bias voltage, very intense and energetic ion fluxes moving outward from the satellite's high-voltage plasma sheath, and a strong enhancement of the AC electric field in the 200 Hz to 2 kHz range—all observed to be concurrent with a satellite ACS yaw thrusters firing. These observations imply a plasma density enhancement by ionization of the neutral gas (nitrogen gas $N_2$) emitted by the satellite thrusters. It is already apparent, therefore that the data gathered during TSS-1R have the potential to significantly refine the present understanding of the physics of neutral gas releases in space plasmas and their effect on both of the above processes [Cosmo].

Tether Break leading to the highest currents of 1.1 A:
As the failure point of the tether entered into the ambient plasma, the current increased to 1.1 A and maintained this level even after the break for approximately 75 s. The principal surprise in these results was that the broken end of the tether, with only a few short strands of copper wire, could support higher currents than the much larger Orbiter conducting surface areas. Analysis of possible current enhancement mechanisms revealed that only a gas enhanced electrical discharge, providing an electron emission source, was plausible. Ground plasma chamber tests confirmed this analysis. The TSS-1R results thus represent the highest electron current emission from a neutral plasma source yet demonstrated in a space plasma. This is of interest for current collection processes in general and plasma contactor development in particular [Gilchrist].

Tether Physics and Survivability Satellite TiPS and Advanced Tether Experiment ATEx
With the SEDS-2 wire tether being cut by space debris after only 3.7 days in orbit the need for different tether designs with increased survivability was imminent. Two experiments using different designs have been flown. TiPS consisted of a 4 km multi braid tether; a 2.5 mm diameter hollow braid of Spectra fibre loosely packed with yarn. Launched in June 1996 has remained orbiting in space uncut till July 2006 with the tether visibility fading, the tether material darkening due to ultraviolet and/or atomic oxygen exposure. The TiPS lifetime correlates to debris models by [Carroll] indicating the extremely short lifetime of the SEDS-2 to probably be due to upper stage debris not taken into account in debris models.

The ATEx tether consisted of a 6 km, 3 cm wide tape reinforced with fibre strands; deployment was terminated after 22 m with the tether being jetisoned due an observed to out of limits condition by the tether angle sensor indicating at least 10 cm of tether had gone slack. This occurred at the same time the tether was moving from eclipse to the solar part of the orbit and the tether temperature increased to 70ºC with an expansion of 15.5 cm of the 22 m deployed tether. The thermal expansion due to heating of the tether was not taken into account in the design of the deployment system and the most likely cause of failure. The tether used on ATEx was selected for long term survivability. The handling features (such as friction, stiction and shape memory) of this tether however made it very difficult to deploy [Gates].

DTUSat
The DTUSat consisted of a $d_t = 0.2$ mm, 450 m long copper wire tether with a FEAC cathode onboard the DTUSat emitting electrons. The maximum tether current using the FEAC was 29 mA lowering the satellite orbit by 5 km per hour [DTUsat1]. Final flight design did not include the FEAC and the tether was to operate in passive mode. The satellite unfortunately did not work in orbit.

ProSEDS
ProSEDS and commercial version Terminator Tether were both designed to prove EDT deboost of an upper stage of a rocket and use a portion of bare tether as a current collection device. ProSEDS was designed to deorbit a Delta II second stage during 2-3 weeks by using an EDT and planned for June 2002. The bare aluminium 5 km tether was designed to induce a 1-2 A current producing a Lorentz drag force in the order of 0.4 N [Ahedo]. This mission was cancelled in 2003 due to its orbit being above the ISS and risk of collision during deorbit was considered to be unacceptable.
Terminator Tether™ and NanoTerminator™

Terminator Tether (TT) is a 26 to 45 kg prototype EDT deorbit system to be attached to satellites and rocket stages. Consisting of a conducting survivable tether, deployer, electron emitter and a tether control unit the system is design to use electrodynamic drag to deorbit spacecraft in the range of 1000-2000 kg. TT initial calculations show a 2.5% mass fraction of the spacecraft EDT system is capable of reducing orbital lifetime from 100-11000 yrs to 11 days- 17 months range depending on initial orbit altitude and inclination [Hoyt].

To address the problem of deorbiting nano and micro-satellites stated in [TN.4122.22] a deorbit system will have a large impact on cost and mass of the satellite Tethers Unlimited recently developed the NanoTerminator™ enabling nano and micro-satellites to adhere to the orbital lifetime <25 yrs recommendation (section 2.2.2). The nano TT is a 54.5 mm x 38 mm diameter device having a mass of 56 grams capable deploying a tether up to a few kilometres in length depending on satellite size. Using the NanoTerminator™ the initial orbit restriction 620-680 km for CubeSats ensuring orbital lifetimes <25 yrs is raised up to 1000 km altitude (100 m tether) [Voronka].

Providence 2

Providence 2 a proposed sounding rocket EDT experiment proposal, two goals a test of OML current collection and the proof-of-flight of a technique to determine the (neutral) density vertical profile in the critical E-layer [Fuji].
APPENDIX 2 DEVELOPING PARTIES

Space Agencies

ESA - European Space Agency:
- TSE Tether System Experiment
- ESOC rotating tethers in GTO orbits e>0.4 self-sustaining (even accelerating) rotation possible by timing tether retraction
- ESA Science interested in observing Auroral effects produced by a EDT
- ESA interested in the LEO demonstration for the Jupiter mission. Main question: how to prove / measure the systems performance and instrumentation in LEO

NASA - National Aerospace Agency:
- Charge
- SEDS
- TSS-1/R
- ProSEDS
- ISS upboost studies
  - In-Space Propulsion Technologies Program NASA
  - Marshall Space Flight Center MXER
  - Air Force Research Lab, Space Vehicles Directorate
  - Naval Research Laboratory (NRL) multi-braid tether 1996 TiPS
  - National Reconnaissance Office (NRO) multi-braid tether 1996 TiPS; ATEx 1999 flat tape

ASI - Italian Space Agency:
- TSS-1/1R
- bare tether plasma chamber research

JAXA - Japanese Aerospace Agency (fold away flat tether deployment system); (STARS mission)
- National Aerospace Laboratory of Japan (NAL)
- Institute of Space and Astronautical Science, Japan
- Tokyo Metropolitan Institute of Technology (Providence)

Companies

- Delta-Utec: YES 1 (not deployed); YES 2; SATAJ proposal; studies ESA; software ETBSim
- Tethers Unlimited; focus on multi-braided Hoyt Tethers and various application concept designs; Terminator Tether
- Tether Applications; (EDDE) various studies 1993 & 1994 mechanical tether, tether lifetime experiment (SEDS)
- STAR Inc. (EDDE)
- Energia Ltd. The Mir Electrodynamic Tether System (METS)

Some Universities-Institutes Working on Tethers

- MIT (ProSEDS)
- University of Michigan, (prof. Gilchrist TSS, ProSEDS etc, TSATT (Tethered SATellite Testbed)), current collection research, plasma tests
- Universidad Politecnica de Madrid Spain deorbiting tethers, bare tethers
- University of Rome and Institute of Space Physics in Italy
- Denmark Politecnica de Madrid Spain deorbiting tethers, bare tethers
- University of Rome and Institute of Space Physics in Italy
- Denmark University of Technology DTU (DTUSat)
- Kagawa University (STARS mission)
- Kyushu University Japan (Quest; QTEX)
- Shizuoka University, Japan (Providence)
- Tokyo Metropolitan Institute of Technology,
- TU Delft
APPENDIX 3 ORIGINAL EXPERIMENT PROPOSALS

Initial proposals for a tether mission onboard the Delfi satellite were described in the DEUS and Delfi DESt reports.

**DEUS Tether Experiment Proposal**

*Source SLR 08*

This tether experiment proposal demonstrates the use of tethers for satellite propulsion and was proposed by Delta-Utec. The main purpose of the experiment is to validate existing theoretical models through measurement of the current produced in the tether and to collect data about the plasma environment and system dynamics. This is to be done while the tether de-orbits the satellite. The components of the de-orbiting tether system are

- conducting (flat) tether with a length of 500 m
- plasma conductor/emitter
- tip mass.

The tip mass will hold various components: the battery, deployment mechanism, and electronics package. In table a 2 the characteristics of the experiment are shown. The system is dormant until the end of the satellite mission is reached, then using a deployment mechanism the tether will be extended from the satellite. A small roll out velocity has to be maintained in the order of 10 cm/s. Roll out will take 3 hours. The motor should be stopped at 10 s intervals to facilitate stabilisation of the tether. The satellites computer controls the electromotor (automated deployment controlling the dynamic behaviour of the tether). The emitter closes the current loop by emitting the collected electrons to the ionospheric plasma environment. The emitter used is a Hollow-Cathode emitter that uses an inert gas to emit electrons and requires a battery of 1.5 V. The emitter is switched off until the tether is deployed to avoid disturbing Lorenz forces acting on the tether during roll out. When the tether is deployed the electronics package in the tip mass can conduct the experiments on the plasma environment. Plasma density, potential and electron temperatures will be measured. A package of 6 accelerometers will determine the motion of the tether. The data from these experiments will be relayed to the satellite with a simple transmitter system. Preliminary results of the ETB-Simulation show that a tip-mass is required to stabilise the tether. Current control will be needed if the tether is deployed at a large altitude and is subjected to a large variation in Lorenz forces during deorbit. The tether does not have to be conducting over its entire length. Simulations have shown that an optimum can be achieved by dividing the tether in a bare part and a mechanical part.

Table a 2: DEUS tether experiment proposal [SLR 08]

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Mass [kg]</th>
<th>Power [W]</th>
<th>Data rate [bps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tether bare 500 x 0.001 x 0.00015 m</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instrumentation (electronics)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current sensor</td>
<td>TBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attitude sensor</td>
<td>TBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerometer (6)</td>
<td>TBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma probe</td>
<td>TBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camera</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tether tip-mass</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma contactor</td>
<td>0.5</td>
<td></td>
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</tr>
<tr>
<td>Electronics</td>
<td>1</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Control unit</td>
<td>1</td>
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</tr>
<tr>
<td>Batteries</td>
<td>0.3</td>
<td></td>
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</tr>
<tr>
<td>Transceiver</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Cutters (2)</td>
<td>0.4</td>
<td></td>
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</tr>
<tr>
<td>Release mechanism and Deployer electromotor</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7</strong></td>
<td><strong>5</strong></td>
<td><strong>56</strong></td>
</tr>
</tbody>
</table>
# Delfi DESt Tether Experiment Proposal

Table a 3: Delfi DESt tether experiment proposal [SLR 09]

<table>
<thead>
<tr>
<th>Hardware</th>
<th>Mass [kg]</th>
<th>Power [W]</th>
<th>Data rate [bps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tether bare wire 3-10kg/km 1-3 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma Contactor</td>
<td>0.5 - 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deployer</td>
<td>1 - 2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Release mechanism</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Springs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Unit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutters</td>
<td>2 x 0.2</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td><strong>Instrumentation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current sensor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma Probe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attitude Sensor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerometer 3 dir.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camera</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tether tip-mass</td>
<td>TBD</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 4 DESIGN APPROACH & PHASES

Figure a 2: Design approach EDT experiment preliminary design phases 0-A-B [TW.4122.01, Hamann]
Design Phases [Andre; Hamann]

Phase – 0 studies: Mission Analysis and Needs Identification
Precise identification of mission objectives, user needs and environmental constraints
Preliminary System Design Concepts
Output:
- Preliminary User Requirements [mission objectives]
- Conceptual System Design
  - Expected performances
  - Possible risks and critical aspects
  - Programmatic prediction costs, schedule, critical path
- Project Development Outline

Phase – A studies: Feasibility Investigation
Propose various system concepts with their characteristics and criticality. Compare concepts against user requirements, levels of risks. Estimate technical and industrial feasibility; identify margins in relation to targets and constraints.

System concept selection
Controlled baseline of functional specification
Technology assessment

Preliminary Requirements Review
Output:
- System Concept Design Baseline
- Preliminary System Requirements
- Preliminary Implementation plan

Phase – B studies: Preliminary Definition
Selection of technical solutions for system concept selected in phase A, definition of performance, costs, schedules, make or Buy decisions, confirmation of the feasibility of recommended solution defining operating conditions

System Requirements Review
Preliminary Design Review
Outputs:
- Preliminary System and Subsystem Drawings
- System & Component Requirements [project, design, technical]
- Interface Control Document
- Budgets
- Critical systems: simulation or breadboard
- Critical Technology: feasibility

Phase – C studies: Detailed Definition of the Product
Detailed study, definitive make or buy, confirmation of set-up, test & qualification conditions, methods and means of verification, Interface establishment
Outputs:
- Detailed Design
- Technological Readiness
- Process Documentation, Material specification, Tools and Handling Procedures

Final Flight Design Review

Phase – D: Production & Ground Testing
Production, qualification, evaluation and updating of flight standard design
Outputs:
- Completed Flight Standard Design Baseline
- Completed Process Documentation, Material specification, Tools and Handling Procedures
- As Built Status and Items
Phase – E: Utilisation in Orbit
E1: Overall test and commissioning phase of the system
  ▪ Launch activities
  ▪ In-flight qualification-acceptance testing of the system allowing for assessment and measurements of performance level

In Space Test Review

E2: Utilisation of the Payload
Operation Reviews
  ▪ Feedback for future missions
  ▪ Obtaining Scientific Data

Phase – F: Disposal
Safe orbit parking; deorbit
Shutdown
### APPENDIX 5 DESIGN METHODS

**Design methods required in preliminary design phase [TN.41212.01]**

<table>
<thead>
<tr>
<th>Goal</th>
<th>Input/Tool</th>
<th>Source</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission goals =&gt; functions (sub) =&gt; HW/SW</td>
<td>Tools: Functional block diagram, system breakdown, product trees</td>
<td>Literature, [Jainandunsing], Ae4-S12 [Hamann]</td>
<td>TBD</td>
</tr>
<tr>
<td>Requirements</td>
<td>Tools: requirements discovery tree</td>
<td>Literature, pi's Ae4-S12 [Hamann]</td>
<td>TBD</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Mass</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Dimensions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Complexity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inputs: Material props Tools: available equations from literature, basic tether performance equations</td>
<td>Literature, [Jainandunsing] [Meeuwen] Modelling the TSS, Ae2-S02 [Zandbergen]</td>
<td>Available</td>
</tr>
<tr>
<td>Dynamics</td>
<td>Inputs: Equations of motion and equations for oscillations; Environmental inputs Tools: ETBSim, (Simple) simulation of equations of motion Tools: Influence mass, length on stability Tools: Control method</td>
<td>Literature [Jainandunsing] [Meeuwen], Ae4-S38 [Ockels]</td>
<td>Available</td>
</tr>
<tr>
<td>Risk Analysis Development and Operating</td>
<td>Tools: Tether lifetime analysis, M/OD environment models</td>
<td>[Jainandunsing] Ae4-S12 [Hamann]</td>
<td>TBD development and operating risk analysis risk approach</td>
</tr>
<tr>
<td>Comparing concepts</td>
<td>Inputs: Use conventional means as baseline to compare performance, Use critical design factors to compare concepts with each other</td>
<td>[Jainandunsing] [Meeuwen], Ae4-S12 [Hamann]</td>
<td>Available</td>
</tr>
<tr>
<td>Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stowed Volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complexity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verification</td>
<td></td>
<td>[Jainandunsing]</td>
<td>TBW 1</td>
</tr>
<tr>
<td>Interfaces satellite</td>
<td></td>
<td>[Jainandunsing]</td>
<td></td>
</tr>
<tr>
<td>Testing</td>
<td>Modelling TSS</td>
<td></td>
<td>TBW 1</td>
</tr>
</tbody>
</table>

4 TBD, factors like mass, power, stowed volume etc. Also used in trade-off, determine what the critical factors in the design are. Linked with determining critical technology for the experiment
Figure a 3: Work breakdown structure preliminary design phase 0-A [TN.4122.04]
Figure a 4: Work breakdown structure & packages final design phase B-C [TN.4122.04]

Figure a 5: Development timeline of a LEO demonstration mission for the SATAJ project [DES.4122.03]
Figure a 6: Functional Flow diagram EDT experiment v 2.0 27-10-03 [SPC.4122.03]
Figure a 7: Function allocation to Bus-EDT-GS version1.1 09-04-03 [SPC.4122.03]
Figure a 8: Functional breakdown EDT payload deployment – operation – termination phases v1.0 09-04-0 [SPC.4122.03]
APPENDIX 8 SYSTEM INTERFACES

Figure a 9: Interfaces EDT payload with Delfi-1 bus
Table a 4: Delfi-1 and EDT interfaces

<table>
<thead>
<tr>
<th>DELFI-1 System</th>
<th>ID</th>
<th>Interface Type</th>
<th>Functions</th>
<th>EDT System onboard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Platform</td>
<td>PL</td>
<td>Structural Power Data</td>
<td>Support payload</td>
<td>EDT</td>
</tr>
<tr>
<td>Structure</td>
<td>SS</td>
<td>PL</td>
<td></td>
<td>STS</td>
</tr>
<tr>
<td>Electrical Power System</td>
<td>EPS</td>
<td>Power Harnessing</td>
<td>Provide power</td>
<td>EPS</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>CDHS</td>
<td>Data :</td>
<td>Provide data storage Monitor EDT health</td>
<td>TLM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Commands</td>
<td></td>
<td>STS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- House Keeping</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Science Harnessing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communications</td>
<td>COMM</td>
<td>Data</td>
<td>Transmit and Receive data GS</td>
<td>None</td>
</tr>
<tr>
<td>Attitude Determination and</td>
<td>ADCS</td>
<td>MOI Disturbance Forces</td>
<td>Stabilise ±5º</td>
<td>DEP TET GAS EM</td>
</tr>
<tr>
<td>Control System</td>
<td></td>
<td>and Torques</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Science data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground Station</td>
<td>GS</td>
<td>Data</td>
<td>Supply data</td>
<td>None</td>
</tr>
</tbody>
</table>
APPENDIX 9 REQUIREMENTS GENERATION

Figure a 10: Requirements generation approach EDT experiment [SPC.4122.01]
APPENDIX 10  MASS BUDGETS

Average percentages of a number of missions and proposals are used and redistributed to a 100% division, then the budget is adjusted for use of a survivable tape tether with a 25% mass percentage, a lower STS (10%) and 0% end mass again redistributing to a 100% giving an initial top down mass budget for the EDT experiment without end mass and with an end mass.

Table a 5: Top down mass distribution using data from other experiments [TN.4122.08]

<table>
<thead>
<tr>
<th>Component</th>
<th>Average [%]</th>
<th>Redistributed [%]</th>
<th>Mass Allocation [kg]</th>
<th>Adjusted Tether, STS,EM Average [%]</th>
<th>Adjusted Redistributed [%]</th>
<th>Adjusted Estimated [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT Payload</td>
<td>131%</td>
<td>100%</td>
<td>6</td>
<td>91%</td>
<td>100%</td>
<td>6</td>
</tr>
<tr>
<td>Deployer</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
<td>16%</td>
<td>17%</td>
<td>1.0</td>
</tr>
<tr>
<td>Telemetry</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
<td>16%</td>
<td>17%</td>
<td>1.0</td>
</tr>
<tr>
<td>Power</td>
<td>9%</td>
<td>7%</td>
<td>0.4</td>
<td>9%</td>
<td>10%</td>
<td>0.6</td>
</tr>
<tr>
<td>Structure &amp; Harnessing</td>
<td>18%</td>
<td>14%</td>
<td>0.8</td>
<td>10%</td>
<td>11%</td>
<td>0.7</td>
</tr>
<tr>
<td>Tether</td>
<td>20%</td>
<td>15%</td>
<td>0.9</td>
<td>25%</td>
<td>27%</td>
<td>1.6</td>
</tr>
<tr>
<td>Gas bottle(s)</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
<td>16%</td>
<td>17%</td>
<td>1.0</td>
</tr>
<tr>
<td>End mass</td>
<td>37%</td>
<td>28%</td>
<td>1.7</td>
<td>0%</td>
<td>0%</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table a 6: Top down mass distribution using data from other experiments including stabilising end mass

<table>
<thead>
<tr>
<th>Component</th>
<th>Average [%]</th>
<th>Redistributed [%]</th>
<th>Mass Allocation [kg]</th>
<th>Adjusted Tether, STS Average [%]</th>
<th>Adjusted Redistributed [%]</th>
<th>Adjusted Estimated [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT Payload</td>
<td>131%</td>
<td>100%</td>
<td>6</td>
<td>128%</td>
<td>100%</td>
<td>6.0</td>
</tr>
<tr>
<td>Deployer</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
</tr>
<tr>
<td>Telemetry</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
</tr>
<tr>
<td>Power</td>
<td>9%</td>
<td>7%</td>
<td>0.4</td>
<td>9%</td>
<td>7%</td>
<td>0.4</td>
</tr>
<tr>
<td>Structure &amp; Harnessing</td>
<td>18%</td>
<td>14%</td>
<td>0.8</td>
<td>10%</td>
<td>8%</td>
<td>0.5</td>
</tr>
<tr>
<td>Tether</td>
<td>20%</td>
<td>15%</td>
<td>0.9</td>
<td>25%</td>
<td>19%</td>
<td>1.2</td>
</tr>
<tr>
<td>Gas bottle(s)</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
<td>16%</td>
<td>12%</td>
<td>0.7</td>
</tr>
<tr>
<td>End mass</td>
<td>37%</td>
<td>28%</td>
<td>1.7</td>
<td>37%</td>
<td>29%</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table a 7: Mass distribution other tether experiments and proposals [TN.4122.08]

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>[%] total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tether</td>
<td>0.7</td>
<td>3%</td>
</tr>
<tr>
<td>Reel mechanism</td>
<td>1.05</td>
<td>5%</td>
</tr>
<tr>
<td>ejection mechanism</td>
<td>4</td>
<td>19%</td>
</tr>
<tr>
<td>magnetometer</td>
<td>0.5</td>
<td>2%</td>
</tr>
<tr>
<td>structure ADC</td>
<td>7</td>
<td>34%</td>
</tr>
<tr>
<td>COMMS</td>
<td>1</td>
<td>5%</td>
</tr>
<tr>
<td>CDHS</td>
<td>1</td>
<td>5%</td>
</tr>
<tr>
<td>power</td>
<td>2.5</td>
<td>12%</td>
</tr>
<tr>
<td>payload</td>
<td>3</td>
<td>14%</td>
</tr>
<tr>
<td>total</td>
<td>20.75</td>
<td></td>
</tr>
<tr>
<td>margin</td>
<td>2.45</td>
<td>12%</td>
</tr>
<tr>
<td>Total</td>
<td>22.5</td>
<td></td>
</tr>
<tr>
<td>Sub satellite</td>
<td>17.5</td>
<td>12%</td>
</tr>
<tr>
<td>total margin</td>
<td>10</td>
<td>26%</td>
</tr>
<tr>
<td><strong>ATEX [Zedd]</strong></td>
<td>mass [kg]</td>
<td>[%] total</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>UEB</td>
<td>11.8</td>
<td>22%</td>
</tr>
<tr>
<td>Tether</td>
<td>13.4</td>
<td>25%</td>
</tr>
<tr>
<td>LEB</td>
<td>27.6</td>
<td>52%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>52.8</td>
<td></td>
</tr>
<tr>
<td><strong>TSE [Gavira Izquierdo]</strong></td>
<td><strong>mass [kg]</strong></td>
<td>[%] total</td>
</tr>
<tr>
<td>Tether deployer &amp; electrical subsystems</td>
<td>60</td>
<td>42%</td>
</tr>
<tr>
<td>sub-satellite</td>
<td>42</td>
<td>29%</td>
</tr>
<tr>
<td>experiment container</td>
<td>41</td>
<td>29%</td>
</tr>
<tr>
<td><strong>35 km tether dyneema</strong></td>
<td><strong>Total</strong></td>
<td>143</td>
</tr>
<tr>
<td><strong>EDDE mass budget [Pearson]</strong></td>
<td><strong>mass [kg]</strong></td>
<td>[%] total</td>
</tr>
<tr>
<td>Conductor/collector 2 x 400 m alufoil</td>
<td>3.4</td>
<td>9%</td>
</tr>
<tr>
<td>solar array</td>
<td>3</td>
<td>8%</td>
</tr>
<tr>
<td>power handling</td>
<td>1</td>
<td>3%</td>
</tr>
<tr>
<td>avionics computer, GPS, telemetry</td>
<td>1</td>
<td>3%</td>
</tr>
<tr>
<td>hollow cathode emitter</td>
<td>10</td>
<td>28%</td>
</tr>
<tr>
<td><strong>EDDE structure</strong></td>
<td><strong>4.9</strong></td>
<td>13%</td>
</tr>
<tr>
<td>structure on delta marman clamp, supports</td>
<td>3</td>
<td>8%</td>
</tr>
<tr>
<td><strong>non conducting tether 4 km + deployer</strong></td>
<td><strong>2</strong></td>
<td>6%</td>
</tr>
<tr>
<td>payloads diagnostic sensors etc</td>
<td>8</td>
<td>22%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>36.3</td>
<td></td>
</tr>
<tr>
<td><strong>Terminator tether mass budget [Hoyt]</strong></td>
<td><strong>mass [kg]</strong></td>
<td>[%] total</td>
</tr>
<tr>
<td>tether</td>
<td>10</td>
<td>28%</td>
</tr>
<tr>
<td>Ejection mechanisms</td>
<td>3.5</td>
<td>10%</td>
</tr>
<tr>
<td>Spool assembly</td>
<td>5.8</td>
<td>16%</td>
</tr>
<tr>
<td>TCU Electronics</td>
<td>3.7</td>
<td>10%</td>
</tr>
<tr>
<td>Structure</td>
<td>2.25</td>
<td>6%</td>
</tr>
<tr>
<td>electron emitter</td>
<td>1.2</td>
<td>3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>26.45</td>
<td></td>
</tr>
<tr>
<td><strong>SEDS [Cosmo]</strong></td>
<td><strong>mass [kg]</strong></td>
<td>[%] total</td>
</tr>
<tr>
<td>Deployer canister</td>
<td>3</td>
<td>8%</td>
</tr>
<tr>
<td>tether</td>
<td>7</td>
<td>18%</td>
</tr>
<tr>
<td>brake/cutter</td>
<td>1</td>
<td>3%</td>
</tr>
<tr>
<td>electronics</td>
<td>2</td>
<td>5%</td>
</tr>
<tr>
<td>end mass</td>
<td>23</td>
<td>58%</td>
</tr>
<tr>
<td>brackets/clamps</td>
<td>4</td>
<td>10%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><strong>DEUS [SLR 09]</strong></td>
<td><strong>mass [kg]</strong></td>
<td>[%] total</td>
</tr>
<tr>
<td>Main satellite</td>
<td>32.5</td>
<td></td>
</tr>
<tr>
<td>tether</td>
<td>2.4</td>
<td>32%</td>
</tr>
<tr>
<td>emitter</td>
<td>0.5</td>
<td>7%</td>
</tr>
<tr>
<td>battery</td>
<td>0.3</td>
<td>4%</td>
</tr>
<tr>
<td>control unit</td>
<td>1</td>
<td>14%</td>
</tr>
<tr>
<td>release mechanism &amp; deployer</td>
<td>1</td>
<td>14%</td>
</tr>
<tr>
<td>electronics package</td>
<td>1</td>
<td>14%</td>
</tr>
<tr>
<td>transceiver system</td>
<td>0.3</td>
<td>4%</td>
</tr>
<tr>
<td>tether cutter</td>
<td>0.4</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Tip mass used as platform</strong></td>
<td><strong>4.5</strong></td>
<td><strong>61%</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>Volna version [Delta-Utec]</td>
<td>mass [kg]</td>
<td>[%] total</td>
</tr>
<tr>
<td>----------------------------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Main mass</strong></td>
<td>25.8</td>
<td>63%</td>
</tr>
<tr>
<td>Deployer</td>
<td>4.0</td>
<td>10%</td>
</tr>
<tr>
<td>Gas bottle</td>
<td>5.0</td>
<td>12%</td>
</tr>
<tr>
<td>EPS</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>Electronics, measurement &amp; control package + EPS</td>
<td>8.0</td>
<td>20%</td>
</tr>
<tr>
<td>Magnetometer &amp; accelerometers</td>
<td>0.5</td>
<td>1%</td>
</tr>
<tr>
<td>Langmuir probe</td>
<td>0.3</td>
<td>1%</td>
</tr>
<tr>
<td>Structure and Harnessing</td>
<td>8.0</td>
<td>20%</td>
</tr>
<tr>
<td><strong>End mass</strong></td>
<td>5.3</td>
<td>13%</td>
</tr>
<tr>
<td>Gas bottle</td>
<td>5.0</td>
<td>12%</td>
</tr>
<tr>
<td>Langmuir probe</td>
<td>0.3</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Extra</strong></td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td><strong>Tether</strong></td>
<td><strong>10.0</strong></td>
<td><strong>24%</strong></td>
</tr>
<tr>
<td><strong>Extra stability mass</strong></td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>Margin</td>
<td>0.0</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>41.0</strong></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 11 EDT DESIGN OPTION TREE & CONFIGURATION TRADE OFF TABLE

![Diagram of EDT Configuration Options]

Figure a 11: Configuration design option tree and trade-off

63/93
Results of the design option trade off at system level using pair wise comparison between options; trade off criteria are given equal weight at this point so a system of + - is sufficient to perform trade off

Table a 8: EDT design configuration trade off table [TN.4122.24]

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Options</th>
<th>Remarks</th>
<th>Mass</th>
<th>Stowed Volume</th>
<th>Complexity</th>
<th>Development Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT operating mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive</td>
<td>De-boost</td>
<td>Natural occurring at floating, no direct current measurements</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Active</td>
<td>De-boost</td>
<td>Measure current directly of tether at cathode end</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-+</td>
</tr>
<tr>
<td></td>
<td>Up-boost</td>
<td>Measure current directly of tether at cathode end Requires active biasing to overcome EMF</td>
<td>-</td>
<td>-</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>TET</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare Anode Tether</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deployed Nadir</td>
<td>Integrated Bus</td>
<td>Special PL platform</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>External antenna PL module</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Integrated GGB</td>
<td>Uncertainties to Deployment boom and Data and Power connection integrity</td>
<td>NA</td>
<td>-+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Deployed Zenith</td>
<td>Integrated Bus</td>
<td>Standard or special PL platform</td>
<td>NA</td>
<td>NA</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>External antenna PL module</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>-+</td>
<td>--</td>
</tr>
<tr>
<td>Active Bias Bare Tether</td>
<td></td>
<td>Requires a power source</td>
<td>-+</td>
<td>-+</td>
<td>-+</td>
<td>-+</td>
</tr>
<tr>
<td>Passive Cathode</td>
<td>Bare tether</td>
<td>Mass efficient</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Sphere</td>
<td></td>
<td>Not an option</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>Delfi-1</td>
<td></td>
<td></td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Active Cathode</td>
<td>FEAC</td>
<td>Requires enough tether voltage to operate or separate high voltage power source HVPS</td>
<td>++</td>
<td>++</td>
<td>-+</td>
<td>--</td>
</tr>
<tr>
<td>Hollow Cathode</td>
<td></td>
<td>Requires a power source and gas source</td>
<td>+</td>
<td>-</td>
<td>-+</td>
<td>--</td>
</tr>
<tr>
<td>Thermionic</td>
<td></td>
<td>High power</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>Plasma Gun</td>
<td></td>
<td>Complex power etc not an option</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
<td>xx</td>
</tr>
<tr>
<td>Gas cathode</td>
<td></td>
<td>Onboard and to be researched</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Cathode Tether</td>
<td>Bare Cathode</td>
<td>Use tether to close current loop via ion collection</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
<td>-----------------------------------------------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Insulated Cathode end</td>
<td>higher current levels, non zero current at tether end, requires cathode emitting electrons to close current loop Degradation - deployability of insulation during 1 year onboard storage time will complicate matters</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Entirely (enforced) conductive</td>
<td>Round wire</td>
<td>Single line multi line</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Tape tether</td>
<td>Enforced foil or thin film type</td>
<td>++</td>
<td>--</td>
<td>+</td>
<td>+-</td>
<td></td>
</tr>
<tr>
<td>Part (enforced) conductive – part mechanical</td>
<td>A bare aluminium tether is relatively rigid this can cause problems during deployment therefore an initial mechanical part can be desirable to achieve good deployment for initial low friction deployment and stabilising (increasing gravity gradient). Also separating a high voltage tether end from the sc bus can be done by using a non conducting part having a mass and complexity advantage over insulated ED tether. Multi strand single strand ; integration: It is unknown if the flat tether can be integrated with a mechanical tether</td>
<td>+</td>
<td>+</td>
<td>-+</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>No EM</td>
<td>TBD if required for deployment and operational phase</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>EM</td>
<td>Active EM</td>
<td>measurements at both tether ends, complexity of data link to CDHS and power source (auxiliary from tether), control of gas release if @tether end</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Passive EM</td>
<td>At most GAS time tagged rest is extra mass if required</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>GAS</td>
<td>@ BUS</td>
<td>External antenna PL module</td>
<td>NA</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>GAS @ tether end</td>
<td>Independent ops required, time tagged an power source</td>
<td>NA</td>
<td>Depends on storage locations</td>
<td>+-</td>
<td>+-</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------</td>
<td>-----------------------------</td>
<td>-------------</td>
<td>----------------</td>
<td>------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td>Fixed axis, tether slides off [TBD 14] feasible for foil tether</td>
<td>not requiring any special winding techniques easy for retraction good for flat foil tether</td>
<td>-+ -+</td>
<td>-+ ++ -+</td>
<td>Tether too short</td>
<td>Not requiring any special winding techniques easy for retraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Several single wound tether reels (platters) parallel to each other, variations in tether speed and radius on the reel when switching from reel to reel can cause problems. Is more complex and during deployment the change between platters will cause a step change in the angular momentum, proposed for EDDE [Pearson]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single Winding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Option for the smaller size tape tether design depending on the material and the unwinding angles this technique was used for the ATEX tether. This winding option is more complex and harder to use when reeling in is required. It does however result in the most compact reel design. For thin foil the angles that the tether will have to make to be able to level wind will cause tears and folds in the aluminium foil degrading the tether</td>
<td>++ -+ -+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Level Winding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Passive Inertial driven reel None GG</td>
<td>TBD if feasible Depends on the end mass and the tether length and deployer design</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pressurised gas canister</td>
<td>-+</td>
<td>-+</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Active Motor driven reel Electromotor</td>
<td>-+</td>
<td>++</td>
<td>-+</td>
<td></td>
</tr>
</tbody>
</table>

<p>| Passive Ejection force | None GG | Spring | Pressurised gas canister | Electromotor |</p>
<table>
<thead>
<tr>
<th>Deployment Control</th>
<th>Advantages of controlling the deployment are the ability to stabilise the tether, prevent slack build-up or too much tension on the tether</th>
<th>Passive</th>
<th>Tether design</th>
<th>Adhesive coating; rip stitches</th>
<th>Friction, eddy current</th>
<th>Active</th>
<th>Deployer design</th>
<th>Motor control</th>
<th>Feedback control</th>
<th>Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>++ ++ ++</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Tether design</td>
<td>Adhesive coating; rip stitches</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Deployer design</td>
<td>[TBD 16]</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Passive break</td>
<td>System Friction, eddy current</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>system</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Active</td>
<td>Motor control</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Friction Brake</td>
<td>Feedback control Complexity</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Magnetic torque</td>
<td>Motor control</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>control</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Tether guidance</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>system pulling</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>system [ATEX]</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Passive stabilisation</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>End mass</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Limit current</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Tether design</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Active Stabilisation</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Feedback control</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Retrieval</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Release mechanism</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Cutter</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Thermal or pyrotechnical device</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>No cutter</td>
<td>Feedback control during deployment, motor driven</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>EPS</td>
<td>Bus EPS</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>generate power</td>
<td>Essentially cathode end insert a load voltage zenith deployed tether</td>
<td>++</td>
<td>++</td>
<td>Craze; rip stitches</td>
<td>Friction, eddy current</td>
<td>++</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>
Dependence of parameters on flat tether dimensions and comparison with equivalent round wire (rw) tethers [TN.4122.13]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Flat Tether</th>
<th>Equivalent Collection and Drag Area Wire Tether $d_{rw} = d_t$</th>
<th>Equivalent Mass Wire Tether</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area $dA_c$</td>
<td>$w \cdot t$</td>
<td>$\frac{1}{4} \pi d_{rw}^2 = \frac{(w+t)^2}{\pi}$</td>
<td>$w \cdot t$</td>
</tr>
<tr>
<td>Current Collection Area $dA_{coll}$</td>
<td>$2(w+t)$</td>
<td>$2(w+t)$</td>
<td>$\pi \sqrt{\frac{4wt}{\pi}}$</td>
</tr>
<tr>
<td>Aerodynamic Drag Area $dA_d$</td>
<td>$d_t = \frac{2(w+t)}{\pi}$</td>
<td>$\frac{2(w+t)}{\pi}$</td>
<td>$d_{rw} = \sqrt{\frac{4wt}{\pi}}$</td>
</tr>
<tr>
<td>Ballistic coefficient $dBall$</td>
<td>$\frac{2(w+t)}{\pi wt}$</td>
<td>$\frac{2}{w+t}$</td>
<td>$\frac{\sqrt{4wt}}{wt}$</td>
</tr>
<tr>
<td>a</td>
<td>b</td>
<td>C_0 – 2.2</td>
<td>L – 1000 m</td>
</tr>
<tr>
<td>-----</td>
<td>----</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>5 mm</td>
<td>0.1 mm</td>
<td>5E-07</td>
<td>8E-06</td>
</tr>
<tr>
<td>10 mm</td>
<td>0.1 mm</td>
<td>5E-07</td>
<td>3E-07</td>
</tr>
<tr>
<td>20 mm</td>
<td>0.1 mm</td>
<td>5E-07</td>
<td>2E-07</td>
</tr>
<tr>
<td>30 mm</td>
<td>0.1 mm</td>
<td>5E-07</td>
<td>1E-07</td>
</tr>
<tr>
<td>50 mm</td>
<td>0.1 mm</td>
<td>5E-07</td>
<td>4E-06</td>
</tr>
<tr>
<td>80 mm</td>
<td>0.1 mm</td>
<td>8E-07</td>
<td>2E-07</td>
</tr>
</tbody>
</table>

**Cross Sectional Area**
- \( A_c \) [m²]: Collection Area
- \( A_d \) [m²]: Drag Area

**Collection Area**
- \( A_{col} \) [m²]: Collection Area

**Drag Area**
- Ball [m²kg⁻¹]: Drag Area

**Ballistic Coefficient**
- Ball [m²kg⁻¹]: Ballistic Coefficient

**Mass**
- Ball [m²kg⁻¹]: Mass

- **Notes:**
  - Thinner tethers equal collection - drag area but less mass.
  - Wire tethers thinner lower mass also less collection drag area.
  - Flat and thinner increases Ball coefficient eq. drag wire tethers.
## APPENDIX 13 TETHER BIAS ORBIT RANGE

Source [TN.4122.24]

### 650 km 70°

<table>
<thead>
<tr>
<th>$L_t$ [m]</th>
<th>EMF [V]</th>
<th>$L_e$ [m]</th>
<th>$l_i$ [m]</th>
<th>anode bias [V]</th>
<th>cathode bias [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>14</td>
<td>8.1</td>
<td>-242</td>
<td>0.47</td>
<td>-14.0</td>
</tr>
<tr>
<td>500</td>
<td>29</td>
<td>16.2</td>
<td>-484</td>
<td>0.94</td>
<td>-28.0</td>
</tr>
<tr>
<td>750</td>
<td>43</td>
<td>24.4</td>
<td>-726</td>
<td>1.41</td>
<td>-42.1</td>
</tr>
<tr>
<td>1000</td>
<td>58</td>
<td>32.5</td>
<td>-968</td>
<td>1.88</td>
<td>-56.1</td>
</tr>
<tr>
<td>1250</td>
<td>72</td>
<td>40.6</td>
<td>-1209</td>
<td>2.35</td>
<td>-70.1</td>
</tr>
<tr>
<td>1500</td>
<td>87</td>
<td>48.7</td>
<td>-1451</td>
<td>2.82</td>
<td>-84.1</td>
</tr>
<tr>
<td>1750</td>
<td>101</td>
<td>56.8</td>
<td>-1693</td>
<td>3.29</td>
<td>-98.2</td>
</tr>
<tr>
<td>2000</td>
<td>116</td>
<td>64.9</td>
<td>-1935</td>
<td>3.77</td>
<td>-112.2</td>
</tr>
</tbody>
</table>

### 1000 km 85°

<table>
<thead>
<tr>
<th>$L_t$ [m]</th>
<th>EMF [V]</th>
<th>$L_e$ [m]</th>
<th>$l_i$ [m]</th>
<th>anode bias [V]</th>
<th>cathode bias [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>3</td>
<td>10.3</td>
<td>-240</td>
<td>0.13</td>
<td>-3.0</td>
</tr>
<tr>
<td>500</td>
<td>6</td>
<td>20.5</td>
<td>-479</td>
<td>0.26</td>
<td>-6.0</td>
</tr>
<tr>
<td>750</td>
<td>9</td>
<td>30.8</td>
<td>-719</td>
<td>0.38</td>
<td>-9.0</td>
</tr>
<tr>
<td>1000</td>
<td>12</td>
<td>41.1</td>
<td>-959</td>
<td>0.51</td>
<td>-12.0</td>
</tr>
<tr>
<td>1250</td>
<td>16</td>
<td>51.3</td>
<td>-1199</td>
<td>0.64</td>
<td>-14.9</td>
</tr>
<tr>
<td>1500</td>
<td>19</td>
<td>61.6</td>
<td>-1438</td>
<td>0.77</td>
<td>-17.9</td>
</tr>
<tr>
<td>1750</td>
<td>22</td>
<td>71.9</td>
<td>-1678</td>
<td>0.90</td>
<td>-20.9</td>
</tr>
<tr>
<td>2000</td>
<td>25</td>
<td>82.1</td>
<td>-1918</td>
<td>1.02</td>
<td>-23.9</td>
</tr>
</tbody>
</table>
## APPENDIX 14 WORK TO BE DONE

Inputs: EDT System Requirements [SPC.4122.01; TN.4122.04] and this document

<table>
<thead>
<tr>
<th>Input</th>
<th>Title</th>
<th>Work Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>EDT Performance</strong></td>
<td>Performance of the baseline EDT system for orbit range Delfi-1</td>
</tr>
<tr>
<td>4.3.2 4122.SC.1-5</td>
<td>EDT Performance</td>
<td>EDT experiment must be able to achieve the scientific objectives stated in chapter 3 for the orbit range of the Delfi-1 mission stated in 4122.EDT.24-26. Generate measurement approach and quantify required EDT performance.</td>
</tr>
<tr>
<td>4122.TET.01</td>
<td></td>
<td>GENERATE System Performance Requirements: Amount of Bias; Current; F_L, orbital effect, other perturbing forces</td>
</tr>
<tr>
<td>4122.TET.02</td>
<td>Analyse induced Bias for Orbit Range Delfi-1 and determine required range for Scientific Objectives</td>
<td></td>
</tr>
<tr>
<td>4122.TET.03</td>
<td>Analyse collected currents for Orbit Range Delfi-1 and determine required range for Scientific Objectives. No separate (active) plasma contactor device used for a cathode end (if floating tether can meet science objectives)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Stability &amp; Dynamics</strong></td>
<td></td>
</tr>
<tr>
<td>4.3.1 4122.EDT.16 4122.EDT.58</td>
<td>Stability &amp; Dynamics</td>
<td>Stability and Dynamics analysis of the SC-Tether system during operational time, during the EDT storage, deployment and operational phase nominal tether operations will have to ensure the SC bus ADCS is able to maintain a nadir pointing direction (± 5° pointing attitude error)</td>
</tr>
<tr>
<td>4.3.1 4122.EDT.16 4122.EDT.13 4122.DEP.02</td>
<td>Influence on SC Stability</td>
<td>Research influence EDT on the ADCS system especially during the deployment and operational phases. System Moments of Inertia will remain within TBD range so sc ADCS remains within operational limits. Determine max allowable tether pendular librations before satellite flip over or uncontrolled dynamics &amp; slack of tether. Allowable range of disturbance torques and duration for deployment and influence on deployment profile do an initial estimate + calculation method</td>
</tr>
<tr>
<td>4.3.2 4122.EDT.09 4122.EDT.37 4122.TET.07</td>
<td>Nominal Tether Operational Limits</td>
<td>Nominal tether operation range will have to be defined for each experiment operational phase. Librations are required to be within ± 30° [TBC 2] during nominal tether operation confirm. input for required deployment profile</td>
</tr>
<tr>
<td>4122.EM.01 4122.EDT.37 4122.TET.04</td>
<td>Tether Stability &amp; Dynamics</td>
<td>Determine tether dynamics and stability limits during each operational phase. Determine if design effort is required to ensure tether meets required stability limits by method of passive stabilisation (EM and or TET). Determine how fast the instabilities will develop. Loads analysis mechanical, tension in tether due to dynamics</td>
</tr>
<tr>
<td>4122.EDT.09 4122.DEP.03 4122.DEP.10</td>
<td>Deployment dynamics and Profile</td>
<td>Nominal Deployment profile to achieve nominal tether operation; Deployment Profile [v_min,v_max] resulting in librations angles &lt; ± 30° [TBC 2] Determine deploy ment profile for deployment mechanism and control system</td>
</tr>
<tr>
<td>4122.DEP.04</td>
<td>Feasibility Rotation</td>
<td>Determine if rotation of the system is feasible</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td><strong>4.3.1</strong></td>
<td><strong>EMC compatibility</strong></td>
<td></td>
</tr>
<tr>
<td>4122.EDT.11</td>
<td>There is also an EMC compatibility requirement [TBW 2] the payload will have to adhere to. This requirement will influence the mounting (STS) and design configuration of the EDT.</td>
<td></td>
</tr>
<tr>
<td><strong>4.5.3</strong></td>
<td><strong>EMC compatibility &amp; charging, arcing</strong></td>
<td></td>
</tr>
<tr>
<td>4122.EDT.12(a-b)</td>
<td>EDT electric circuit diagram for different configurations research and design minimising risk of arcing</td>
<td></td>
</tr>
<tr>
<td>4122.EDT.17</td>
<td>Residual Magnetic Dipole effect of stored and operational tether on magnetic dipole sc</td>
<td></td>
</tr>
<tr>
<td><strong>4.5.3</strong></td>
<td><strong>Environment</strong></td>
<td></td>
</tr>
<tr>
<td>4122.EDT.40-46</td>
<td>Environmental Analysis DELFI-1 Orbit range Effect on tether Performance</td>
<td></td>
</tr>
<tr>
<td>4.5.1</td>
<td>Magnetic field The tether orientation to the magnetic field lines needs to be taken into account as does the magnetic field tilt of 11.5º and diurnal rotation for more accurate values of the induced EMF for the Delfi-1 orbit range as it is situated at high inclinations</td>
<td></td>
</tr>
<tr>
<td>4122.EDT.40-47</td>
<td>Environment Define Operating environment and effects on EDT operation. The magnetic field components strength and orientation to the tether and the plasma environment for the Delfi-1 orbit range are required for more accurate performance at high inclinations and stability calculations.</td>
<td></td>
</tr>
<tr>
<td>4122.EDT.40-47</td>
<td>M/OD Environment Analysis</td>
<td></td>
</tr>
<tr>
<td>4122.DEP.03</td>
<td>Thermal analysis Determine steady state temperatures tether in orbit and effect on deployability of the tether</td>
<td></td>
</tr>
<tr>
<td><strong>Measurements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.TLM.02</td>
<td>Measurement Approach Performing measurements to achieve scientific objectives; measurement approach</td>
<td></td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.GAS.01</td>
<td>Operational Timeline Combined with measurement approach and failure modes and effects analysis</td>
<td></td>
</tr>
<tr>
<td><strong>Operational Risks</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.EDT.56</td>
<td>Failure Modes Failure modes and affect analysis – operational risk – collision risk and mitigation plan</td>
<td></td>
</tr>
<tr>
<td>4.5.1</td>
<td>M/OD Lifetime Failure Modes and Impact - Severity Analysis EDT LIT 4.5.2 EDT OPS &amp; DES</td>
<td></td>
</tr>
<tr>
<td>4.5.2</td>
<td>Wider shorter tethers increased lifetime expectancy according to equation (3-8) however this approximation is considered to conservative, research alternative approaches to Risk Analysis in M/OD</td>
<td></td>
</tr>
<tr>
<td>4.5.2</td>
<td>M/OD Environment Analysis + tether lifetime analysis. Ensure survivability tether operational lifetime</td>
<td></td>
</tr>
<tr>
<td>[REG.4122.TET.06b]</td>
<td>Tether Integrity 95% chance of tether integrity being maintained during EDT experiment duration. [M/OD, Collision, tether material properties tether rupture-break] Analysis of tether severance risks in orbit will have to be performed to determine the tether survivability statistics and if this is a realistic requirement generating tether dimension constraints.</td>
<td></td>
</tr>
<tr>
<td>4122.EDT.57</td>
<td>Collision Risk Determine if cutting the tether for faster deorbit is a viable collision risk strategy as opposed to lowering flight orbit. Sweep Area or Area product time of severed tether. Collision Risk Analysis &amp; Risk Mitigation approach. what is an acceptable minimal area-time or sweep volume</td>
<td></td>
</tr>
<tr>
<td>4.5.4</td>
<td>Contingency</td>
<td>Alternative flight opportunities will be documented if the Delfi-1 mission is found not to be feasible concerning the flight altitude.</td>
</tr>
<tr>
<td>4122.EDT.57</td>
<td>Design EDT Systems</td>
<td>Design all systems; Design configuration management</td>
</tr>
<tr>
<td>4122.EDT.58</td>
<td>4122.UR.01</td>
<td></td>
</tr>
<tr>
<td>4.5.2</td>
<td>Design Margins</td>
<td>EDT insufficient bias and or current to induce measurable effects; design margin</td>
</tr>
<tr>
<td>Tether TET</td>
<td>Development of tether</td>
<td></td>
</tr>
<tr>
<td>4.5.1</td>
<td>Tension</td>
<td>For a stable tether operational tension forces are not a critical design parameter, it will have to be determined if tether librations, deployment and handling forces will put more stringent requirements on tether material strength. Loads analysis mechanical (TET) in combination with tether dynamics</td>
</tr>
<tr>
<td>4122.TET.04</td>
<td>Deployability Tether</td>
<td>Research what defines deployability and what effect does temperature and deployment tension has on this characteristic, storage effect on deployability TET. How does deployability translate to material and tether dimensions. Research factors contributing to deployability and effects of storage and methods of removing storage effects. Input for Set Up Test</td>
</tr>
<tr>
<td>4122.EDT.05/09</td>
<td>Tether Dimensions</td>
<td>Initial design wide and thin as possible link to measurement approach and effect of tether dimensions on whole system [incl. air drag] increasing survivability and susceptibility to drag for fast deorbit. Determine dimensions for required performance, mass, volume and lifetime 95%, subsequently look at drag performance loose deorbit. Deployability</td>
</tr>
<tr>
<td>4122.TET.06</td>
<td>Tether material</td>
<td>Enforcing material is required to prevent the tether from ripping and a coating protecting the aluminium from cold-welding maybe required, material choice outgassing requirements, environmental mechanical loads deployability</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Volume</td>
<td>Tether storage method dimensions</td>
</tr>
<tr>
<td>4122.EDT.09</td>
<td>Thermal</td>
<td>Determine operating temperature range of tether and if design effort is required to reduce temperature (Resistance, mechanical) Thermal analysis deployed tether</td>
</tr>
<tr>
<td>4122.TET.08/10</td>
<td>Deployment mechanism DEP</td>
<td>Consists of tether storage system, ejection mechanism and deployment control device. This system will also provide for tether retraction and or release mechanism if required. Removing storage effects. Reel design, motor or inertial driven system, combined with deployment profile and control required Passive</td>
</tr>
<tr>
<td>4122.TLM.01/02/04</td>
<td>Telemetry System TLM</td>
<td>Sensors used combine with measurement approach Define all data according to timeline Detailed design, list commands - science data - housekeeping data Operational Timeline</td>
</tr>
<tr>
<td>4122.GAS.01</td>
<td>Gas Release Mechanism GAS</td>
<td>Design of gas release system, amount of gas, type of gas, gas storage and release device, one or two canisters both ends?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Launch load analysis</td>
</tr>
<tr>
<td></td>
<td>Project management</td>
<td>Detailed cost estimation of entire project bottom up; requirement generation, management, verification and traceability</td>
</tr>
<tr>
<td>4122.M.24</td>
<td>Test and Verification Plan</td>
<td>Test and Verification Plan: Integrated tests-checkout; EDT Bread-boarding, TET Storage effect on deployability, thermal expansion, material props, strength etc</td>
</tr>
</tbody>
</table>
APPENDIX 15 COST ESTIMATION

Using a parametric cost model and scaling cost data of previously flown missions initial cost estimates for the experiment have been done. Flying the payload on the Delfi-1 satellite is estimated to cost €1.4 - €2M, with the payload mass set at 6 kg. With the development costs of the payload estimated at €236,000 the payload on the Delfi-1 satellite is estimated to cost a total of €1.6 to €2.2 M [TN.41212.07]. For the Delfi-1 mission an existing satellite bus design will be used resulting in a shorter development time when compared to a dedicated mission with a one of satellite bus being designed for the mission. However suitable flight opportunities can become a problem (if Delfi-1 is not an option) and delay operation of the experiment. In appendix 6 a project development time line for the EDT experiment is given [dated 2003] adhering to Delfi-1 mission requiring the payload to be available for integration on the payload platform in 2007.

SEDS
Development of SEDS from feasibility study in 1983 to the delivery of two sets of flight hardware to NASA 1990 cost $1.3M. Recurring costs for SEDS hardware are <$40K for a deployer, tether and brake-cutter. Brake control laws for SEDS-1 and 2 were developed for <$50K each. PMG design, analyses, production, wind and test two flight deployers <$100K [Carroll]

Terminator Tether
Tethers Unlimited is a commercial company that intends to produce a bolt-on tether system for de-orbiting satellites: the Terminator Tether. This tether is similar in operation to the EDT experiment and is a good cost reference. Hoyt estimates that a deorbiting tether, with its own power source independent of the satellite, will be commercially available for a cost of about $250,000 [Hoyt 1999]. Based on the commercial costs of a Terminator Tether an estimate for the EDT payload can be made by scaling the Terminator Tether to the EDT size and complexity. A weight factor is applied to the scaling factors to emphasis the influence of the major cost drivers. An estimate of the TFU for the Terminator Tether can be made using the learning curve principle [Wertz] for an assumed production of 20 units.

Production costs of the Nth unit \( Y = TFU \times L \)

Learning curve factor \( L = N^B \) with \( B = 1 - \frac{\ln((100\%) / s)}{\ln 2} \)

- Less than 10 units \( s = 95\% \)
- Between 10 and 50 \( s = 90\% \)
- More than 50 \( s = 85\% \)

Then using the scaling factors a TFU cost for the EDT is calculated, see table a 9

Table a 9: Values used to calculate TFU costs of Terminator Tether

<table>
<thead>
<tr>
<th>Total production number</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price per unit</td>
<td>$250,000</td>
</tr>
<tr>
<td>Total production costs</td>
<td>$5000000</td>
</tr>
<tr>
<td>S</td>
<td>90</td>
</tr>
<tr>
<td>B</td>
<td>0.8480</td>
</tr>
<tr>
<td>L</td>
<td>12.684</td>
</tr>
<tr>
<td>TFU</td>
<td>$394,185</td>
</tr>
</tbody>
</table>

As this TFU cost is based on a simple version of the terminator tether the costs for developing the EDT experiment will be similar. One has to take into account that Tethers Unlimited is a profit based company and needs to cover costs made during the development including actual flight tests whereas the EDT experiment is a one of a kind mission and does not need to cover previous test flights this could reduce the costs. Scaling Terminator Tether cost to EDT Experiment to obtain an upper limit for total development and manufacturing costs [based on parametric cost model type method].
Table a 10: Scaling costs of TFU for the Terminator Tether to the EDT system [TN.4122.07]

<table>
<thead>
<tr>
<th>Property</th>
<th>TT</th>
<th>EDT</th>
<th>Scale Factor</th>
<th>Weight Factor</th>
<th>Weighted Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complexity</td>
<td>7</td>
<td>3</td>
<td>0.43</td>
<td>0.3</td>
<td>0.13</td>
</tr>
<tr>
<td>Ltether</td>
<td>5</td>
<td>1</td>
<td>0.20</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Mtether</td>
<td>15</td>
<td>1.6</td>
<td>0.11</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>Mass system</td>
<td>26.25</td>
<td>6</td>
<td>0.23</td>
<td>0.2</td>
<td>0.05</td>
</tr>
<tr>
<td>Power</td>
<td>20</td>
<td>5</td>
<td>0.25</td>
<td>0.3</td>
<td>0.08</td>
</tr>
<tr>
<td>Volume</td>
<td>0.67</td>
<td>0.079</td>
<td>0.12</td>
<td>0.02</td>
<td>0.002</td>
</tr>
<tr>
<td>Mass satellite</td>
<td>1500</td>
<td>45</td>
<td>0.03</td>
<td>0.1</td>
<td>0.003</td>
</tr>
<tr>
<td>average factor</td>
<td></td>
<td></td>
<td>0.23</td>
<td>1.00</td>
<td>0.27</td>
</tr>
</tbody>
</table>

20 % margin

**EDT scaled** $89,422 $107,306

**weighted scaled result** $104,840 $125,807 €101,904

Table a 11: Total costs for various micro satellites [Wertz; SSHP]

<table>
<thead>
<tr>
<th>Micro Satellites</th>
<th>Mass [kg]</th>
<th>Total [$]</th>
<th>[$/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLOMR</td>
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$101,084

Based on the average cost per kg a 45 kg Delfi-1 satellite will cost $4.5 M, total project costs for Delfi-1 are limited to €5.6 M [SLR 70]. When using previous University micro satellite projects the total cost for the Delfi-1 satellite is estimated at a lower $2.4 M, see table a 12.

Table a 12: Costs for university micro satellites [SSHP]

<table>
<thead>
<tr>
<th>University Satellites</th>
<th>Mass [kg]</th>
<th>Development [$]</th>
<th>Launch [$]</th>
<th>Total [$]</th>
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$46,986

The cost of a Volna dedicated launch is estimated to be €0.8 to €1.2M. The ASAP has a total loading capacity of 200kg, with a limit of 50kg per spacecraft. A typical cost for the ASAP launch is about $1.2M [SSHP], which is shared amongst the secondary payloads. The primary payload is deployed first, followed by the secondary payloads, using own deployment mechanisms. Launch costs using ASAP ring will be $300.000 if the ring is shared with 3 other 50 kg payloads. If the payload is required to cover the entire Delfi-1 project cost the total cost for developing and flying a 6 kg EDT experiment onboard Delfi-1 will range between €1.15-3.5 M.

---

5 Exchange rate January 2004 1 USD = 0.81 Euro
## APPENDIX 16  TBD TBC TBW LIST

<table>
<thead>
<tr>
<th>ID</th>
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<td>TBD 1</td>
<td>external payload volume available</td>
<td>Delfi-1-lau ncher</td>
<td>determine allowable dimensions for mounting a special payload module externally</td>
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<tr>
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<td>Allowable disturbance torques and duration payload</td>
<td>Delfi-1 REQ.4122.EDT.13</td>
<td>analysis system dynamics</td>
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<td>TBD 3</td>
<td>tether librations nominal tether operation</td>
<td>REQ.4122.TET.07</td>
<td>tether and system dynamics</td>
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<td>TBD 4</td>
<td>gas cathode</td>
<td>REQ.4122.SC.03</td>
<td>feasibility gas cathode experiment</td>
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<td>contingency factor dep. time</td>
<td>REQ.4122.DEP.09</td>
<td>determine margin of error deployment time</td>
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<td>REQ.4122.EDT.04a</td>
<td>determine fundamental frequencies stored EDT experiment</td>
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<td>temperature analysis</td>
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<td>appendix 13</td>
<td>analysis</td>
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<td>TBD 14</td>
<td>use of spool for tape tether</td>
<td>appendix 13</td>
<td>test</td>
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<td>TBD 15</td>
<td>Z-fold storage method for tape tether</td>
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<td>EMC plan TBW</td>
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<td>minimum experiment time 2 weeks</td>
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<td>Test and Verification plan</td>
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<td>write a test and verification plan for the EDT payload</td>
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<td>Operational timeline</td>
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DELFI-1 Project

EDT Experiment onboard Delfi-1

Operation and Design

DELFI.1.TW.4122.11

10-01-12

Thesis Report
A.S. Wijnans

Space Systems Engineering
Faculty of Aerospace Engineering
Delft University of Technology
Kluyverweg 1, 2629 HS Delft
The Netherlands
### NOTATIONS, SYMBOLS & ACRONYMS

<table>
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<th>Unit</th>
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<td>v</td>
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<td>[ms^{-1}]</td>
</tr>
<tr>
<td>v(^*)</td>
<td>tether velocity at rupture</td>
<td>[ms^{-1}]</td>
</tr>
<tr>
<td>v_c</td>
<td>circular orbit velocity</td>
<td>[ms^{-1}]</td>
</tr>
<tr>
<td>v_e</td>
<td>exit velocity gas</td>
<td>[ms^{-1}]</td>
</tr>
<tr>
<td>V_{EM}</td>
<td>end mass deployment velocity</td>
<td>[ms^{-1}]</td>
</tr>
</tbody>
</table>
$v_{\text{mag}}$ rotational velocity magnetic field $[\text{ms}^{-1}]$

$V_{\text{orb}}$ orbital velocity $[\text{ms}^{-1}]$

$v_{\text{rel}}$ satellite velocity relative to atmosphere $[\text{ms}^{-1}]$

$v_{\text{th}}$ thermal velocity $[\text{kms}^{-1}]$

$\Delta V$ velocity change orbit or potential bias $[\text{ms}^{-1}]$ or $[\text{V}]$

$V$ voltage-potential $[\text{V}]$

$V_{\text{LP}}$ LP potential $[\text{V}]$

$V_{\text{fi}}$ floating potential $[\text{V}]$

$V_{\text{p}}$ undisturbed plasma potential $[\text{V}]$

$V_{\text{t}}$ tether potential $[\text{V}]$

$V_{\text{T}}$ tank volume $[\text{m}^3]$  

$w$ tether width $[\text{m}]$

**Sub and superscripts**

a albedo

ad aerodynamic drag

b end mass

c conducting

dep deployment

D drag

DIST disturbance

e electron

E Earth

i ion

ir infrared

gas gas

GG gravity gradient

GGB gravity gradient boom

L Lorentz

orb orbit

p plasma

s solar

sc spacecraft

ss steady state

sub substrate (tether enforcing material)

t tether

T temperature

ult ultimate
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tr>
<td>$\alpha$</td>
<td>absorption coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>temperature resistance coefficient of material</td>
<td>[K$^{-1}$]</td>
</tr>
<tr>
<td>$\alpha_L$</td>
<td>linear expansion coefficient of the material</td>
<td>[m°C$^{-1}$]</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>solar-zenith incidence angle of solar radiation</td>
<td>[°]</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>CTE thermal expansion</td>
<td>[°C$^{-1}$]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Sun out of plane angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\chi_i$</td>
<td>Earth shielding factor</td>
<td>[-]</td>
</tr>
<tr>
<td>$\delta$</td>
<td>orbital latitude</td>
<td>[°]</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>emission coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>strain</td>
<td>[-]</td>
</tr>
<tr>
<td>$\varepsilon_p$</td>
<td>pressure loss</td>
<td>[-]</td>
</tr>
<tr>
<td>$\varepsilon_{stab}$</td>
<td>disturbance – stabilising torque ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>longitude</td>
<td>[°]</td>
</tr>
<tr>
<td>$\phi_i$</td>
<td>deviation from subsolar point ecliptic angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\phi_b$</td>
<td>roll angle body reference frame</td>
<td>[°]</td>
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<tr>
<td>$\phi_i$</td>
<td>flux incident particles energies E-dE</td>
<td>[atomsm$^{-3}$]</td>
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<tr>
<td>$\phi_s$</td>
<td>sputtered particle flux</td>
<td>[atomsm$^{-3}$]</td>
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<tr>
<td>$\phi_t$</td>
<td>out-of-plane tether angle</td>
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<tr>
<td>$\gamma$</td>
<td>specific heat ratio</td>
<td>[-]</td>
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<tr>
<td>$\phi_b$</td>
<td>roll angle body reference frame</td>
<td>[°]</td>
</tr>
<tr>
<td>$\lambda_D$</td>
<td>Debye length</td>
<td>[m]</td>
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<tr>
<td>$\mu$</td>
<td>tether – ballast mass ratio</td>
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<tr>
<td>$\theta$</td>
<td>geomagnetic latitude</td>
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<tr>
<td>$\theta$</td>
<td>true anomaly</td>
<td>[°]</td>
</tr>
<tr>
<td>$\theta_b$</td>
<td>pitch angle body reference frame</td>
<td>[°]</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>co-latitude = $90^\circ$-$\theta$</td>
<td>[°]</td>
</tr>
<tr>
<td>$\theta_S$</td>
<td>orbit angle with respect to. the subssolar point</td>
<td>[°]</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>in-plane tether angle</td>
<td>[°]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>atmospheric density</td>
<td>[kgm$^{-3}$]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>material density</td>
<td>[kgm$^{-3}$]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density of test sample</td>
<td>[gcm$^{-3}$]</td>
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<tr>
<td>$\rho_c$</td>
<td>propellant mass density chamber</td>
<td>[kgm$^{-3}$]</td>
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<tr>
<td>$\rho_s$</td>
<td>mass flow density at the nozzle exit</td>
<td>[kgm$^{-3}$]</td>
</tr>
<tr>
<td>$\rho_E$</td>
<td>angular radius Earth</td>
<td>[°]</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>specific tether density</td>
<td>[kgm$^{-1}$]</td>
</tr>
<tr>
<td>$\sigma_{ult}$</td>
<td>ultimate strength material</td>
<td>[Nm$^{-2}$]</td>
</tr>
<tr>
<td>$\tau$</td>
<td>time of perigee passage</td>
<td>[s]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>poisson ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>argument of the periapsis</td>
<td>[°]</td>
</tr>
<tr>
<td>$\omega_b$</td>
<td>orbital frequency</td>
<td>[rads$^{-1}$]</td>
</tr>
<tr>
<td>$\omega_n$</td>
<td>system libration frequency</td>
<td>[rads$^{-1}$]</td>
</tr>
<tr>
<td>$\psi_b$</td>
<td>yaw angle body reference frame</td>
<td>[°]</td>
</tr>
<tr>
<td>$\Phi/2$</td>
<td>half rotation angle corresponding to the eclipse duration</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>van den Kerckhove parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>right ascension of ascending node</td>
<td>[°]</td>
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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>a.m.u.</td>
<td>atomic mass unit</td>
</tr>
<tr>
<td>bps</td>
<td>bits per second</td>
</tr>
<tr>
<td>c.a.p.</td>
<td>centre of aerodynamic pressure</td>
</tr>
<tr>
<td>c.m.</td>
<td>centre of mass</td>
</tr>
<tr>
<td>c.o.m</td>
<td>centre of motion</td>
</tr>
<tr>
<td>c.s.p.</td>
<td>centre of solar radiation pressure</td>
</tr>
<tr>
<td>ACC</td>
<td>Accelerometer</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>ADCS</td>
<td>Attitude Determination &amp; Control System</td>
</tr>
<tr>
<td>AO</td>
<td>Atomic Oxygen</td>
</tr>
<tr>
<td>APE</td>
<td>Absolute Pointing Error</td>
</tr>
<tr>
<td>APL</td>
<td>Antenna Payload</td>
</tr>
<tr>
<td>ATEx</td>
<td>Advanced Tether Payload</td>
</tr>
<tr>
<td>CDHS</td>
<td>Delfi-1 Command and Data Handling System</td>
</tr>
<tr>
<td>CGT</td>
<td>Cold Gas Thruster</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial off the Shelf</td>
</tr>
<tr>
<td>COMM</td>
<td>Delfi-1 Communications System</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>CVCM</td>
<td>Collected Volatile Condensable Material</td>
</tr>
<tr>
<td>DDTS</td>
<td>Delfi Doppler Tracking System</td>
</tr>
<tr>
<td>DEP</td>
<td>EDT Deployment System</td>
</tr>
<tr>
<td>DCS</td>
<td>Deployment Control System</td>
</tr>
<tr>
<td>DISCOS</td>
<td>Database and Information System Characterising Objects in Space</td>
</tr>
<tr>
<td>DVS</td>
<td>Digital Vane Sensor</td>
</tr>
<tr>
<td>DoD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>ECEF</td>
<td>Earth Centred Earth Fixed</td>
</tr>
<tr>
<td>ECI</td>
<td>Earth Centred Inertial</td>
</tr>
<tr>
<td>ECSS</td>
<td>European Cooperation for Space Standardization</td>
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<tr>
<td>ED</td>
<td>Electrodynamic</td>
</tr>
<tr>
<td>EDDE</td>
<td>Electrodynamic Delivery Express</td>
</tr>
<tr>
<td>EDT</td>
<td>Electrodynamic Tether</td>
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<tr>
<td>EM</td>
<td>End Mass System</td>
</tr>
<tr>
<td>EMC</td>
<td>Electromagnetic Compatibility</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive Field</td>
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<tr>
<td>EOL</td>
<td>End of Life</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ETBSim</td>
<td>Electrodynamic Tether Bead Simulator</td>
</tr>
<tr>
<td>FEAC</td>
<td>Field Emitting Anode Cathode</td>
</tr>
<tr>
<td>GAS</td>
<td>EDT Gas Storage and Release System</td>
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<tr>
<td>GG</td>
<td>Gravity Gradient</td>
</tr>
<tr>
<td>GGB</td>
<td>Gravity Gradient Boom</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<tr>
<td>GS</td>
<td>Ground Station</td>
</tr>
<tr>
<td>HC</td>
<td>Hollow Cathodes</td>
</tr>
<tr>
<td>HDRM</td>
<td>Hold Down and Release Mechanism</td>
</tr>
<tr>
<td>HSK</td>
<td>House Keeping</td>
</tr>
<tr>
<td>HW</td>
<td>Hardware</td>
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<tr>
<td>I/O</td>
<td>Input Output</td>
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<td>IGRF</td>
<td>International Geomagnetic Reference Field</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<tr>
<td>IRI</td>
<td>International Reference Ionosphere</td>
</tr>
<tr>
<td>IP</td>
<td>In Plane</td>
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<tr>
<td>ISS</td>
<td>International Space Station</td>
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<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>LP</td>
<td>Langmuir Probe</td>
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<tr>
<td>LVDIT</td>
<td>Linear Variable Differential Transducer</td>
</tr>
<tr>
<td>M/OD</td>
<td>(Micro) Meteoroid and Orbital debris</td>
</tr>
<tr>
<td>MAG</td>
<td>Magnetic - Magnetometer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>--------------</td>
<td>-----------------------------------------</td>
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<tr>
<td>MoI</td>
<td>Moment of Inertia</td>
</tr>
<tr>
<td>MS</td>
<td>Margin of Safety</td>
</tr>
<tr>
<td>MSISE</td>
<td>Mass Spectrometer Incoherent Scatter</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>OML</td>
<td>Orbit Motion Limited</td>
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<tr>
<td>OOP</td>
<td>Out of Plane</td>
</tr>
<tr>
<td>OR</td>
<td>Orbital Reference</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
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<tr>
<td>PL</td>
<td>Payload</td>
</tr>
<tr>
<td>PLM</td>
<td>Payload Module</td>
</tr>
<tr>
<td>RAAN</td>
<td>Right Ascension of the Ascending Node</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotations per Minute</td>
</tr>
<tr>
<td>RTD</td>
<td>Resistive Temperature Detector</td>
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<tr>
<td>RVDT</td>
<td>Rotary Variable Differential Transducer</td>
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<tr>
<td>SA</td>
<td>Selective Availability</td>
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<td>SC</td>
<td>Spacecraft</td>
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<tr>
<td>SCC</td>
<td>Stress Corrosion Cracking</td>
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<td>SEDS</td>
<td>Small Expendable Deployer System</td>
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<tr>
<td>SEL</td>
<td>Single Event Latchup</td>
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<tr>
<td>SEU</td>
<td>Single Event Upset</td>
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<tr>
<td>SF</td>
<td>Safety Factor</td>
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<td>SMA</td>
<td>Semi Major Axis</td>
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<td>SPENVIS</td>
<td>Space Environment Information System</td>
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<tr>
<td>SPG</td>
<td>Single Point Ground</td>
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<tr>
<td>SPL</td>
<td>Special Payload Module</td>
</tr>
<tr>
<td>SSI</td>
<td>Subsystem Interface</td>
</tr>
<tr>
<td>SW</td>
<td>Software</td>
</tr>
<tr>
<td>TBC</td>
<td>To be Confirmed</td>
</tr>
<tr>
<td>TBD</td>
<td>To be Determined</td>
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<tr>
<td>TBM</td>
<td>Tether Bias Measurement</td>
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<tr>
<td>TBW</td>
<td>To be Written</td>
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<tr>
<td>TC</td>
<td>Turn Counter</td>
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<td>TDS</td>
<td>Tether Deployment System</td>
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<tr>
<td>TEN</td>
<td>Tension Transducer</td>
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<tr>
<td>TES</td>
<td>Tether Ejection System</td>
</tr>
<tr>
<td>TET</td>
<td>EDT Tether System</td>
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<tr>
<td>TSS</td>
<td>Tethered Satellite System-Tether Storage System</td>
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<tr>
<td>TLM</td>
<td>EDT Telemetry System</td>
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<tr>
<td>TML</td>
<td>Total Mass Loss</td>
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<tr>
<td>TVS</td>
<td>Transient Voltage Suppression</td>
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<tr>
<td>TTFF</td>
<td>Time to First Fix</td>
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<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver / Transmitter</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra Violet</td>
</tr>
<tr>
<td>YES</td>
<td>Young Engineers Satellite</td>
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### Physical Constants

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<th>Physical Constant</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>Mean Earth radius</td>
<td>$R_E$</td>
<td>6378150</td>
<td>m</td>
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<tr>
<td>Geocentric Earth mass</td>
<td>$M_E$</td>
<td>5.974x10^{24}</td>
<td>kg</td>
</tr>
<tr>
<td>Universal gravitational constant</td>
<td>$G$</td>
<td>6.673x10^{-11}</td>
<td>m$^3$kg$^{-1}$s$^{-2}$</td>
</tr>
<tr>
<td>Earth's gravitational constant</td>
<td>$\mu$</td>
<td>3.986x10^{-14}</td>
<td>m$^3$s$^{-2}$</td>
</tr>
<tr>
<td>Standard gravitational acceleration</td>
<td>$g$</td>
<td>9.807</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>Earth's rotational velocity</td>
<td>$\omega_E$</td>
<td>7.292x10^{-5}</td>
<td>rads$^{-1}$</td>
</tr>
<tr>
<td>Magnetic permeability of free space</td>
<td>$\mu_0$</td>
<td>4$\pi$x10^{-7}</td>
<td>TmA$^{-1}$</td>
</tr>
<tr>
<td>Magnetic field strength @ magnetic equator</td>
<td>$B_{eq}$</td>
<td>3.012x10^{-5}</td>
<td>T</td>
</tr>
<tr>
<td>Magnetic field tilt</td>
<td>$t_m$</td>
<td>10.46</td>
<td>°</td>
</tr>
<tr>
<td>Elementary electron charge</td>
<td>$e$</td>
<td>1.602x10^{-19}</td>
<td>C</td>
</tr>
<tr>
<td>Electron mass</td>
<td>$m_e$</td>
<td>9.109x10^{-31}</td>
<td>kg</td>
</tr>
<tr>
<td>Boltzmann constant</td>
<td>$k_B$</td>
<td>1.38x10^{-23}</td>
<td>JK$^{-1}$</td>
</tr>
<tr>
<td>Universal gas constant</td>
<td>$R$</td>
<td>8.314</td>
<td></td>
</tr>
<tr>
<td>Power output of the sun</td>
<td>$P_s$</td>
<td>3.84 x 10^{26}</td>
<td>W</td>
</tr>
<tr>
<td>Electron Volt as unit of energy as unit of temperature</td>
<td>$eV$</td>
<td>1.602x10^{-19}</td>
<td>J</td>
</tr>
<tr>
<td>Permittivity constant of free space</td>
<td>$\epsilon_0$</td>
<td>8.854x10^{-12}</td>
<td>C$^2$N$^{-1}$m$^{-2}$</td>
</tr>
<tr>
<td>Stephan Boltzmann constant</td>
<td>$\sigma$</td>
<td>5.67x10^{-8}</td>
<td>Wm$^{-2}$K$^{-4}$</td>
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<tr>
<td>Solar constant at 1 A.U.</td>
<td>$S_s$</td>
<td>1366</td>
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<tr>
<td>Speed of light</td>
<td>$c$</td>
<td>3.00x10^{8}</td>
<td>ms$^{-2}$</td>
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<tr>
<td>Blackbody Temperature Earth</td>
<td>$T_{E,BB}$</td>
<td>254.3</td>
<td>K</td>
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</tbody>
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1 IGRF 2000
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1 INTRODUCTION

The main objective of this thesis is to design and size an electrodynamic tether experiment for operation onboard the Delfi-1 micro satellite demonstrating the deorbit capability of a bare passive tether. This experiment is fundamental in the development of a fully passive deboost capability for Low Earth Orbit spacecraft. The main objectives of the experiment are proof of concept of a bare electrodynamic tether deorbit and the use of a tape tether. A tape tether exhibits enhanced current collection and increased survivability in the micrometeoroid and orbital debris environment compared to previously used wire tethers. Moreover a tape tether has favourable drag properties when cut allowing for rapid deorbit. A secondary objective for the experiment is to determine if the release of a neutral gas can enhance the current of the tether and the deorbit performance. As a first step in this work a baseline design for the electrodynamic tether experiment onboard the Delfi-1 satellite has been generated. This design is documented in the first part of this thesis work, EDT Preliminary Design [TW.4122.10], and is characterised by

- Passive bare floating electrodynamic tether deployed in nadir direction
- Passive stabilisation and deployment system
- All sensors located at the satellite end, limited mass (5 kg to 6 kg), volume (D ≤ 200 mm), power (6 W to 1 W during eclipse) and data rate budgets (210 bps)
- Operating altitude 650 km - 1000 km; Inclination range 70° - 85° and 95° - 110°
- Maximum experiment duration three months, minimum time for measurable effects two weeks [TBC 11]

The second part of this thesis reports on the feasibility of the proposed experiment primarily regarding to the performance at high inclinations while adhering to the storage and mass constraints set by the Delfi-1 satellite. With the tether operating at floating potentials no direct current measurements can be obtained as the current at both ends is zero. The challenge will be to dimension the system allowing for indirect measurements determining the amount of Lorentz force the electrodynamic tether generates during a minimum two week experiment time frame. With Delfi-1 orbit range being at high altitude and high inclinations this is a critical design aspect for the proposed baseline system. Orbit environmental effects influencing tether performance and design are summarised in the table below.

Table 1.1: Overview of environment and effects on EDT system design

<table>
<thead>
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<th>Environment</th>
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<tr>
<td>Gravity Field</td>
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<td>Magnetic Field</td>
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<td>Ionospheric Plasma</td>
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<tr>
<td>M/OD</td>
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</tr>
<tr>
<td>Vacuum</td>
<td></td>
<td>Out-gassing; Cold welding</td>
</tr>
</tbody>
</table>

In chapter 2 the performance of the electrodynamic tether for the Delfi-1 orbit range is determined as a function of tether dimensions. For the Delfi-1 orbit and tether design parameters the induced bias and collected current are determined. The forces acting on the electrodynamic tether (EDT) are calculated and the effects of the EDT on the Delfi-1 satellite orbit and the static stability of the system are determined in chapter 3. In chapter 4 a measurement approach for obtaining scientific data is set up quantifying the EDT performance requirements and a selection of instruments is made for the experiment. The design of the other EDT systems consisting of the tether and gas cathode is addressed in chapter 5. Combining the design constraints, loads and performance requirements a set of feasible configurations for the tether and end mass are derived in chapter 6. In chapter 7 conclusions on the baseline design performance are listed and using the design options generated in the first part of this study alternative designs are proposed including alternative missions suggested where the experiment is critical or unfeasible to operate onboard the Delfi-1 mission.
2 EDT PERFORMANCE MODELLING

The performance of an EDT as an electric propulsion device is primarily a function of the induced electric field $E$, electric current $I$ and the resulting Lorentz force $F_L$. Other forces in orbit will affect the operation of the tether. For example the aerodynamic drag will produce a disturbance torque and a drag force on the system. With the proposed experiment limited to indirect measurements of the (orbital) effects produced by the Lorentz drag force the aerodynamic drag force acts as noise for these measurements.

This chapter will determine the performance of the floating bare tether as a function of the conducting tether design parameters [length, width and thickness] across the orbit range of the Delfi-1 satellite, their initial values are listed below:

- Orbit Altitude $h$: 650 km – 1000 km
- Orbit Inclination Range $i$: $70^\circ$ - $85^\circ$, $95^\circ$ - $110^\circ$
- Orbit Eccentricity Range $e$: 0
- Tether length $L_t$: 250 m – 2500 m
- Tether width $w_c$: 5 mm – 80 mm
- Tether thickness $t_c$: 15 $\mu$m

2.1 Induced Bias

Moving through Earths magnetic field the conductive tether will induce a voltage drop along the tether biasing it with respect to the surrounding plasma thus enabling current collection from the ionosphere to take place. The induced electromotive force (EMF) will drive a current in the tether and is a function of magnetic field strength, tether length, relative velocity and orientation of the magnetic field lines and tether. To determine the amount of induced bias and Lorentz force by the EDT both the strength and orientation of the local magnetic field in orbit are required.

2.1.1 Magnetic Field

For EDT performance calculations a tilted centred dipole model is used to calculate the magnetic field strength and direction in orbit. In appendix 3 a description of Earths magnetic field model is given. The tilted centred dipole model is a first order approximation of the dipole field generated by the internal magnetic field and incorporates the diurnal precession of the magnetic field effects noticeable for the high inclination range of the Delfi-1 orbit influencing the angles of the magnetic field to the tether affecting the induced bias and Lorentz forces shown in figure a3- 2 of appendix 3. The centred dipole model is symmetric and azimuth angle independent [Fraser-Smith], the longitudinal position of the dipole axis is neglected as the model is used to determine the average and extremes of the magnetic field components and induced bias.

![Dipole magnetic field model](image)
The magnetic field components in the magnetic reference frame (MAG) see appendix 1 and figure 2.1, with the dipole oriented in the negative \(Z_{\text{MAG}}\) direction are derived in appendix 3 as

\[
\begin{bmatrix}
B_x \\
B_y \\
B_z \end{bmatrix}_{\text{MAG}} = \frac{1}{r^3}
\begin{bmatrix}
3X_{\text{MAG}}Z_{\text{MAG}} \\
3Y_{\text{MAG}}Z_{\text{MAG}} \\
3Z_{\text{MAG}}^2 \end{bmatrix}
\]

\[
B_x = -\frac{2B_{\text{eq}}R_E^3}{r^3} \sin \theta \\
B_y = \frac{B_{\text{eq}}R_E^3}{r^3} \cos \theta
\]

\(B\) – magnetic field strength [T]

\(B_{\text{eq}}\) – magnetic field strength at equator \(3.012 \times 10^5\) [T]

\(\theta\) – geomagnetic latitude [°]

\(r\) – orbital radius [km]

With values derived from the international geomagnetic reference field (IGRF 2000) calculated in appendix 3 for the magnetic field properties the equatorial magnetic field strength \(B_{\text{eq}}\) is \(30119.61\) nT and the tilt \(\theta_m\) of the dipole axis is \(10.5°\). Ignoring the offset of the dipole axis and assuming a conservative magnetic field and the average magnetic field strengths are obtained for the Delfi-1 orbit range using the EDT Environment tool [TN.4122.12] and shown below with near polar orbits having higher values of the field strength as the magnetic field line density increases.

![Figure 2.2: Total magnetic field strength for Delfi-1 orbit range](image)

2.1.2 Induced Electromotive Force

As mentioned in the first part of this study a conducting tether moving through a magnetic field induces an electromotive force. According to Faraday’s law for induction (second Maxwell law) the induced EMF and resulting current in the tether circuit is equal to the rate of change of the magnetic flux through the circuit. This applies for a stationary circuit and a changing magnetic flux or a moving circuit in a static magnetic field or for both (superposition principle) \(\varepsilon_{\text{mag}} = \varepsilon_{\text{induced}} + \varepsilon_{\text{motional}}\).

The induced EMF in the tether circuit due to motion of the tether relative to the magnetic field to which the ionosphere is subjected is determined using the Lorentz force law depicting the total force on a moving charge \(q\) in the presence of an electric field \(E\) and a magnetic flux density vector \(B\) moving at a velocity \(v\) relative to the magnetic field

\[
F = q(E + v \times B)
\]

\(F\) – force [N]

\(E\) – Electric Field [Vm\(^{-1}\)] subsequent use of symbol E will depict induced E by the tether

\(q\) – particle charge [C]

\(^2\) Averaged over 15 orbits
\( v \) — velocity relative to magnetic field \([\text{ms}^{-1}]\)

External electric field contributions \( E \) to \( F \) are assumed zero, self-induction due to current variations in the tether are assumed to have a negligible contribution to the tether potential \([\text{Beletsky}]\). These effects might become important for deorbiting tether with a fully conductive cross section, for tethers with a thin conductive outer layer (thin film) self-field effects are known to be weak \([\text{Sanmartin^n}]\). Effects possibly induced by self-induction are:

- Gyro - motion charged particles
- Drift effect \( qv \times B \) (Lorentz)

Plasma chamber tests have shown self-induced magnetic field effects for wire samples consist of significant drift effects but also show a negligible effect on electron collection, decreasing for lower current levels \([\text{Vannaroni; Kruijff}]\). EDT current levels are not expected to exceed 1 A as was shown in part I of this work and shielding effects due to self-induced magnetic field are ignored in first analysis of the tether performance. The motional electromotive field \( E \) per unit length of moving tether \( dl \) is calculated as

\[
E = (v \times B) \cdot dl
\]  
\( dl \) — increment of tether length \([\text{m}]\)

The induced EMF results in a voltage drop over the tether with respect to the plasma, for prograde orbits the upper end of the tether is charged positive and the lower end negative with respect to the plasma. With the bare tether electrically connected to the ionospheric plasma the positively charged upper end collects electrons, the lower end ions. By convention the direction of the current is taken against the motion of the load carrying particles (electrons) shown figure a3- 2 of appendix 3. For performance calculations the tether is assumed to be straight and rigid deployed in the nadir direction along the \( Z_{\text{OR}} \) axis, see appendix 1 for reference frame definitions. The average electromotive voltage per meter of conducting tether \( E \) for the Delfi-1 orbit range has been calculated per unit of tether length \( dl \) equation (2-3) using the EDT Environment tool \([4122.12]\).

As can be seen in figure 2.3 the induced \( E \) decrease for increasing altitude due to decreasing velocity and magnetic field strength.

![Figure 2.3: Average induced E for Delfi-1 orbit range](image)

The rotational velocity of magnetic field results in a higher electromotive force being generated in retrograde orbits as the tether crosses the magnetic field lines at a higher velocity shown in figure 2.3.

\[
v = v_{\text{orb}} + v_{\text{mag}}
\]  
\( v_{\text{mag}} \) — rotational velocity magnetic field \([\text{ms}^{-1}]\)
\( v_{\text{orb}} \) — orbital velocity \([\text{ms}^{-1}]\)
Using the orbital velocity instead of relative velocity for \( E \) calculations results in an approximate \( \sim 7\% \) error as the rotational velocity of the Earth is 6.8\%-7.4\% of orbital velocity for the 650 km - 1000 km range. Higher inclinations induce a significantly lower \( E \) due to orientation of tether with the magnetic field, the increased magnetic field density does not compensate for this. This can also be seen in equation (2-1), with increasing orbital inclination and latitude \( \theta \) the magnetic field component perpendicular the rigid nadir oriented tether \( B_{\perp} \) decreases significantly, for this reason inclinations for flying the EDT experiment have already been adapted to exclude near polar orbits in the preliminary design phase of this thesis work.

Table 2.1: Extreme values of orbit averaged induced \( E \) values for Delfi-1 orbit range

| \( E_{\text{avg, max}} \) | 0.062 V\( \text{m}^{-1} \) | drives electro-hardware design and EMC plan |
| \( E_{\text{avg, min}} \) | 0.008 V\( \text{m}^{-1} \) | drives tether dimensions \( \text{EMF} = E \cdot L \) |
| \( E_{\text{avg, avg}} \) | 0.033 V\( \text{m}^{-1} \) | design value average \( E \) |

2.1.3 Floating Potential

The amount of current the tether collects is directly related to the flux of ions and electrons the tether encounters. The potential bias across an electrically floating tether, see section 2.1.2, will arrange itself due to space charging effects balancing the electron current with ion current collected by the tether according to Kirchhoff’s current law charging the tether to floating potential. A consequence of the tether being exposed to a larger electron flux than ion flux in Low Earth Orbits (LEO), see appendix 4, is that a significantly larger amount of area is required to collect sufficient ion current to balance the electron current. The EDT has to collect ions across most of its length to reach floating potential and is biased negatively for most of its length [Sanmartin\(^3\)]. This reduces the achievable current levels significantly compared to an insulated EDT configuration when using an active electron emitter (cathode). The ratio of electron (section of tether biased positively) to ion collecting length (negatively biased) of the tether is \( l_e/l_i \) obtained by balancing the electron and ion current levels is related to the physical length of the tether \( L_t \) and the mass ratio of the electrons and ions as [Heide; LeBreton]

\[
\frac{l_e}{l_i} = \left( \frac{m_i}{m_{\text{eq}}} \right)^{\frac{1}{2}}
\]  

(2-5)

\[
l_e \quad \text{– electron collecting tether length [m]}
\]

\[
l_i \quad \text{– ion collecting tether length [m]}
\]

\[
m_e \quad \text{– electron mass [kg]}
\]

\[
m_{\text{eq}} \quad \text{– equivalent ion mass [kg]}
\]

\[
m_{\text{eq}} = \left( \sum f_i \sqrt{\frac{n_{\text{charge},i}}{m_i}} \right)^{-2}
\]

(2-6)

\[
f_i \quad \text{– fraction of ion density (0..1)}
\]

\[
m_i \quad \text{– ion mass [a.m.u.]} 
\]

\[
n_{\text{charge},i} \quad \text{– number of missing electrons per ion [-]}
\]

At higher orbit altitudes having lower plasma densities \( n_0 \) the ratio \( m_e/m_i \) increases and the zero bias point shifts downward increasing the electron collecting surface part of the tether as the ion and electron current maintain equilibrium, the system automatically adjusts for variations in density, floating tether operation is less sensitive to plasma density fluctuations [Sanmartin\(^3\)]. In table 2.2 the variation of electron and ion collecting lengths with altitude for a 1000 m tether is shown based on ionospheric data derived from LEOPOLD [described in appendix 3].
Values of the bias at the suspension are calculated using equation (2-5) and range from +0.09 V for a 250 m tether at minimum induced EMF values 0.008 Vm⁻¹ to +5.0 V for a 2500 m tether at the maximum induced EMF of 0.062 Vm⁻¹. This is below the 10 V required by the Delfi-1 interface requirement [REQ-1]. In appendix 5; table a5-2 the values of the bias at the suspension are listed for tether lengths varying from 250 m - 2500 m for the extreme values of E.

### Table 2.2: Electron and ion collecting length \( L \) for tether lengths \( h = 1000 \) m

<table>
<thead>
<tr>
<th>( h ) [km]</th>
<th>( l_e ) [m]</th>
<th>( l_i ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>62</td>
<td>968</td>
</tr>
<tr>
<td>700</td>
<td>32</td>
<td>967</td>
</tr>
<tr>
<td>750</td>
<td>33</td>
<td>967</td>
</tr>
<tr>
<td>800</td>
<td>34</td>
<td>966</td>
</tr>
<tr>
<td>850</td>
<td>35</td>
<td>965</td>
</tr>
<tr>
<td>900</td>
<td>37</td>
<td>963</td>
</tr>
<tr>
<td>950</td>
<td>39</td>
<td>961</td>
</tr>
<tr>
<td>1000</td>
<td>41</td>
<td>959</td>
</tr>
</tbody>
</table>

### 2.2 Collected Current

The bare EDT operates as a passive anode and cathode for positive and negative biased sections of tether collecting electrons and ions from the plasma environment with the induced voltage drop over the tether driving the current in the tether. To estimate the amount of current collected by the EDT knowledge of the plasma parameters affecting the collection of charged particles from the ionosphere is required. Passive current collection to a charged object in ionospheric plasma is governed by thermal current collection, ion ram current effects, secondary emitted electron and ion current and photoelectron current, listed in appendix 4, these will influence the bias distribution of the floating EDT. The current collection of a long and sufficiently thin bare conducting tether is described by the orbit motion limited (OML) current collection theory [Sanmartin] valid for a non flowing plasma and when the tether perimeter is within limits to avoid both electrical shielding and magnetic guiding effects. The amount of electrons and ions collected by the tether is predominantly determined by the orbital motion of the tether system when current collection is within the OML regime.

#### 2.2.1 OML Current Collection

When the tether perimeter is within limits to avoid both electrical shielding and magnetic guiding effects the collected current for a section of bare tether achieves a maximum orbital motion limited (OML) value for a given potential bias and geometry [Sanmartin; Gilchrist]. Using the effective tether diameter \( d_t \), the tape tether geometry is modelled as a cylinder with equal drag area. Assuming the tether bias \( \Delta V \) has a potential energy much larger than the thermal and kinetic energy of the ions and electrons being collected by a segment \( dl \) of tether the OML current collection per unit of tether length for a bare tape tether can be derived for a non flowing plasma by simplifying equation (A5-1) [appendix 5] to [Sanmartin; LeBreton]

\[
\frac{dl_{OML}}{dl} = en_o d_t \sqrt{\frac{2e\Delta V}{m_i}}
\]

if \( e|\Delta V| >> k_B T_e \), \( \frac{1}{2} m_i v_i^2 > v_e \), for ion collection replace \( m_e \) with \( m_i \), [Sanmartin]

- \( l_{OML} \) – OML current level [A]
- \( \Delta V \) – potential bias between tether and plasma [V] with \( \Delta V = V_t - V_p \)
- \( V_o \) – undisturbed plasma potential [V]
- \( V_t \) – tether potential [V]
- \( n_o \) – quasi-neutral plasma concentration electrons and ions [m⁻³]

---

3 In this part of the thesis a separate report numbering (REQ-#) is used for the system requirements, in section 8 a reference is provided to the project unique identifiers (PUID) used in project as explained in part I of this thesis work

4 LEOPOD plasma data
\( d_t \) – effective tether diameter [m] \( \frac{2(w_c + l_c)}{\pi} \) (2-8)

e – elementary charge \( 1.602 \times 10^{-19} \) [C]

\( k_B \) – Boltzmann constant \( 1.38 \times 10^{-23} \) [JK\(^{-1}\)]

\( T_{e,i} \) – electron, ion temperature [K]

Taking into account possible unknown system resistance losses assumed to be 50 \( \Omega \) [Roozendaal] the effective tether length is reduced by a maximum of 10%, see appendix 6, table a6-1. This voltage loss is ignored for simplicity in the following sections and will be taken into account in the final configuration selection and sizing in section 6.1. Consequently for the floating EDT the bias of the tether relative to the undisturbed plasma surrounding the tether, \( \Delta V = V_c - V_p \), varies along the tether length with the amount of induced EMF and the Ohmic voltage drop of the tether. For the low current levels induced in passive short tether operation the Ohmic voltage drop along the tether is considered negligible when [Kruijff; LeBreton]

\[
\frac{r}{\lambda} \ll L_E
\] (2-9)

Material, dimensions and orbit influence temperature and subsequently the resistance of the tether. Using the maximum tether specific resistance given in table a6-2 the \( \frac{I}{E_ML_{\text{max}}} \) current levels have been shown to be sufficiently low for (2-9) to be a valid approximation for most tether dimensions being considered over the orbit range depending on the selected thickness of the tether, see appendix 6 for some results derived using the Tether Design tool. During the eclipse part of orbit the tether temperature \( T_1 \) and \( n_0 \) drops reducing both the tether specific resistance and lowering the current levels.

- \( n_0 \) drops \( I_0 \) increases \( I_0 \) decrease \( I_{\text{OML}} \) drops
- \( T_1 \) drops and \( R_t \) drops \( I_{\text{OML}} \) increases

Taking the above into account tether resistance losses are not taken into account in the initial performance calculations. The bias distribution along the tether is assumed to vary due to the induced electromotive force

\[
\frac{d \Delta V}{dl} = E
\] (2-10)

**REQ-2 Tether Length \( L_t \)**

The effective tether length \( L_t \) is reduced by \( \frac{I_{\text{OML}}}{E_M} \frac{50 \Omega}{E} \) due to possible system resistances occurring due to ionospheric closure and sheath impedances

Integrating the current along the tether results in the current distribution along the tether as a function of distance \( s \) from the zero bias point [LeBreton]

\[
I_e(s) = en_e d_t \sqrt{\frac{Se E \cos \theta}{9m_e}} \left( l_c^2 - s^2 \right)
\]

\[
I_i(s) = en_i d_t \sqrt{\frac{Se E \cos \theta}{9m_{i,n}}} \left( l_i^2 - s^2 \right)
\] (2-11)

\( I_e \) – electron current [A]

\( I_i \) – ion current [A]

\( \theta \) – tether in plane angle from \( z_{\text{OR}} \) axis (assumed to be 0° in this section)

\( s \) – distance from the zero bias point [m]

For tether potentials larger than the surrounding plasma the tether collects electrons from the plasma, when the tether bias is negative to the surrounding plasma the tether collects ions similar to electron collection [Hoyt] however at a much slower rate due to higher mass and lower thermal velocity of the ions as was shown in appendix 4.
The maximum current level at the zero bias point $s$, $\Delta V = V_i - V_e = 0$ see figure 2.5, is given as [Heide; LeBreton]

$$I_{\text{OML}}(\text{max}) = e n_c d \sqrt{\frac{8\varepsilon_0 E \cos \theta}{9m_e}} I_c^2$$  \hspace{1cm} (2-12)

### 2.2.2 Electrostatic Shielding & Magnetic Guiding

For the tether to collect within the OML regime the perimeter of the tether is required to be within certain limits to avoid both electrical shielding and magnetic guiding effects. Crosswise tether dimensions are limited by the plasma electron Debye length $\lambda_{De}$ and the Debye length is required to be smaller than the electron gyro radius $r_{Le}$ [appendix 5]. OML current collection also holds for various geometries, tape and multi-strand tethers with plasma chamber experiments indicating OML current collection still holds when deviating from idealised case [Gilchrist, Kruijff] and showing that current collected by tape tether geometries beyond the electron Debye length agree with OML predictions for a cylinder with an equal drag area having an effective tether diameter $d_t$.

#### Debye Length and Electrostatic Shielding

When a charged object is immersed in plasma it attracts opposite charge elements from within the plasma forming a space-charge field around the object, the Debye sheath, with a thickness of several Debye lengths, is the transition layer between plasma and the object. For distances beyond the Debye length the electrostatic potential field diminishes exponentially ($1/e$) effectively screening the potential of the charged object from the rest of the plasma. The OML regime occurs when the sheath becomes sufficiently thick that orbital effects are a dominant factor in particle collection. The OML law depends only on the electron distribution [Ahedo], the electron Debye length $\lambda_{De}$ the characteristic shielding length for the ionospheric plasma is calculated as

$$\lambda_{De} = \left[ \frac{e^2 k_B T_e}{n_e e^2} \right]^{1/2}$$ \hspace{1cm} (2-13)

$\lambda_{De}$ – electron Debye Length [m]

valid for plasma with ions colder than electrons (timescale [TBC 59])

$\varepsilon_0$ – permittivity constant of free space $8.854 \times 10^{-12} \text{[C}^2\text{N}^{-1}\text{m}^{-2}]$

The Debye length varies in orbit due to plasma density and charged particle temperature variations ($T_e$ and $T_i$). For conducting tape tether widths of $w_c$ up to $2-4\lambda_{De}$ the OML regime is valid according to current theoretical models [Sanmartin; Estes]. Plasma chamber experiments have shown tape widths $w_c$ of $4-15\lambda_{De}$ follow the OML current predicted for an equivalent cylinder with effective diameter $d_t$ [Kruijff; Gilchrist; Vannaroni], see appendix 5.

#### Larmor Radius and Magnetic Guiding Effects

In magnetised plasma the motion of the particles is affected by the magnetic field. A charged particle moves in a circular motion around the magnetic field lines due to the Lorentz force acting on the particle while it traverses the magnetic field. The gyro radius, also known as the Larmor radius, is the radius of the resulting circular motion around the magnetic field lines. In theory the tether crosswise dimensions need to be of comparable or smaller dimensions than the Larmor radius to avoid magnetic guiding effects limiting current collection allowing maximum OML current to be collected. To find the mean gyro radius of a particle the perpendicular velocity is set equal to the thermal velocity of the particle [appendix 4, equation (A4-1)] resulting in the electron gyro radius [Sanmartin]

$$r_{Le} = \frac{v_{th,e} m_e}{eB} = \sqrt{\frac{k_B T_e}{m_e}} \frac{eB}{m_e}$$ \hspace{1cm} (2-14)

$r_{Le}$ – electron gyro or Larmor radius [m]

$v_{th,e}$ – electron thermal velocity [ms$^{-1}$]
The electron gyro radius is inversely proportional to the magnetic field strength $B$, constraining tether dimensions more for low altitudes and high inclination orbits. Using ionospheric plasma data derived from LEOPOLD the Debye length and gyro radius for Delfi-1 orbit altitude range have been derived for mean ionospheric activity and plotted in figure 2.4. The electron Debye length and electron gyro radius for Delfi-1 orbit altitudes range from 7.3-16 mm and 48-51 mm, shown below.

![Figure 2.4: Electron Debye length and electron gyro radius for orbit altitude range](image)

The OML current collection theory has been theoretically derived for stationary un-magnetised collisionless plasma. The assumption of collisionless plasma is considered to be a good approximation for the orbiting electrodynamic tether case [Sanmartin}. Plasma chamber tests have shown OML theory still holds when taking magnetic field and flowing plasma effects into consideration, the influence of these effects decreasing for lower current and bias levels. These effects should not have a significant influence on the derived EDT OML current levels with plasma chamber experiments indicating current collection values exceeding the theoretical OML current values. According to [Sanmartin] magnetic guiding effects increase for higher inclinations and altitudes. However with the electron gyro radius being in the order of centimetres and larger than the electron Debye length [Sanmartin; Ahedo], see table 2.3, effects of Earth’s magnetic field on OML current collection can be assumed negligible for tether dimensions. This has been confirmed by plasma chamber experiments conducted by [Vannaroni - Kruijff]. Also self-induction effects increase with increasing current levels can be assumed negligible [Kruijff] noting that for a conducting (heavy) tape these effects could possibly become an issue [Sanmartin], more research is required.

**Validity OML Regime EDT onboard Delfi-1**

For derivation of the OML theory, equation (2-7), the potential energy (the bias $\Delta V$) along the tether is assumed to be much larger than the kinetic and thermal energies of the charged particles being collected; the plasma is considered to be cold in comparison to the potential energy of the tether [Sanmartin].

$$\epsilon |\Delta V| \gg k_B T_e, \frac{1}{2} m_i v_{orb}^2$$

This is not the case for the relatively short EDT in the Delfi-1 orbit range as can be seen in table a5-1 and table a5-2 of appendix 5. This in combination with the increased magnetic guiding effects at high altitudes and inclinations current collection for sections of tether length could potentially fall out of the OML regime increasing in length for the higher inclinations of the orbit range being considered. Taking this into account a conservative maximum tether width of $2-4 \lambda_{De}$ is taken instead of the possible $15 \lambda_{De}$ suggested by plasma chamber experiments [Gilchrist]. For the EDT operating in the Delfi-1 orbit range OML current collection is assumed to be valid for short passive tethers inducing a low bias in magnetised plasma when the conductive tape tether width is limited to

$$w_t \leq 2 - 4 \lambda_{De}$$

$$\lambda_{De} \leq r_e$$
The maximum effective tether diameters for Delfi-1 orbit altitude range based on the average magnetic field strength B, see 2.1.1, and ionospheric data from LEOPOLD are given in the table 2.3.

Table 2.3: Maximum tether dimensions for OML Regime

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>(2 \cdot 4 \lambda_{De} ) [mm]</th>
<th>( t_{Le} ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>15-29</td>
<td>48</td>
</tr>
<tr>
<td>700</td>
<td>17-33</td>
<td>49</td>
</tr>
<tr>
<td>750</td>
<td>17-34</td>
<td>51</td>
</tr>
<tr>
<td>800</td>
<td>17-34</td>
<td>52</td>
</tr>
<tr>
<td>850</td>
<td>20-39</td>
<td>53</td>
</tr>
<tr>
<td>900</td>
<td>24-49</td>
<td>55</td>
</tr>
<tr>
<td>950</td>
<td>27-55</td>
<td>56</td>
</tr>
<tr>
<td>1000</td>
<td>32-64</td>
<td>58</td>
</tr>
</tbody>
</table>

A maximum tether width of 20 mm-40 mm [TBC 4] is currently assumed to collect current within or close to the OML regime for the entire orbit altitude range. The deviation from ideal \( I_{OML} \) current levels for tether widths beyond the OML regime does not show a rapid reduction from theoretical \( I_{OML} \) for dimensions beyond OML regime [Estes²]. A design consideration to be made is if the tether dimensions are flexible until the actual flight orbit is known allowing for optimisation of the width for OML current collection or if a fixed width \( w_c \) will give an acceptable performance for entire orbit range taking into account variation of OML regime with altitude and inclination and assuming degradation in performance is limited for tether dimensions beyond OML regime [Estes²], see appendix 5.

**REQ-3 Tether Conducting Width for OML Validity**

\[ w_c \leq 20 – 40 \text{ [mm]} \]

For the short floating tether at relatively low induced bias levels the ion ram current, photoemission and secondary electron-ion emission can effect the tether current levels and the bias distribution as the tether is not at a supra-thermal potentials for a significant part of \( l_e \) compared to both ion ram current and random thermal electron current temperatures, see appendix 5. With the tether moving faster than the thermal velocity of ions the tether rams into the ions and collecting ion current on the ram side with a wake created behind the SC and tether being void of ions. This also occurs for the positively biased part of the tether \( l_e \) with the ions able to ram through the positively charged section of tether the ion ram current could decrease the amount of electron current collected [TBC 60]. Assuming the ion ram current only effects the \( I_{OMLe} \) current collected over \( l_e \) the loss of current collected calculated using equation (A4-2) in appendix 4 is 4.7e-5 A to 1.6e-4 A for a 1000 m 30 mm wide aluminium EDT. The loss is approximately 1-3% of \( I_{OML(max)} \) of for the tether length range being considered and is subsequently not taken into account. At higher altitudes where \( H^+ \) is dominant and the plasma velocity is lower ion ram energy is not large compared to thermal energy and ram current effects will decrease [Estes²]. For the low bias potential of the relatively short EDT and ion ram current will possible have to be taken into account [TBC 60]. Secondary emission is a material property and can be considered to be \(-1\%\) of the collected electron current [Sanmartin]. Photoelectron emission current in LEO is also approximately \(-1\%\) of the electron current collected only occurring for tether surface area facing the sun.

The current distribution along the bare floating tether is assumed to be consistent with the Orbit Motion Limited theory in this thesis. Further research is required to determine the deviation from the OML theory current collection model for the low bias EDT, in section 6.1.6 two approaches for dealing with uncertainties in the amount of collected current are introduced and their effects on the final tether configuration are calculated. In section 4.2 a margin on the required performance of the EDT is applied in part to cover uncertainties in the amount of current collected. Assuming an average induced \( E \) along the tether of 0.036 Vm\(^{-1}\) for 650 km altitudes with inclinations ranging from 70°-85° and 95°-110° the current and bias profile for an aluminium tape tether are given in figure 2.5 using plasma parameters derived from LEOPOLD.
2.2.3 Effect of Various Design Parameters on OML Current Collected

From the previous section constraints for the effective diameter of the EDT have been obtained for current collection by the tether occurring within the OML regime. OML current collection is a function of the tether potential bias to the local plasma; plasma density; electron and ion temperature and electric shielding and magnetic guiding effects of the charged ionospheric particles and the tether collection area, a function of the tether perimeter and length. In this section the effect of various parameters on OML current levels are investigated.

Average values of the ionospheric plasma parameters for the Delfi-1 orbit range are used for initial tether performance calculations using monthly mean plasma densities, composition and temperatures obtained from LEOPOLD, IRI95/2001 and MSISE90 models accessed from [SPENVIS]. In appendix 3 a description of these models is given. The auroral region between latitudes 60° to 70° and the polar cap region above 70° of the ionosphere are not modelled accurately in these models. For the Delfi-1 orbit range extremes 650 km and 1000 km with inclinations of 70° to 90° 22%-30% of the orbit is situated in the auroral ionospheric region and for inclinations above 75° 13%-19% of orbital period is situated in the polar cap region with an uncertainty as to ionospheric properties. In this thesis performance calculations are performed assuming average (nominal) values of the ionosphere obtained from SPENVIS are valid for the entire orbit. More research into ionospheric plasma modelling and data for the auroral ionospheric region is required with current performance calculations for the EDT having an uncertainty for latitudes above 60°. If not mentioned otherwise plasma data used is consistent with average solar activity (F10.7 = 150). For the proposed baseline EDT experiment design parameters affecting current levels \( I_{\text{OML}} \) are varied, initially an entirely aluminium tape tether of 15 \( \mu \)m thick is assumed based on commercial household foil. The Delfi-1 satellite is assumed to be an unbiased object at this point; the floating potentials for the satellite are in the order of -0.9 V to -1.3 V calculated using (A4-3) in appendix 4].

\( I_{\text{OML}} \) as function of length and width and thickness

In the first part of this thesis it was shown that tether thickness has a minimum influence on \( I_{\text{OML}} \) levels. The tether thickness is assumed constant at 15 \( \mu \)m in this section and will determined by strength, mass, volume and tether resistance requirements at a later stage. Varying tether width and length increasing both tether bias and current collection surface area \( A_{\text{coll}} \) will result in higher current levels seen in figure 2.6 using the induced \( E \) values averaged over the inclination range and plasma parameters derived from LEOPOLD for the 650 km orbit altitude.
IOML variation across orbit altitude and inclination range 

Using induced E values averaged over the inclination range combined with LEPOLD plasma data the IOML\textsubscript{max} current levels are calculated for the orbit altitude range using the Tether Design tool [TN.4122.19-21]. Current levels decrease with increasing altitudes due to lower electron densities shown in appendix 3. As can be seen in figure 2.7 current levels are low and self shielding due to magnetic field formation around the tether, see section 2.1.2 and appendix 5, can be neglected. As expected high altitude and high inclination orbits reduce the amount of current collected significantly due to lower plasma densities and unfavourable angels between the tether and magnetic field decreasing E, see figure 2.3. The effect of retrograde orbits inducing a higher EMF, see section 2.1.2, is also seen with maximum current levels slightly higher for these orbits.

In orbit variation of electron and ion densities occur between solar and eclipse extremes of the orbit resulting in current variations occurring in the tether shown figure 2.8 with a drop of approximately 0.20-0.26 in current during eclipse, see below.

Figure 2.6: I_{OML \textsubscript{max}} values at 650 km\textsuperscript{4} [TN.4122.27]

IOML in orbit variation

In orbit variation of electron and ion densities occur between solar and eclipse extremes of the orbit resulting in current variations occurring in the tether shown figure 2.8 with a drop of approximately 0.20-0.26 in current during eclipse, see below.

Figure 2.7: Average I_{OML \textsubscript{max}} over orbit range\textsuperscript{4}

When taking the SC location in orbit as a variable for plasma data current levels are expected to decrease near polar latitudes due to lower electron densities occurring at higher latitudes, see figure a3-4. This needs to be confirmed however with more accurate data for auroral and polar cap ionosphere regions.

Figure 2.8: In orbit variation of I_{OML \textsubscript{max}} at 70\degree using data from [MSISE-90]
2.2.4 Bias and Current Distribution during Gas Release

Previous flight experience from the TSS-1R mission indicated that neutral gas release was capable of sustaining sufficient electron emission at the cathode end of the tether to sustain a current. This was experienced when the tether was cut and leaking N\textsubscript{2} gas allowing current levels of 1.1 A to flow through the tether [Gilchrist]. A similar situation occurred with the CHARGE-2 sounding rocket mission when electron current collection increased coinciding with cold N\textsubscript{2} gas emissions from control jets. A fraction of the gas was ionised increasing the local plasma density resulting in enhanced electron collection capabilities at the positively charged vehicle end [Gilchrist\textsuperscript{4}]. Assumptions made when determining effect of gas release are [LeBreton]

- A constant current I\textsubscript{gas} can be achieved at the cathode end of the tether as a function of the amount of gas released and the availability of electrons according to OML relationship
- The gas discharge will sustain a maximum current of 50 mA in this section

Assuming the gas discharge current I\textsubscript{gas} is independent of the local plasma density the zero bias point of the tether will move to a new equilibrium due to space charge effects to balance the electron OML current I\textsubscript{e} with I\textsubscript{gas} [LeBreton], see section 0. The required electron collecting part of the tether l\textsubscript{e} is a function of plasma density n\textsubscript{0} and the EMF as shown in equation (2-11), for higher densities n\textsubscript{0} the zero bias point s moves towards the satellite, for lower plasma densities it moves down towards the cathode end as a larger section of tether is required to collect the amount of electron current to balance with I\textsubscript{gas}. The I\textsubscript{gas} current level remains practically constant, the additional ion current effect is assumed small in comparison causing a slight drop from I\textsubscript{max} to I\textsubscript{gas} shown in figure 2.9.

![Figure 2.9: Gas release effect on bias and current distribution](image)

Figure 2.9: Gas release effect on bias and current distribution

Depending on plasma density and magnetic field strength two extreme current distribution cases can occur [LeBreton].

**Unsaturated current collection (I\textsubscript{gas} \leq I\textsubscript{gas,max})**

The entire tether is used as an anode for current collection; this occurs at low plasma densities and weak magnetic field strengths (low EMF). To estimate how much the unsaturated case can improve on the floating tether current and Lorentz force, using equations (2-11) and (2-20). Ignoring the contribution of the electron part for the floating case assuming l\textsubscript{e,gas} \sim l\textsubscript{e,float} the current enhancement over Delfi-1 orbit range when compared to bare floating tether performance is equal to [LeBreton]

\[ \sqrt{\frac{m_\text{e,rg}}{m_\text{e}}} \sim 113-163 \]
Fully saturated current collection ($I_{gas} = I_{gas,max}$)
The electron collection part required is very short, this occurs for high plasma density and EMF
environment. Most of the tether length will have current levels $I_{gas,max}$. In reality depending on
plasma density and induced EMF the current and bias distribution will be located between the
saturated and un-saturated extremes.

Figure 2.10: Current distribution extremes gas discharge current [LeBreton]
For orbit extremes in plasma density and induced EMF the current and bias distribution are shown
in figure 2.11 for a 50 mA gas discharge current for a 1500 m and 5 mm wide tether. Both orbits do
not achieve a fully unsaturated current distribution for this gas discharge current level, the 1000 km
85° approximates unsaturated, 650 km 110° approximates a saturated current distribution.

Figure 2.11: 650 km-110° & 1000 km-85° km, $I_{gas} = 50$ mA, $L_t$ -1500 m;w-5 mm [TN.4122.27]
Widths of 5 mm can reach the unsaturated current distribution for 250 m-1300 m of tether length as
seen below for 250 m tether at 1000 km-85° orbit with a 50 mA gas current.

Figure 2.12: 1000 km-85° km, $I_{gas} = 50$ mA, $L_t$ 250 m w 5 mm [TN.4122.27]
2.3 Forces in Orbit

The main force acting on a nadir-zenith oriented tether in orbit is the gravity gradient force. Other (perturbing) forces consist of higher harmonics of Earth's potential expansion and gravitational perturbations; see appendix 3, aerodynamic, electrodynamic, thermal and other non gravitational forces consisting of internal friction, residual stress and stiffness of the tether, motion of the end bodies and deployment forces [Beletsky]. For the electrodynamic tape tether the main forces acting on the system in orbit are

- Gravity Gradient Force $F_{GG}$
- Lorentz Drag $F_L$
- Aerodynamic drag $F_{ad}$
- Solar radiation pressure $F_s$
- Plasma drag $F_{pl}$

These forces affect the systems attitude and orbital dynamics acting as drag forces and producing disturbance torques on the system. In appendix 7 the system properties used in this chapter are shown, every design parameter is a variable input in the Tether Design tool [TN.4122.19]. The tether is assumed to be straight and rigid; bowing of the tether due to Lorentz forces is not taken into account.

2.3.1 Gravity Gradient Force

The EDT experiences significant effects from the gravity gradient (GG) torque due to its length and displacement from the systems centre of mass (c.m.) similar to gravity gradient booms used to stabilise spacecraft. The dynamical behaviour of most EDT systems predominantly depends on the ratio of the disturbing electrodynamic torque and the restoring gravity gradient torque. The gravity gradient force is also the main source of tension occurring in the tether.

![Diagram of Gravity Gradient Force and Tension Force](image)

The gravity gradient force is the difference between the centrifugal force $F_c$ due to motion of system and the gravity force $F_G$, see appendix 3 and figure 2.13.

$$F_c = m r \omega_o^2$$  \hspace{1cm} (2-15)  

$$F_G = -\frac{\mu m}{r^2}$$  \hspace{1cm} (2-16)

$m$ – total system mass [kg]  
$\mu$ – gravitational constant $3.986 \times 10^{14}$ [m$^3$ s$^{-2}$]  
$\omega_o$ – orbital frequency [rads$^{-1}$]
For short tethers assuming a circular orbit the resulting gravity gradient force is approximated as

\[
F_{GG} = \frac{d}{dr} \left( \frac{\delta F_C}{dr} + \frac{\delta F_G}{dr} \right) = 3m^* \omega^2 \delta r dr
\]  

(2-17)

\[dr \] – distance from the c.m. of the system [m]
\[m^* \] – mass above or below systems c.m. [kg]

The gravity gradient force increases with decreasing orbital radius and for increasing end mass and tether length. Tension forces are highest for the lower orbit altitudes and heavier systems being considered for Delfi-1 and for vertical tether orientations (largest displacements from c.m.). The gravity gradient force produces a restoring torque on the system when it is displaced from the nadir due to disturbing torques acting on the system enabling gravity gradient stabilisation of the system.

**Resulting Tether Tension**

For any pendular motion the tether tension profile is similar to a static tension profile with the maximum tension always occurring at the mass centre of the system and parallel to the tether assuming a perfectly flexible tether [Beletsky; figure 2.13]. For stable tether libration the tension is predominantly determined by the gravity gradient force, tether length and system mass distribution.

For short tethers the centre of motion (c.o.m) of the system, where the gravitational forces equal the centrifugal forces, is located near the c.m. [Roozendaal] at approximately 4 m to 240 m from the satellite depending on tether length, end mass and tether angle [appendix 7 (A7-1)]. Assuming the c.m. is located at the SC and neglecting other perturbing forces the maximum static tether tension \( T \) can be approximated using equation (2-17) with the tether and ballast mass at the tether end modelled as 2 point masses located at \( 0.5L_t \) and \( L_t \)

\[
T = 3(m_b + \frac{1}{2} m_t)L_t \omega^2 
\]  

(2-18)

\[T \] – tension force [N]
\[m_t \] – tether mass [kg]
\[m_b \] – end mass [kg]

Tether tension can also be derived from the linearised in plane (IP) unperturbed equations of motion for the tether system shown in appendix 8, equation (A8-7) assuming a massless tether. For the tether dimension range being considered the static tension varies from 7.38e-4 N to 4.39e-2 N, verified for average tensions in orbit using ETBSim.

**2.3.2 Lorentz Force**

With the EDT experiment operating in passive mode the system is limited to drag operation with (part of) the Lorentz force opposing the orbital velocity. The Lorentz force acting on the EDT is

\[
F_L = \mathbf{Ld} \mathbf{\times B}
\]  

(2-19)

The Lorentz force consists of an electron and ion current induced component \( F_L = F_{Le} + F_{Li} \). For design performance calculations the magnitude of the Lorentz force perpendicular to the tether and the magnetic field as a function of tether dimensions is calculated by integrating (2-19) using (2-11) [LeBreton]

\[
F_{Le} = B_\perp e_n d_t \sqrt{\frac{8eE \cos \theta_t}{9m_e}} \frac{3}{5} L_t^2 
\]  

(2-20)

\[
F_{Li} = B_\perp e_n d_t \sqrt{\frac{8eE \cos \theta_t}{9m_{i_{eq}}}} \frac{3}{5} L_t^2 
\]  

The perpendicular magnetic field component \( B_\perp \) to the tether and velocity vector is calculated using \( B_\parallel \) from (2-1) and \( F_L \) is calculated using orbit averaged values of \( E \) and \( B_\parallel \) for the orbit range.
In figure 2.14 average values for the Lorentz force induced at an altitude of 650 km for various tether dimensions is shown for tethers oriented along the z OR axis. Values obtained correlate with ETBSim orbit averaged Lorentz drag forces.

![Figure 2.14: Lorentz force for various tether dimensions at 650 km](image)

For initial performance calculations the tether is assumed straight and rigid; in reality bowing of the tether will reduce the amount of Lorentz force generated. Tether pendular motion reduces the amount of Lorentz force as shown in figure 2.15 for a 0° and 30° angle of the tether from the z OR axis for a 650 km and 70° inclination orbit.

![Figure 2.15: Effect tether angle θ on Lorentz force](image)

As expected the Lorentz force is slightly higher for retrograde orbits with a higher E (see section 2.1.2) and follows a similar trend to the IOML induced across the orbit range with low inclination and altitude orbits giving the highest Lorentz force as can be seen in figure 2.16. For the drop in current during eclipse shown in figure 2.8, the Lorentz force also decreases.

![Figure 2.16: Lorentz force variation over the orbit range](image)
Expanding equation (2-19) in the orbital reference frame and assuming the tether is oriented along the $z_{OR}$ axis inclined orbits to the magnetic field are shown to have an out-of-plane force component perpendicular to the orbital velocity vector.

$$\vec{F}_L = \begin{pmatrix} \vec{I}_L \times \vec{B}_r \\ \vec{I}_L \times \vec{B}_u \end{pmatrix} = \begin{pmatrix} (\vec{H}_r, \vec{B}_r - \vec{H}_u, \vec{B}_u)_L \\ -(\vec{H}_r, \vec{B}_r - \vec{H}_u, \vec{B}_u)_L \\ (\vec{H}_r, \vec{B}_r - \vec{H}_u, \vec{B}_u)_L \end{pmatrix} \approx \begin{pmatrix} -|I_L| B_r \\ |I_L| B_r \\ 0 \end{pmatrix}$$ (2-21)

The out of plane component effects the inclination of the orbit and the out of plane librations of the tether.

![Figure 2.17: Components $d|XB$ in plane and out of plane](image)

Using the transformation of the Lorentz force calculated in the Earth centred Inertial reference frame (ECI) to the orbital reference frame (OR) [Appendix 1] or by determining the parallel and perpendicular component of the Lorentz force to the orbit plane $F_p = \vec{F}_L \cdot \vec{v}$, the in plane and out of plane components of the $d|XB$ vector are calculated during 1 orbit in figure 2.17 [TN.4122.12].

The amount of in and out of plane Lorentz force for a straight tether along the $z_{OR}$ and non-tilted dipole magnetic field varies with orbital inclination according to [Cosmo; Tragesser]

$$F_{LIP} \approx -|I_L| B \cos i$$

$$F_{LOOP} = |I_L| B \sin i \cos(\omega + \theta)$$

(2-22)

$\omega$ – argument of the periapsis [º]

$\theta$ – true anomaly [º]

At higher inclinations the in plane component decreases see figure 2.17 and figure 2.18, for equatorial orbits almost the entire Lorentz force is an in plane drag force with the slight out of plane force component due to the magnetic field tilt $t_m$.

![Figure 2.18: In plane drag component of $F_L$ for inclination range](image)
Gas Release Effect on Lorentz Force

Saturated Case
For the saturated current distribution case the Lorentz force can be assumed constant over the tether with the force acting at \( \frac{1}{2} L_t \) and can be calculated using equation (2-19) for the current \( I_{\text{gas,max}} \).

Unsaturated Case
For the unsaturated current distribution case the Lorentz force will act at approximately at as a point force at \( \frac{5}{14} L_e \) from the tether end as with the bare tether case with the force calculated as \( F_{Le} \), see equation (2-20).

2.3.3 Aerodynamic Drag Force
The aerodynamic drag force due to atmospheric particles for near circular orbits is approximated as [Beletsky]

\[
F_{ad} = -\frac{1}{2} \rho C_D A_d v_{rel}^2
\]  
(2-23)

\( v_{rel} \) – satellite velocity relative to atmosphere [\( \text{ms}^{-1} \)]
\( \rho \) – atmospheric density [\( \text{kgm}^{-3} \)]
\( A_d \) – projected drag area normal to the airflow [\( \text{m}^2 \)]
\( C_D \) – drag coefficient assumed 2.2 [\( \cdot \)] [Cosmo]

The force is directed against the spacecraft velocity vector relative to the atmosphere; in this analysis it is assumed to be oriented opposite the orbital velocity along \( x_{OR} \) perpendicular to the \( z_{OR} \) vector. Subsequently only IP aerodynamic drag forces occur dissipating the kinetic energy of the spacecraft lowering the orbit altitude. In reality the relative velocity is at an angle to the orbital velocity with aerodynamic drag also having an out of plane component perpendicular to the orbit plane affecting the inclination of the orbit and the out of plane librations of the tether. A high ballistic drag coefficient \( B_{all} \) is inherent to tape tethers optimised for current collection area as mentioned in the first part of this study. This causes the aerodynamic drag force and resulting deceleration and torque on the system to be significant. The atmospheric density decreases with increasing altitude, shown in figure a3- 3, and is also a function of solar activity. A diurnal variation in atmospheric density can be observed [ECSS] it is assumed that density decreases to minimum values for the eclipse part of the orbit. Largest uncertainties in predicting the amount of drag are in the density \( \rho \) and the drag coefficient \( C_D \). Maximum surface areas normal to the velocity vector have been considered for the straight tether aligned with the \( z_{OR} \) axis. The highest aerodynamic drag force will occur at orbit altitudes of 650 km and retrograde inclinations of 110° producing the highest relative velocity \( v_{rel} \) of the spacecraft with respect to the atmosphere. The projected area normal to \( x_{OR} \) of the combined gravity gradient boom (GGB), spacecraft (SC) and tether (TET) systems \( A_d \) is given in appendix 7.

Figure 2.19: Aerodynamic drag force as a function of tether width \( w_c \) and length \( L_t \)
Tether design parameters affecting the aerodynamic drag force; torque and acceleration on the system with tether mass \( m_t \ll m \) are located in the drag area \( A_d \) of the tether. Taking tether twist into account the drag area is \( A_d = d_t L \cos \theta_t \) with \( d_t \) defined in equation (2-8). Assuming \( v_{rel} = v_{orb} \) the aerodynamic drag force as a function of tether width \( w \) and length \( L_t \) for average atmospheric densities is shown in figure 2.19.

### 2.3.4 Solar Radiation Pressure

The solar radiation pressure depends on the reflective properties of the surface areas exposed and the angle of incidence of the radiation and surface shading occurring. Assuming specular reflection and only considering the component of force normal to the irradiated area \( A_s \), the worst case solar radiation pressure acting at the centre of solar pressure centre (c.s.p) of the system [defined in appendix 7] is calculated as [Wakker]

\[
F_s = \frac{S_s}{c} A (1 + r) \cos^2 \alpha_s \tag{2-24}
\]

- \( A_s \) – irradiated area \([m^2]\)
- \( \alpha_s \) – incidence angle of solar radiation on \( A_s \) \([\degree]\)
- \( r \) – surface reflectivity \([-]\)
- \( c \) – speed of light \(3.00 \times 10^8 [m/s]\)
- \( S_s \) – solar radiation flux \([W/m^2]\)

Solar radiation pressure has a significant effect on objects having a large surface area and a low mass as is the case with solar sails and tape tethers designed for maximising current collection area and aerodynamic drag area when cut. For the EDT this force can be significant when considering worst case values with \( \alpha_s = 0^\circ \). This is illustrated in table 2.4 which shows the contributions of SC, EDT, End Mass (EM), GGB and the boom tip module (TIP).

#### Table 2.4: Worst case solar radiation pressure \( L_t=1000 \text{ m} \) w-30 mm

<table>
<thead>
<tr>
<th>SUBSYSTEM</th>
<th>( F_s ) [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>1.18E-06</td>
</tr>
<tr>
<td>EDT</td>
<td>1.55E-04</td>
</tr>
<tr>
<td>EM</td>
<td>5.59E-08</td>
</tr>
<tr>
<td>GGB</td>
<td>2.21E-06</td>
</tr>
<tr>
<td>TIP</td>
<td>8.19E-08</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.58E-04</td>
</tr>
</tbody>
</table>

Albedo \( S_a = 20-246 \text{ Wm}^{-2} \) and Earth’s infrared radiation \( S_{ir} = 216-258 \text{ Wm}^{-2} \) [appendix 13] also induce an radiation forces on the system. These forces have not been taken into account as their effects decrease rapidly with increasing distance from Earth, see appendix 13. With the tether oriented vertically along the nadir the irradiated surface area by these radiation forces will not be as significant and are ignored at this point.
The radiation force will cause a significant torque on the system if there is an offset between the c.m. and c.s.p., see section 3.2. As the spacecraft moves toward the sun the force will decelerate and decrease orbital energy while accelerating the spacecraft when moving away from the sun as shown in figure 2.20. With part of the orbit in eclipse (eclipse times are calculated in appendix 13) the change in semi major axis due to solar radiation perturbation can be non zero depending on Sun-Earth-SC geometry [Wakker] and will influence the orbit eccentricity by lowering the perigee \( r_p \) and increasing the apogee \( r_a \) altitude creating an eccentricity vector perpendicular to the solar radiation vector increasing with time [Sidi].

### 2.3.5 Plasma Drag

The plasma drag on a conducting tether is governed by the amount of ions colliding with the tether or deflected by the electric field inside the Debye sheath. The Debye sheath region a function of the tether potential and the plasma Debye length \( \lambda_D \) with the sheath region given as \( D_e=6 \lambda_D \) [Beletsky]

\[
F_{\text{plasmadrag}} = \frac{\pi e L \Delta V}{\ln(D_e/d)} v_{\text{rel}} B \tag{2-25}
\]

\( D_e \) – Debye sheath [m]

For a 1000 m - 30 mm tether at 650 km and 1000 km altitude for average orbital induced \( E \) the plasma drag ranges from 0.13 - 0.05 \( \mu N \) and can consequently be ignored.

### 2.3.6 Summary of Extreme Drag Forces

In figure 8.1 the extremes for the drag forces in orbit are summarised for a tether of the following dimensions \( L_t \) - 1000 m \( W_c \) - 30 mm \( t_c \) - 15 \( \mu m \) and \( \theta_t \) - 0°. LEOPOLD data excludes a separate data entry for eclipse conditions and solar activity \( F_{10.7} \) is 150 used for Lorentz force calculations. \( F_{\text{Lmax}} \) – \( F_{\text{Lmin}} \) in figure 8.1 indicate extreme values of \( F_L \) during the solar part of the orbit. As can be seen at high atmospheric densities and high relative velocities \( v_{\text{rel}} \) the aerodynamic drag force is the dominant drag force for orbits up to 750 km altitude acting as a significant disturbance for indirect measurements of the orbital effect induced by the Lorentz drag force. At low atmospheric densities and velocities the effect of the aerodynamic drag can practically be discounted. Accelerations due to the perturbing drag forces on the system are shown below.

Table 2.5: Accelerations on the system for tether dimension extremes

<table>
<thead>
<tr>
<th>Total</th>
<th>Lorentz</th>
<th>Aerodynamic drag</th>
<th>Solar radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250 m</td>
<td>2500 m 80 mm</td>
<td>250 m 5 mm</td>
</tr>
<tr>
<td></td>
<td>250 m 80 mm</td>
<td></td>
<td>2500 m 5 mm</td>
</tr>
<tr>
<td>( a_{\text{max}} ) [ms^{-2}]</td>
<td>9.18E-07</td>
<td>1.19E-04</td>
<td>1.35E-08</td>
</tr>
<tr>
<td></td>
<td>1.35E-08</td>
<td>5.69E-05</td>
<td>5.84E-07</td>
</tr>
<tr>
<td>( a_{\text{min}} ) [ms^{-2}]</td>
<td>2.36E-07</td>
<td>1.95E-05</td>
<td>2.24E-09</td>
</tr>
</tbody>
</table>

\( a_{\text{max}} \) 9.18E-07 1.19E-04 1.35E-08 5.69E-05 5.84E-07 4.18E-05 2.36E-07 1.95E-05
\( a_{\text{min}} \) 3.24E-07 2.64E-05 1.42E-09 6.02E-05 2.24E-09 1.60E-07
3 SYSTEM DYNAMICS

In this section the influence of EDT operation on the systems orbital parameters and the attitude dynamics of the Delfi-1 satellite are determined. Also a description of tether librations and deployment dynamics is outlined.

3.1 Orbital Dynamics

Knowing the in plane and out of plane forces acting on the system the perturbation of the Kepler orbit can be determined using the Gauss planetary equations [appendix 2 (A2-10)]. When using an electrodynamic tether for orbit manoeuvres as a general rule changes in orbit inclination and line of nodes are more effective at high inclinations due to a larger out of plane component, changes in orbital energy and eccentricity at low inclination orbits where in plane component of Lorentz force is dominant [less; Tragesser]. The EDT experiment is limited to passive drag operation, for initial performance calculations of the EDT deorbit Lorentz and aerodynamic drag effects on orbital parameters are determined with the tether oriented along the $z_{OR}$

\[
F_{x_{OR}} = F_D = F_{LIP} + F_{ad}
\]
\[
F_{y_{OR}} = F_{LOOP}
\]

Orbit parameters varying due to the aerodynamic and Lorentz drag force acting on the system consist of the semi major axis, inclination, eccentricity, argument of perigee and the mean anomaly [$a, i, e, \omega, M$] as can be seen in the Gauss planetary equations in [appendix 2]. The change in semi major axis dominant for passive EDT drag operation and secondary effects occurring mostly in the inclination and eccentricity [West; Tragesser, less]. The out of plane force component influences the inclination and the line of nodes [$i, \Omega$] of the orbit, see appendix 2 (A2-10). The atmospheric drag force has a component perpendicular to the orbit plane affecting the inclination of the orbit, however this force component is not taken into account. With solar radiation predominately having an effect on orbit eccentricity, see section 2.3.4, solar radiation pressure is not taken into consideration for initial EDT deorbit calculations.

**Semi Major Axis Change**

From the Gauss planetary equations the change in semi major axis (SMA) is rewritten using equation (A2-11) as

\[
\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}} \left\{ \left[ 1 + e \cos \theta \right] S_{OR} \right\} = \frac{2}{n\sqrt{1-e^2}} \left\{ \frac{a(1-e^2) - F_{LIP}}{m} \right\} = -\frac{2a\sqrt{1-e^2}F_D}{nmr}
\]

\[
\frac{dS_{OR}}{dt} = \frac{dF_{LIP}}{dt} = \frac{dF_{ad}}{dt}
\]

\[
\frac{dF_{LIP}}{dt} = \frac{dF_{ad}}{dt} = \frac{dF_D}{dt}
\]

\[
\frac{dE}{dt} = E \cdot \mathbf{v} = F_D \cdot \mathbf{v}_{orb}
\]

\[
E = \frac{\mu m}{2a} \quad \frac{dE}{dt} = \frac{\mu \cdot da}{2a^2} dt
\]

\[
F_{LIP} = F_{ad} = F_D
\]
Eclipse Conditions

During eclipse the current in the tether can be expected to drop to 1/3 of its value [Hoyt\(^2\)] depending on ambient ionospheric densities, see also figure 2.8. Temperature effects on tether resistance \(R_t\) can (in part) compensate for the drop in ionospheric density. The voltage losses due to tether resistance drop by a factor 10 when the tether is in eclipse, this effect will be more noticeable for high current systems [appendix 6]. For the EDT system the tether resistance drop in eclipse has minimal effect on performance due to the low current levels. Overall deorbit performance is expected to drop to 30% during eclipse phase. For the Delfi-1 orbit range eclipse times range from 0.33 to 0.36 part of the orbit, see appendix 13. Assuming a drop of Lorentz force to 30% over the eclipse period and using average aerodynamic drag values dropping to minimum aerodynamic drag values in the eclipse period the average deorbit performance of the tether is calculated for mean solar conditions \(F_{10,7} = 150\). The resulting average deorbit for a 1000 m - 30 mm tether is shown for the altitude range of Delfi-1 below.

![Figure 3.1: Change in SMA for 1 day](image)

Using the extreme values for the drag forces acting on the orbiting system for the orbit altitude range the change in semi major axis for a two week experiment duration are shown below for \(F_{10,7} = 150\) solar conditions in \(F_L\) calculation with the tether angle at 0° and \(F_{ad}\) values taking relative velocity and atmospheric density extremes into account.

<table>
<thead>
<tr>
<th>(\Delta)SMA [m]</th>
<th>650 [km]</th>
<th>700 [km]</th>
<th>750 [km]</th>
<th>800 [km]</th>
<th>850 [km]</th>
<th>900 [km]</th>
<th>950 [km]</th>
<th>1000 [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>max</td>
<td>17588</td>
<td>10902</td>
<td>7920</td>
<td>5957</td>
<td>4449</td>
<td>3009</td>
<td>2359</td>
<td>1825</td>
</tr>
<tr>
<td>average</td>
<td>6303</td>
<td>4315</td>
<td>3730</td>
<td>3412</td>
<td>2617</td>
<td>1830</td>
<td>1515</td>
<td>1211</td>
</tr>
<tr>
<td>min</td>
<td>2942</td>
<td>2231</td>
<td>2109</td>
<td>2035</td>
<td>1592</td>
<td>1130</td>
<td>948</td>
<td>761</td>
</tr>
</tbody>
</table>

Table 3.2 showing the percentage of the total drag force due to the induced Lorentz drag indicates that the preferable orbits for the experiment are at high altitudes and low inclinations where a change in orbital period is predominantly due to Lorentz drag force effect.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>70°</td>
<td>65%</td>
<td>73%</td>
<td>82%</td>
<td>88%</td>
<td>89%</td>
<td>89%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>75°</td>
<td>60%</td>
<td>69%</td>
<td>79%</td>
<td>86%</td>
<td>87%</td>
<td>87%</td>
<td>88%</td>
<td>88%</td>
</tr>
<tr>
<td>80°</td>
<td>54%</td>
<td>63%</td>
<td>75%</td>
<td>82%</td>
<td>84%</td>
<td>84%</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>85°</td>
<td>42%</td>
<td>52%</td>
<td>65%</td>
<td>75%</td>
<td>77%</td>
<td>77%</td>
<td>78%</td>
<td>79%</td>
</tr>
<tr>
<td>90°</td>
<td>51%</td>
<td>60%</td>
<td>72%</td>
<td>80%</td>
<td>82%</td>
<td>81%</td>
<td>82%</td>
<td>82%</td>
</tr>
<tr>
<td>100°</td>
<td>58%</td>
<td>67%</td>
<td>77%</td>
<td>84%</td>
<td>86%</td>
<td>85%</td>
<td>86%</td>
<td>86%</td>
</tr>
<tr>
<td>105°</td>
<td>63%</td>
<td>71%</td>
<td>81%</td>
<td>87%</td>
<td>88%</td>
<td>88%</td>
<td>89%</td>
<td>89%</td>
</tr>
<tr>
<td>110°</td>
<td>67%</td>
<td>75%</td>
<td>83%</td>
<td>89%</td>
<td>90%</td>
<td>89%</td>
<td>90%</td>
<td>90%</td>
</tr>
</tbody>
</table>
In figure 3.2 the percentage Lorentz drag over total drag force is shown for three tether widths as a function of tether length. The extreme values of this ratio are shown being a maximum for 1000 km 110° inclination and a minimum for 650 km and 85° inclination as derived from table 3.2. As can be seen the tether length has an effect on the ratio of Lorentz over aerodynamic drag force component acting on the system. This is due to the \( L^2 \) term present in the \( F_L \) component (2-20) and the \( L \) term in the \( F_{ad} \) component (2-23). At shorter lengths wider tethers have a slight advantage in the ratio \( F_L \) to \( F_{ad} \) as for the shorter tethers the aerodynamic drag area of the GGB and SC play a more significant role when small crosswise dimensions of the tether are considered.

![Figure 3.2: Percentages \( F_L \) of \( F_D \) for various tether dimensions over the orbit range](image)

**Inclination Change**

The rate of inclination change is equal to the rate of orbit precession due to the electrodynamic torque with the \( F_{OOP} \) force causing the inclination change of orbit, primarily when system passes equator [Hoyt]

\[
\frac{d\delta}{dt} = \frac{T_{OD}}{\Omega} \tag{3-6}
\]

\( T_{OD} \) – net out of plane drag torque [Nm]

\( \Omega \) – orbital angular momentum [Nms]

Using the Gauss Planetary equations from appendix 2 the rate of inclination change due to the out of plane Lorentz force acting on the system is

\[
\frac{d\delta}{dt} = \frac{F_{OOP}}{nma} \cos(\omega + \theta) = \frac{F_{OOP}}{v_c m} \cos(\omega + \theta) \cdot \frac{d\delta}{dt} = \frac{F_{OOP}}{mv_{orb}} \cos(\delta) \tag{3-7}
\]

\( \delta \) – orbital latitude \([\degree]\)

\( v_c \) – circular orbit velocity \([\text{ms}^{-1}]\)

**Table 3.3: Required drag force for 2 week orbit change**

<table>
<thead>
<tr>
<th>( \Delta t ) - 2 weeks</th>
<th>( \Delta SMA ) - 100 m</th>
<th>( \Delta ) - 1° [Hoyt]</th>
<th>( \Delta ) - 1°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H ) [km]</td>
<td>( v_c ) [\text{ms}^{-1}]</td>
<td>( P_{req} ) [W]</td>
<td>( F_{req} ) [N]</td>
</tr>
<tr>
<td>650</td>
<td>7531</td>
<td>0.015</td>
<td>2.02E-06</td>
</tr>
<tr>
<td>700</td>
<td>7504</td>
<td>0.015</td>
<td>2.00E-06</td>
</tr>
<tr>
<td>750</td>
<td>7478</td>
<td>0.015</td>
<td>1.98E-06</td>
</tr>
<tr>
<td>800</td>
<td>7452</td>
<td>0.015</td>
<td>1.96E-06</td>
</tr>
<tr>
<td>850</td>
<td>7426</td>
<td>0.014</td>
<td>1.94E-06</td>
</tr>
<tr>
<td>900</td>
<td>7400</td>
<td>0.014</td>
<td>1.92E-06</td>
</tr>
<tr>
<td>950</td>
<td>7375</td>
<td>0.014</td>
<td>1.90E-06</td>
</tr>
<tr>
<td>1000</td>
<td>7350</td>
<td>0.014</td>
<td>1.88E-06</td>
</tr>
</tbody>
</table>
In table 3.3 a comparison between an inclination change of 1° and SMA change of 100 m is shown assuming the entire Lorentz drag force is used for inclination change. An inclination change requires too much power for the bare tether to be design as minimum mass experiment compared to SMA change. The experiment will be designed to induce a measurable change in SMA of the Delfi-1 orbit over a minimum operational period of two weeks.

**Eccentricity Change**

From the Gauss equations using equation (A2-11) [appendix 2] the rate of change of the orbit eccentricity can be written as

\[
\frac{de}{dt} = \frac{2F_D}{nma} \cos \theta = \frac{2F_D}{\nu \cos \theta}
\]  

(3-8)

When comparing equations (3-7) and (3-8) with (3-3) it can be seen that inclination changes \( \Delta i \) vary with \( \Delta t F_{OOP}/nma \) and eccentricity \( \Delta e \) with \( \Delta t 2F_{IP}/nm \) both are expected to be small in comparison to the semi major axis \( \Delta a \) - \( \Delta t F_{IP}/nm \) and orbital changes due to the operation of the EDT experiment will be most noticeable in the semi major axis.

### 3.2 System Attitude Dynamics

The EDT attitude dynamics during deployment and operation will influence the attitude (control) of the Delfi-1 satellite as the tether will generate disturbance torques on the system. To operate the experiment successfully the EDT- SC system will have to be able to maintain a nadir pointing orientation with a \( \pm 5^\circ \) attitude pointing error from the \( z_{OR} \) axis ensuring communications with the ground station (GS) by means of a predominantly passive attitude control system; the gravity gradient boom. In this paragraph the influence of the tether during the operational phase on Delfi-1 attitude dynamics and EDT design parameters influencing the stability of the system are determined. In first part of this study the following requirements where derived concerning the attitude of the SC-EDT system [SPC.4122.01]

- Absolute Pointing Error (APE) requirement \( \pm 5^\circ \) around \( x_b \) and \( y_b \) axes of the spacecraft body frame [REQ-4] using GG stabilisation with the satellite pointing to nadir
  - Roll and Pitch motion are restricted to \( \pm 5^\circ \)
- Disturbance Torques payload [REQ-5] [TBD 2]
- Residual Magnetic Dipole SC < 1 Am² [REQ-6]
The static and dynamic behaviour of tether and satellite system depends on the disturbing torques including the electrodynamic (ED) torque and the (restoring) gravity gradient (GG) torque being a function of the dimensions and mass distribution of the system, see appendix 7. Initial static stability analysis of the attitude dynamics of the system is performed to determine if the system is capable of meeting the attitude control requirements with the EDT payload being deployed and operating phase. For this analysis all disturbance forces-torques are assumed to act in the same x, y, z plane (IP) providing a worst case disturbance torque. The tether is modelled as a straight and rigid rod with a fixed connection to the centre of the nadir SC panel resulting in a dumbbell IP pendular libration motion about the y axis of the system [Cosmo]. The body reference frame (B) is assumed to coincide with the orbital reference (OR) frame neglecting spacecraft rotations in orbit (θb, φb, ψb = 0) for the static torque equilibrium calculations. The effect of tether libration angles on the static equilibrium is analysed by assuming a range of fixed tether IP angles θt. The centres of mass and pressure and moments of inertia (I) of the system are calculated for the (variable) system parameters and shown in table 3.4 with the calculation is shown in appendix 7.

### Table 3.4: Centres and system moments of inertia for configuration θt - 0°[appendix 7]

<table>
<thead>
<tr>
<th>Centres (T)</th>
<th>x</th>
<th>z</th>
<th>x</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>c.m.</td>
<td>0</td>
<td>31.5</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>c.a.p.</td>
<td>485</td>
<td>-</td>
<td>-</td>
<td>339</td>
</tr>
<tr>
<td>c.s.p.</td>
<td>489</td>
<td>-</td>
<td>-</td>
<td>342</td>
</tr>
<tr>
<td>Moments of Inertia (OR)</td>
<td>Ixx = Iyy = (kgm²)</td>
<td>Izz = (kgm²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>1.32</td>
<td>37973</td>
<td>1.32</td>
<td>0.0000</td>
</tr>
<tr>
<td>EDT</td>
<td>1.01E-05</td>
<td>368810</td>
<td>0.0000</td>
<td>1.32</td>
</tr>
<tr>
<td>EM</td>
<td>1.88E-03</td>
<td>779865</td>
<td>1.88E-03</td>
<td>1.88E-03</td>
</tr>
<tr>
<td>GGB</td>
<td>1.27E+01</td>
<td>3149</td>
<td>7.98E-04</td>
<td>7.98E-04</td>
</tr>
<tr>
<td>TIP</td>
<td>5.21E-03</td>
<td>3039</td>
<td>6.25E-02</td>
<td>6.25E-02</td>
</tr>
<tr>
<td>System</td>
<td>1192235</td>
<td>1.381</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stored EDT</td>
<td>169</td>
<td>1.381</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using the forces calculated in the previous section the torque balance of the EDT-SC-GGB system is calculated. Assuming the disturbance torques (T_DIST) resulting from EDT operation have to be stabilised by passive gravity gradient (GG) stabilisation the following general attitude requirements need to be fulfilled by the system

- **REQ-7** System stability region for passive GG stabilisation
  \[ I_x > I_z, I_y > I_x > I_z, I_y < I_x + I_z \] [Sidi]

- **REQ-8** Librations about each axis shall be separated from orbital frequency ω_b by at least 20% to avoid resonance occurring [Hamann²]

- **REQ-4** T_GG magnitude chosen so the steady state angle about the local z OR: \( θ_b ≤ (5° - ω_b) \) including a design margin of three to compensate for simplified linear model [Hamann²]

- **REQ-9** \( T_{GG\text{STAB}} / T_{DIST\text{max}} ≥ 3 \)

### Table 3.5: Passive GG stabilisation criteria θt - 0°

<table>
<thead>
<tr>
<th>GG stable</th>
<th>Lx &gt; Lz</th>
<th>Stable</th>
<th>stability y, axis pitch motion; no damping factor -&gt; oscillates in stable motion about y axis for any Txy is zero or initial θb(0); uncoupled from other 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lx &lt; Lz + Ly</td>
<td>Stable</td>
<td>stability x, y, axis roll yaw; coupled motions with damping factor</td>
</tr>
<tr>
<td></td>
<td>Lx &gt; Lz</td>
<td>UNSTABLE</td>
<td>pitch stability; add mass to Ly, Region B; easiest to change structurally [Sidi]</td>
</tr>
<tr>
<td></td>
<td>Lx &lt; Ly</td>
<td>Stable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lx &gt; Ly + Ly</td>
<td>Stable</td>
<td></td>
</tr>
</tbody>
</table>

The current configuration is symmetric about the z OR, Lx = Ly, this is not a passive GG stable configuration [Sidi], the system dimensions and mass distribution will have to be altered and/or some method of damping will need to be included to achieve pitch stability. This is also the case for the SC-GGB with the EDT stored, see table 3.4.
System Libration Frequencies

Time domain behaviour of passive GG stabilised system using the linearised equations of motion for GG stabilised motion given in appendix 8 results in the following system libration - orbital frequency ratio’s [Sidi] valid for small angles neglecting the coupling of the roll and yaw motion

\[
\frac{\omega^2_x}{\omega^2_y} = \sqrt{\frac{4(I_y - I_z)}{I_y}} \quad \frac{\omega^2_y}{\omega^2_z} = \sqrt{\frac{5(I_x - I_z)}{I_z}} \quad \frac{\omega^2_z}{\omega^2_x} = \sqrt{\frac{4(I_x - I_z)}{I_x}}
\]

(3-9)

Table 3.6: Libration frequencies system passive GG stabilisation \( \theta_k = 0^\circ \)

<table>
<thead>
<tr>
<th>Orbit</th>
<th>( \omega_0^2/\omega_n^2 )</th>
<th>( \Delta \omega_x )</th>
<th>( \Delta \omega_y )</th>
<th>( \Delta \omega_z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>650 km</td>
<td>0.00214 0%</td>
<td>0.00186 27%</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>850 km</td>
<td>0.00205 8%</td>
<td>0.00178 34%</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1000 km</td>
<td>0.00199 14%</td>
<td>0.00173 39%</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The roll motion libration frequency of the system about the \( x_{OR} \) axis is twice the orbital frequency, resonance phenomena are to be expected, this is also the case for the SC without deployed tether. Librations about the \( y_{OR} \) axis meet the required 20% separation from orbital frequency.

System Torques

Restoring Gravity Gradient Torque

Gravity Gradient Torque [appendix 8 (A8-1)] for the \( x_{OR} \) \( z_{OR} \) plane

- \( \theta_b \) – system libration angle from \( Z_{OR} \)

\[
\omega = \frac{3\mu}{2r^3} \left| I_z - I_x \right| \sin(2\theta_b)
\]

(3-10)

Control Torque

- \( T_c = CB \)

B – local magnetic field strength [T], see section 2.1.1 worst case

\( B_{\text{min}} \) absolute value 2.0e-5 [T]

C – control dipole - 0.03 [Am^2] [Hamann\(^2\); Crichton]

Initial design assumes that no control torque \( T_c \) is available for correcting attitude disturbances due to operation of the EDT experiment after the deployment phase. During deployment of the experiment it is conceivable that a control torque is available, for orbit range values of the magnetic field the \( T_c \) ranges from 6e-7 to 1.4e-6 Nm.

Worst Case Disturbance Torques

- Electrodynamic torque \( T_L \) with \( F_{Le} \) and \( F_{Li} \) from (2-20), the forces act at \( z_e \) and \( z_i \) in the OR frame producing a torque \( T_L = T_{Le} + T_{Li} \) on the system [LeBreton]

\[
T_L = F_{Le} \cos \theta \left[ z_e - z_{sat} \right] + F_{Li} \cos \theta \left[ z_i - z_{sat} \right]
\]

(3-12)

Current enhancement due to gas release will alter the current and Lorentz force distribution during and will be somewhere between the unsaturated and saturated case. Current distribution gives the following torques on the system for unsaturated and saturated current distribution, see figure 2.10.

Unsaturated

\[
T_{L,\text{unsat}} = F_{Le,\text{unsat}} \cos \theta \left[ z_{\text{unsat}} - z_{\text{sat}} \right]
\]

(3-13)
Saturated 
\[ T_{L\text{sat-unsat}} = F_{L\text{sat}} \cos \theta_s (z_{\text{unsat}} - z_{\text{cm}}) \]
\[ z_{\text{unsat}} = \frac{1}{2} L_i \cos \theta_i \]  
(3-14)

- Aerodynamic drag torque \( T_{\text{ad}} = F_{\text{ad}} (z_{\text{cp}} - z_{\text{cm}}) \)
- Solar Radiation Pressure Torque \( T_s = F_s (z_{\text{cp}} - z_{\text{cm}}) \)
- Plasma Drag Torque \( T_{\text{pl}} \approx 0 \)
- Magnetic Torque \( M = DB \)

D – SC dipole either control or SC residual dipole (disturbance) [Am²]
B – \( B_{\text{max}} \) absolute value 4.5e-5 [T] Worst case \( T_M \)

Residual magnetisation in the SC due to current loops or ferromagnetic materials in the bus cause a disturbance torque \( T_M \). Residual magnetic dipole ranges from 0.1 Am² to > 20 Am² and is function of spacecraft size and onboard compensation. Small sized uncompensated satellites have dipoles in the order of 1 Am² [Wertz]. Aluminium is a non-ferromagnetic material and when stored the tether coil has no current running through it and will not contribute to a residual dipole of the SC bus. For Delfi-1 D is assumed to be \((1e-3)x_{\text{m}} = 4.57 \text{ Am}^2 \) [Hamann²].

- Gas Release Torque \( T_{\text{gas}} = F_{\text{gas}} (z_{b} - c.m.) \)
- Deployment Torque \( T_{\text{dep}} \)

Absolute Pointing Error

For defining the absolute pointing error (APE) a body related reference frame is required, the SC Body Reference (B) coinciding with the Orbital Reference (OR) frame in this thesis work are used. The origins of both the OR and B reference frames are always situated at the instantaneous centre of mass [SLR 114], both for boom extended and retracted modes. Modelling the system as a rigid dumbbell rotating about its c.m., the APE for the system as a whole is calculated with respect to rotations about the systems c.m. With the tether deployed the systems c.m. is shifted a maximum of 135 m below the SC body and 47 m with respect to the \( z_{\text{OR}} \) axis for a 2500 m tether. The effect on the orientation of the \( z_{\text{OR}} \) axis used for defining the APE over this distance is negligible and APE at the systems c.m. is assumed to be similar to the APE at the spacecraft body. An attitude error requirement about the \( z_{\text{OR}} \) axis will restrict the pitch and roll angles \( \theta_b \phi_b \) of the spacecraft body. This analysis is performed in the \( z_{\text{a}} x_{\text{a}} \) plane of the orbit with only the pitch motions are taken into account. With the main disturbances occurring in this plane and the symmetry of the system this seems sufficient for initial design analysis. One should note that the gravity gradient torque differs for the out of plane motion [appendix 8] and the system is subject to out of plane forces such as the Lorentz force \( F_{\text{LOOP}} \). Using (3-10) the static equilibrium angle of the system is calculated as

\[ \theta_{\text{seq}} = \frac{1}{2} \sin^{-1} \left( \frac{T_{\text{DIST}}}{T_{\text{GG}}(45°)} \right) \]  
(3-16)

Table 3.7: Disturbance - Restoring torque ratio \( L_1 - 1000 \text{ m w} - 30 \text{ mm m}_{\text{b}} - 0.83 \text{ kg} \theta_1 - 0 ^\circ \)

<table>
<thead>
<tr>
<th>30% enforced EDT</th>
<th>650 km</th>
<th>850 km</th>
<th>1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{\text{DIST MAX}} )</td>
<td>2.62E-01</td>
<td>1.10E-01</td>
<td>8.65E-02</td>
</tr>
<tr>
<td>( T_{\text{DIST MIN}} )</td>
<td>1.74E-02</td>
<td>8.87E-03</td>
<td>4.20E-03</td>
</tr>
<tr>
<td>( T_{\text{GG/45 MAX}} )</td>
<td>2.093</td>
<td>1.924</td>
<td>1.847</td>
</tr>
<tr>
<td>( T_{\text{DIST MAX}} / T_{\text{GG/45 MAX}} )</td>
<td>0.13</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>( \theta_{\text{seq MAX}} )</td>
<td>3.59°</td>
<td>1.63°</td>
<td>1.34°</td>
</tr>
<tr>
<td>( T_{\text{DIST MIN}} / T_{\text{GG/45 MAX}} )</td>
<td>8.29E-03</td>
<td>5.78E-03</td>
<td>2.27E-03</td>
</tr>
<tr>
<td>( \theta_{\text{seq MIN}} )</td>
<td>0.24°</td>
<td>0.17°</td>
<td>0.07°</td>
</tr>
<tr>
<td>required APE</td>
<td>4.88°</td>
<td>4.88°</td>
<td>4.89°</td>
</tr>
<tr>
<td>( T_{\text{GG/51}} / T_{\text{DIST MAX}} )</td>
<td>1.4</td>
<td>3.0</td>
<td>3.6</td>
</tr>
</tbody>
</table>

APE 3APE 3APE
In figure 3.4 all torques are summarised for the orbit range. Table 3.7 shows the total disturbance torque, stability torque and the system's steady state angle for three altitudes. Up to an altitude of 720 km the aerodynamic torque is dominant, at higher altitudes the solar radiation pressure torque is the most significant disturbance torque. Results are obtained using the Tether Design tool.

![Figure 3.4: Torques on the system L - 1000 m w - 30 mm m_b - 0.83 kg θ_t - 0°](image)

The gravity gradient torque exceeds the maximum disturbance torque for each altitude with the system at an angle of 5° to the z_{OR} axis shown in figure 3.5. Static torque balance shows that for worst case disturbance torques generated by a 1000 m tether at a 0° angle from the z_{OR} the system is able to meet the absolute pointing requirement of 5° also shown in figure 3.5. Above 850 km altitudes the required design margin of three added to the APE is also met for this specific tether configuration.

![Figure 3.5: APE vs. altitude for L - 1000 m w - 30 mm m_b - 0.83 kg θ_t - 0°](image)
**Tether Dimensions \((L_t, w)\) and End Mass \(m_b\)**

**Tether Length:** For a short 250 m tether the APE is met, a 2000 m tether is capable of meeting 3APE above 850 km due to both increased GG torque and decreased disturbance torques effects shown in figure 3.4 and below.

![Figure 3.6: Effect of \(L_t\) on ratio of stabilising and disturbing torques at 650 km](image)

Gravity gradient stabilising torque increases more than disturbance torques with increasing length of the tether.

**Tether width:** 5 mm meets 3APE due to lower disturbance torques acting on the system having a decreased aerodynamic drag and current collection area on the system. An 80 mm wide tether does not meet APE at 650 km and never achieves a 3APE margin, disturbance torques increase \((T_{L_{\text{max}}})\) by almost a factor 10 with GG torque almost not affected by the tether width expect for a slight increase in mass. For a short 250 m tether the width is constrained to \(w \leq 35\) mm for the system to be able to meet the absolute pointing requirement, while a 2000 m tether is still within the attitude requirement of 5° for a 80 mm wide tether [TN.4122.19].

![Figure 3.7: Effect of \(w\) on ratio of stabilising and disturbing torques at 650 km](image)

**End mass \(m_b\):** Without an end mass the tether with \(L_t = 1000\) m and \(w = 30\) mm is not able to achieve the required 5°APE below 850 km. Increasing the ballast mass to 2 kg allows the system to reach 3APE for the entire orbit range with ballast mass having a significant stabilising effect.
Tether Angles $\theta_t$

To determine the attitude of the system with the tether at an angle the centre of mass and moments of inertia are recalculated. The moments of inertia for the system with tether at an angle are determined by modelling the system as 2 point masses, $m_{SC}^* = m_{SC} + m_{GGB} + m_{tp} + \frac{1}{2} m_c$ and $m_b^* = \frac{1}{2} m_c + m_b$ located at $z_{OR} = L_{z} \cos \theta_{t}$ displaced by $dx = L_{z} \sin \theta_{t}$ when the tether is at an in plane (IP) angle $\theta_{t}$.

\[
I_{ab} = m_c^* d_{x,b}^2 + I_b = m_c^* (L_{z} \sin \theta_{t} - x_{cm, \bot})^2 + I_b
\]
\[
I_{cb} = m_b^* d_{z,b}^2 + I_b = m_b^* (L_{z} \cos \theta_{t} - z_{cm, \bot})^2 + I_b
\]

(3-17)

Table 3.8: System c.m. and MoI’s at various tether angles $\theta_t$ [1000 m; 30 mm]

<table>
<thead>
<tr>
<th>$\theta_t$</th>
<th>$x_{cm}$ [m]</th>
<th>$z_{cm}$ [m]</th>
<th>$I_{xx}$ [kgm$^2$]</th>
<th>$I_{yy}$ [kgm$^2$]</th>
<th>$I_{zz}$ [kgm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0</td>
<td>32</td>
<td>1430185</td>
<td>1430185</td>
<td>1.38</td>
</tr>
<tr>
<td>5°</td>
<td>2.9</td>
<td>31.9</td>
<td>1419332</td>
<td>1419332</td>
<td>10489</td>
</tr>
<tr>
<td>20°</td>
<td>11</td>
<td>30</td>
<td>1263049</td>
<td>1263049</td>
<td>161511</td>
</tr>
<tr>
<td>30°</td>
<td>16.4</td>
<td>27.6</td>
<td>1072977</td>
<td>1072977</td>
<td>345172</td>
</tr>
<tr>
<td>45°</td>
<td>23.2</td>
<td>22.4</td>
<td>715705</td>
<td>715705</td>
<td>690343</td>
</tr>
<tr>
<td>60°</td>
<td>28.4</td>
<td>15.6</td>
<td>358311</td>
<td>358311</td>
<td>1035513</td>
</tr>
</tbody>
</table>

Table 3.9: GG stabilisation criteria MoI at various tether angles $\theta_t$ [1000 m; 30 mm]

<table>
<thead>
<tr>
<th>$\theta_t$</th>
<th>$I_x &gt; I_z$</th>
<th>$I_y &lt; I_x + I_z$</th>
<th>$I_y &gt; I_x &gt; I_z$</th>
<th>$I_x &lt; I_y + I_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>STABLE</td>
<td>STABLE</td>
<td>UNSTABLE</td>
<td>STABLE</td>
</tr>
<tr>
<td>20°</td>
<td>STABLE</td>
<td>STABLE</td>
<td>STABLE</td>
<td>STABLE</td>
</tr>
<tr>
<td>30°</td>
<td>STABLE</td>
<td>STABLE</td>
<td>UNSTABLE</td>
<td>UNSTABLE</td>
</tr>
<tr>
<td>45°</td>
<td>UNSTABLE</td>
<td>UNSTABLE</td>
<td>UNSTABLE</td>
<td>STABLE</td>
</tr>
<tr>
<td>46°</td>
<td>UNSTABLE</td>
<td>UNSTABLE</td>
<td>UNSTABLE</td>
<td>UNSTABLE</td>
</tr>
</tbody>
</table>

Figure 3.9: Effect of $\theta_t$ on ratio of stabilising and disturbing torques at 650 km

The effect of an increasing tether libration angle is to increase the absolute pointing error of the system when modelled as a rigid dumbbell as is shown in figure 3.10 due to $\theta_t > \theta_c$, i.e., the $|I_x - I_z|$ term in (3-10) decreases. During the operational phase of the experiment data needs to be transmitted to the ground station requiring the $\pm 5^\circ$ APE to be met. To ensure this tether libration angles are limited to a maximum of $\pm 20^\circ$ from the $z_{OR}$ axis.
Fig. 3.10: APE at various $L_t$ and $\theta_t$ for $w$ - 30 mm $m_b$ - 0.83 kg @ 650 km

REQ-4 APE

The EDT shall allow the Delfi-1 satellite to maintain an absolute pointing error (APE) of $\pm 5^\circ$. To this end tether libration angles $\theta_t, \phi_t$ shall be within $\pm 20^\circ$ from $z_{OR}$ during nominal tether operations as a function of ($L_t, m_b$) for a minimal period of three months.

Gas Discharge Current Enhancement

Depending on orbital environment, tether dimensions, amount of gas released and gas discharge current the bias and current distribution and levels will alter, see section 2.2.4. The torque due to Lorentz force will change accordingly. The system will need to be designed with an additional margin on the $T_{GG(5^\circ)}/T_{DIST}$ ratio to ensure the increase in $F_L$ does not result in loss of the required $\pm 5^\circ$ APE. Gas release will limit the amount of stable configurations reducing tether width and increasing tether ballast mass requirements for configurations in orbits where the system has a low stability ratio. This can be seen for the case shown below, the saturated current distribution for $I_{gas}$ is 50 mA increases the disturbing Lorentz force on the system resulting in loss of APE requirement.

Table 3.10: Saturated current 650 km - 70° orbit 1000 m 30 mm 0.83 kg, $w_{sub}$ - 0%

<table>
<thead>
<tr>
<th>Summation of Torques about C.M.</th>
<th>650 km</th>
<th>$T_{L(max)}$ X13</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{DIST MAX}$</td>
<td>2.68E-01</td>
<td>7.49E-01 N</td>
</tr>
<tr>
<td>$T_{GG(45^\circ) MAX}$</td>
<td>2.12</td>
<td>2.12 N</td>
</tr>
<tr>
<td>$T_{DIST MAX} / T_{GG(45^\circ) MAX}$</td>
<td>0.13</td>
<td>0.35 -</td>
</tr>
<tr>
<td>SSE [°]</td>
<td>3.62</td>
<td>10.16 °</td>
</tr>
<tr>
<td>$T_{GG(5^\circ)}/T_{DIST MAX}$</td>
<td>1.4</td>
<td>0.5 -</td>
</tr>
</tbody>
</table>

 Unsaturated current distribution occurs for the orbits with low plasma density and lower induced $E$ values, these orbits are have significantly lower disturbance torques on the system and although the gas release current increases the torques significantly the system stability does not alter significantly. Even when increasing the torque by a factor 337 for $I_{gas}$ is 50 mA the system is still within the absolute pointing error requirement as can be seen below.

Table 3.11: Unsaturated current 1000 km - 85° orbit 250 m 5 mm 0.83 kg, $w_{sub}$ - 0%

<table>
<thead>
<tr>
<th>Summation of Torques about C.M.</th>
<th>1000 km</th>
<th>$T_{L(max)}$ X337</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{DIST MAX}$</td>
<td>8.42E-04</td>
<td>5.75E-3 N</td>
</tr>
<tr>
<td>$T_{GG(45^\circ) MAX}$</td>
<td>0.08</td>
<td>0.08 N</td>
</tr>
<tr>
<td>$T_{DIST MAX} / T_{GG(45^\circ) MAX}$</td>
<td>0.01</td>
<td>0.07 -</td>
</tr>
<tr>
<td>SSE [°]</td>
<td>0.3</td>
<td>2.07 °</td>
</tr>
<tr>
<td>3APE APE</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$T_{GG(5^\circ)}/T_{DIST MAX}$</td>
<td>16.1</td>
<td>2.36 -</td>
</tr>
</tbody>
</table>
**Other Payload Disturbance Torques**

Short duration torques on the system consist of the $T_{dep}$ due to off axis thrust alignment of the CGT and $T_{gas}$ torque due to gas release at the tether cathode end. Determine the impulsive deployment forces [Ns] and moments [Nms] [REQ-10] and the gas release impulsive forces [Ns] and moments [Nms] [REQ-11] that the system can handle without losing the $\pm 5^\circ$ APE and $\theta_t \leq \pm 20^\circ$.

Using the OPSim simulator a maximum momentum induced by the tether deployment on the spacecraft of $H_{dep} = 0.18$ Nms was obtained with the satellite in eclipse using only gravity gradient stabilisation and taking aerodynamic and magnetic disturbance torques into consideration [Heijning]. This allows the tether and bus [TBC 5] to maintain a maximum angle of 30° from the $z_{OR}$. For the EDT deployment system the requirements derived by [Heijning] are:

**Disturbance Momentum [REQ.4122.TDS.72]**
The TES shall not exert a disturbance momentum on the satellite more than 0.18 [Nms]

**Disturbance Impulse [REQ.4122.TDS.73]**
The TDS shall not induce a disturbance impulse on the satellite of more than 50 [Ns]

Re-evaluation of the maximum deployment disturbance impulse and momentum allowing the system to maintain a $\pm 5^\circ$ APE with a margin of three is required by performing tether deployment dynamic analysis to determine the allowable deployment angle of the end mass. The allowable angular rates of the end mass, the tip off rates [TBD 37], are constrained by the tether coming into contact with the end mass and potentially wrapping around the end body of the tether and by the no slack requirement [REQ-12].

**Gas Release Torque** $T_{gas}$
The gas release torque $T_{gas}$ at 650 km (worst case for system stability) is a function of end mass location relative to the c.m., tether length and angle, end mass $m_b$, tether width $w$ and gas release direction. The gas release cathode can be designed to deploy the gas in such a way that disturbances on the system are minimised however a margin of error due to unknown tether angles and librations is required.

REQ-11 **Gas Release Disturbance Torque**
Gas Release Torque $T_{gas} < [TBD 43]$ to maintain a $\pm 5^\circ$ APE [TBC 53]

Determination of the allowable gas release impulsive force and momentum on the tether-satellite system requires a dynamical analysis determining the allowable torques on the system for the short duration disturbance of gas release.

### 3.3 Tether Operational & Deployment Dynamics

The tether librations need to remain within operational limits of to ensure a measurable deorbit performance and tether integrity for the duration of the experiment and enabling the Delfi-1 satellite to meet the APE requirement of $\pm 5^\circ$. In the previous section a fixed connection between the rigid tether and SC was assumed for static equilibrium calculations. In reality the tether has a rotation point at the tether suspension point allowing the tether to liberate relative to the SC and the tether is flexible. Because of this the tether will experience a range of dynamic motions in orbit changing the tethers orientation to the magnetic field and its performance. This induces internal forces in the tether material and affects the systems attitude dynamics. The equilibrium of the system and the corresponding libration angles change continuously with time due to variations in ionospheric plasma density and magnetic field strength therefore the equilibrium cannot be described statically [Corsi]. The resulting tether oscillations modes are [Beletsky]

- Pendulum in plane librations (1) and out of plane librations (2) (rigid tether assumption)
- Longitudinal oscillation (compression and stretching of the tether) (3) (instabilities)
- Skip rope (circular) oscillations (4) (current sensitive)
- Transverse wave oscillations (5) (instabilities)

Analysis performed by [Kruijff] has shown that of all the tether oscillations the pendulum motion imposes the most stringent constraints on the design for long term stability of a bare passive tether.
In appendix 8 the equations of motion are derived using Lagrange equations. Assuming a straight and rigid massless tether having an equivalent end mass \( m_2 = \frac{1}{2}m_t + m_b \), the resulting equations of motion describing the pendulum librations of the tether (1,2). The linearised unperturbed equations of motion for the gravity gradient stabilised (rigid) tether can be expressed in two uncoupled modes of libration in plane and out of plane. The in plane librations (1) caused by variations in the disturbing drag force have a period of \( \omega_0 = \sqrt{3}\omega_o \) with \( \omega_o \) the orbital frequency. The inclination of the EDT with the magnetic field resulting in \( F_{\text{LOOP}} \) combined with the out of plane \( F_{\text{ad}} \) components will cause out of plane librations (2) of the tether. The out of plane librations have a period of \( 2\omega_o = 2\omega_o \).

\[
\begin{align*}
\ddot{\theta} + 3\theta &= 0 \\
\dot{\phi} + 4\phi &= 0
\end{align*}
\quad (3-18)
\]

An EDT is considered to be unstable predominantly due to resonance phenomena occurring in the out of plane motion with magnetic field components having frequencies close to \( 2\omega_o \) causing out of plane librations to grow resulting in large librations. Transverse wave excitations as a result of out of plane forces occurring due to the inclination of magnetic field, magnetic dipole offset and ionospheric irregularities cause transverse wave instabilities [Kruijff]. Non-linear mode coupling between in and out of plane librations, see equation (A8-9), results in energy being transferred to the in plane libration eventually leading to
- Large libration angles
- Loss of tether tension (slack tether) and resulting tether jerk
- Flip over of the satellite due to large amplitudes of the librations resulting in tumbling

**Tether Jerk**

When tether slack occurs the system goes into a free unconstrained motion of the tether within a sphere of a radius \( r < L_t \) and is in an unstable equilibrium. The free motion consists of horizontal drift with oscillations having the orbital period. When the motion returns the end mass to a radius of \( r = L_t \) the tether tension comes back abruptly in a so called tether jerk motion absorbing a portion of energy. The velocity \( v \) at which the sub satellite reaches \( r = L_t \) must be limited so the peak tension at tether jerk does not exceed the ultimate tether tension at rupture \( T_{\text{ult}} \) [Belitsky].

\[
T_{\text{jerk}} = v \sqrt{\frac{E \left( m_b + \frac{1}{2} m_t \right)}{L_t}}
\quad (3-19)
\]

\[
v < v^* = \sqrt{\frac{3}{\varepsilon_0}} \omega_o L_t \delta,
\quad (3-20)
\]

With

\[
\varepsilon_* = \frac{T_{\text{ult}}}{E/A_t}, \quad \varepsilon_0 = \frac{3 \left( m_b + \frac{1}{2} m_t \right) \omega_o^2 L_t}{E/A_t}
\]

\( A_t \) – cross sectional area tether \( [m^2] \)
\( T_{\text{ult}} \) – ultimate tension \( [N] \)
\( T_{\text{jerk}} \) – tension jerk \( [N] \)
\( v \) – tether velocity \( [m/s] \)
\( v^* \) – tether velocity at rupture \( [m/s] \)
\( \varepsilon_* \) – strain at rupture \([-]\)
\( \varepsilon_0 \) – strain at vertical equilibrium \([-]\)
\( E \) – longitudinal stiffness \( E = E/A_t \) \( [N] \)
\( E_t \) – tether modulus of elasticity \( [Nm^{-2}] \)
For tether systems $v^*$ is generally in the order of the velocity of the end mass after tether goes slack [Beletsky]. To mitigate the risk of unstable tether motions and tether jerk occurring prevent slack tether motion and design the tether strength with a safety factor (SF) of 3 [Kruijff] to ensure tether can survive some amount of tether jerk occurring.

**REQ-13 SF Operating Tether Strength**

The design strength of the tether will incorporate a SF of 3 for tether jerks

Tension jerk can occur when the tether librations exceeds in plane angles of 60° and out of plane angles of 65° angles according to [Cosmo] for dumbbell librations in a circular orbit or when the tether exceeds 45° as it can go slack at the peak of its librations and the system is rotationally unstable [Hoyt].

**Static Stability**

The disturbing torques acting on the EDT displace the tether from the $z_{QR}$ until the gravity gradient torque is sufficiently large to balance the disturbing torque. The dynamical behaviour of the tether depends on the ratio of the disturbing torque and the restoring gravity gradient torque similar to the torque balance of the entire system in the previous section. For this analysis the system is reduced to three point masses $m_1=m_{SC}+m_{GGB}+m_{TP}$; $m_b$ and $m_t$. The tether is assumed to liberate about the suspension point $(0,0,0)$; with the c.m. located at $m_1$ and $m_1$; see figure 3.3. For the EDT the Lorentz force and other disturbance forces decrease with increasing tether angle shown in section 2.3 and 3.2. The systems disturbance torque drops, see figure 3.13, this however occurs at a slower rate than the drop in $T_{GG}$ for angles beyond 45°; the system is rotationally unstable and will liberate to larger angles [Hoyt, Beletsky]. Eventually the gravitationally unstable system will return to a stable configuration, this however can be either with the tether oriented to the nadir or the zenith. Simplictic control of tether dynamics can be achieved by having the tether tension $T$ due to the gravity gradient force larger than the maximum drag force acting on the EDT [Gilchrist, Beletsky]. Tether librations shall be limited to ±20° for a period of three months the design including a margin of 3 to compensate for simplified model [Hamann], this requirement ensures the system also meets the slack and tumbling requirements mentioned above.

**REQ-14 Tether Librations and TET-EM Stability Ratio**

- $\theta_{\text{max}} < 20° - \omega_p$
- $T_{GG}(20°)/T_{DIST \, \text{max}} > 3$

The orbit of 650 km - 110° has the highest disturbance forces and torques acting on the system and is used for stability analysis of the tether. The ballast mass $m_b$ is assumed to have negligible affect on the disturbance torques. With maximum angles $T_{GG}$ at 20° the stability ratio is calculated for 3 separate cases

- case 1 $F_L$, $F_{ad}$ and $F_S$ acting on the tether
- case 2 $I_{gas}$ for saturated current case 1000 m 30 mm tether in a 650 km 70° orbit
- case 3 $I_{gas}$ for unsaturated current 250 m 5 mm tether in a 1000 km 85° orbit

![Figure 3.11: Effect of $w$ and $m_b$ on ratio of stabilising and disturbing torques at 650 km](image)

```plaintext
<table>
<thead>
<tr>
<th>Tether Width w [mm]</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGG(20°)/TDIST max</td>
<td>8</td>
<td>7.5</td>
<td>7</td>
<td>6.5</td>
<td>6.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ballast Mass $m_b$ [kg]</th>
<th>0.0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGG(20°)/TDIST max</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>
```

Figure 3.11: Effect of $w$ and $m_b$ on ratio of stabilising and disturbing torques at 650 km
As can be seen in figure 3.11 results for case 1 show similar trends when varying tether dimensions as in section 3.2. Larger tether width’s increase the disturbance torques on the system and a larger ballast mass increases the stability ratio of the tether and end mass system. When using a wider tether for increased current collection area larger disturbance torques occur that can be stabilised by adding more ballast mass. General rule is higher power systems increase mass and volume of the experiment.

A ballast mass is required for static equilibrium for a number of configurations to be able to achieve the stability ratio $T_{GG(20)}/T_{DIST} > 3$. When increasing the tether length initially longer tethers have a slightly higher stability ratio with the gravity gradient force exceeding the increase in disturbance forces. Tethers longer than 1500 m-1750 m show a slight drop in stability ratio, disturbance torques increase and restoring torques decrease relatively to each other in the model used, this is shown in figure 3.12.

![Figure 3.12: Effect of $L_t$ on ratio of stabilising and disturbing torques at 650 km](image)

**Gas Release Current Increase Case 2-3**

The 1000 m-30 mm tether with 0.83 kg end mass can sustain a gas current $I_{gas} = 50$ mA for the saturated current distribution resulting in a 11.2° tether angle.

<table>
<thead>
<tr>
<th>Summation of Torques about C.M @SC</th>
<th>650 km</th>
<th>$T_{L\text{(max)}}$ X11</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{DIST\text{MAX}}$</td>
<td>2.83E-01</td>
<td>7.72E-01</td>
</tr>
<tr>
<td>$T_{GG(45)\text{MAX}}$</td>
<td>1.98</td>
<td>1.98</td>
</tr>
<tr>
<td>$T_{DIST\text{MAX}}/T_{GG(45)\text{MAX}}$</td>
<td>0.14</td>
<td>0.39</td>
</tr>
<tr>
<td>$\theta_t$ 1°</td>
<td>4.10</td>
<td>11.24</td>
</tr>
<tr>
<td>$T_{GG(20)}/T_{DIST\text{MAX}}$</td>
<td>4.5</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Table 3.12: Saturated current 650 km - 70°orbit 10 00 m 30 mm; $m_b$ 0.83 kg $w_{sub}$ - 30%

<table>
<thead>
<tr>
<th>Summation of Torques about C.M. @SC</th>
<th>1000 km</th>
<th>$T_{L\text{(max)}}$ X337</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{DIST\text{MAX}}$</td>
<td>8.77E-04</td>
<td>6.31E-03</td>
</tr>
<tr>
<td>$T_{GG(45)\text{MAX}}$</td>
<td>7.85E-02</td>
<td>7.85E-03</td>
</tr>
<tr>
<td>$T_{DIST\text{MAX}}/T_{GG(45)\text{MAX}}$</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>$\theta_t$ 1°</td>
<td>0.32</td>
<td>2.3</td>
</tr>
<tr>
<td>$T_{GG(20)}/T_{DIST\text{MAX}}$</td>
<td>66.5</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Table 3.13: Unsaturated current 1000 km - 85°orbit 250 m 5 mm; $m_b$ 0.83 kg $w_{sub}$ - 30%

For an unsaturated current distribution the system is already at lower disturbance torques due to the environment and the smaller length and width of the tether, the tether stability ratio is significantly larger and the tether can maintain the required 20° angle to the nadir with ease shown in table 3.13.
Stable Configurations

Operating the tether at small angles from the \( z_{OF} \) maximises the Lorentz force generated by the EDT as seen in figure 2.15 and when looking at the system as a whole using the rigid dumbbell approximation used in section 3.2 the entire system is more stable for small tether angles. When looking at the motion of the tether relative to the spacecraft however for a 1000 m-30 mm tether the maximum disturbance torque exceeds the gravity gradient torque acting on the tether for angles above 5° as can be seen in figure 3.13. Operating the tether at an angle with respect to the vertical leads to a more stable configuration as \( \theta > \theta_{T} \) and \( T_{GG} > T_{\text{dist}} \) as shown in below for a 1000 m 30 mm tether with \( m_{b} = 0.83 \) kg for \( F_{L} \) and \( F_{ad} \) disturbance forces acting on the tether.

\[
T_{\text{GG}} \quad T_{\text{DIST max}}
\]

Figure 3.13: \( T_{GG} \) and \( T_{DIST} \) as a function of \( \theta_t \)

The tether in drag mode will tend to liberate behind the Delfi-1 satellite when deployed to the nadir. The drag mode has two operational equilibrium configurations for downward and upward deployed tethers providing the current does not exceed the first critical current \( I_{\text{crit}} \) when only considering Lorentz disturbance forces [Beletsky].

Assuming a small tether length compared to geocentric radius and ignoring tether elasticity the first critical current is calculated with the c.m. located at the main satellite as [Beletsky]

\[
I_{\text{crit}} = \frac{3 \omega^2}{B} \left( m_{b} + \frac{1}{2} m_{1} \right)
\]

\( I_{\text{crit}} \) – first critical current [A]

Electrodynamic equilibrium position of the tether is achievable when

1. \( I_{\text{OMLmax}} < I_{\text{crit}} \) [REQ-15]

Aerodynamic drag effects will also tend to push the tether to a stable configuration dragging behind the SC above or below the orbital plane [Beletsky]. The tether will remain at an equilibrium point below the orbital plane when deployed downwards as the maximum ballistic coefficient for an EDT of \( L_{t} = 2500 \) m w-80 mm tether is 32.8 m²/kg being well below the theoretical 100 m²/kg required to push it upwards [Beletsky].
Inclined equilibria for the aerodynamic drag on a tether exist for a massless tether approximation, taking into consideration the high ballistic coefficient of the tether the criteria for aerodynamic equilibrium are achievable when [Beletsky]

\[ E_A > 3(m_b + 0.5m_t)\omega \ell L_t \]  
\[ F_{ad} < 3(m_b + 0.5m_t)\omega ^2 r^* \] for 1-2  
\[ F_{ad} > 3(m_b + 0.5m_t)\omega ^2 r^* \] for 3

\( r^* \) \( \) strained tether length in equilibrium position [m]

\[ k = \frac{E}{(m_b + 0.5m_t)\omega ^2 L_t} = \frac{E_A}{(m_b + 0.5m_t)\omega ^2 L_t} \]  

\( k \) \( \) 0 tether goes slack

\( k > 3 \) tether in vicinity inclined equilibria

For a 2500 m-80 mm tether the worst case disturbance orbit of 650 km with highest current levels shows the above equilibrium requirements are met.

Table 3.14: Equilibria for worst case disturbance orbit 650 km

| Tether 2500 m - 80 mm -15 \( \mu \)m \( m_b \) 0.83 kg |  |
|---|---|---|
| I_{catal} | 0.129 | A |
| I_{crit} | 0.51 | A |
| 1 | YES |  |
| E | 84000 | N |
| T | 0.0439 | N |
| F_{ad,max} | 2.2e-03 | N |
| r^* | 2500.0002 m |  |
| 2 | YES |  |
| 3 | YES |  |

With the tether capable of achieving equilibrium positions it still needs to be determined if the configuration is dynamically stable. The eventual instability of the electrodynamic tethers is known to happen for tethers operating at constant current levels [Beletsky; Corsi]. The EDT current levels are significantly lower than most deorbiting EDT systems. With the system self adjusting to variations in ionospheric density fluctuations (see 0.) the system is potentially more stable [TBC 6] than constant current tethers. For higher inclinations the out of plane (OOP) force component increases, the current however drops at higher inclinations so the largest instabilities are expected to occur at medium inclinations 70° & 110°. The stability of the tether is one of the design drivers for the tether length, width and the ballast mass. Reducing the current in the tether will avoid tumbling and increase the time frame in which instabilities will occur. As the EDT is a passive low current tether not designed for fast deorbit of the SC it is conceivable that for this design the inherent destabilisation of electrodynamic tethers is a relatively slow process [Hoyt \(^2\)]. Ensuring sufficient long term stability of the EDT will have to be achieved using passive stabilisation by design, dimensions, limitation of current and increase of system mass. Some effects of the design and configuration are shown to have favourable effects on the long term stability of a passive bare tether system by [Kruijff]

- Design the tether with a part mechanical tether increasing \( T_{GG} \) without increasing \( T_{DIST} \) being more mass effective than increasing the ballast mass \( m_b \)
- Longer tether length is more stable
- Coating the bare tether for optical properties \( \alpha/\varepsilon \) - 1 with both \( \alpha \) and \( \varepsilon \) << increased the long term stability. Limitations on how low \( \alpha \) (absorption) and \( \varepsilon \) (emission) can be taken due to surface degradation in orbit affecting the equilibrium temperature of the tether
- Low stiffness/viscosity ratios of the tethers were shown to have a significant effect on stability. Increase in temperature decreases \( E_Ac \) and vice versa and large variations of \( E_Ac \) have been shown to occur at low tensions [Tomlin]. \( E_Ac \) is dependant on the load history and temperature of the tether so hard to control in reality
• Minimise the disturbance torque arm (deployment direction), already the case for nadir deployment of EDT.
• Maximise the gravity gradient torque by increasing system mass, \(m_b\) or \(m_b + m_t\). For long term stability in the libration modes for a bare passive tether \([\text{Kruijff}]\) suggests a factor 1 between \(F_{GG(TET)}\) and \(F_{DIST}\) torques and the ballast mass \(m_b\) is a factor 4 of the tether mass \(m_t\) , \(\mu = \frac{m_t}{m_b} - 0.25\)

**Recommendation REC-1 Long term Libration Stability [TBC 7]**

\[ \mu = \frac{m_t}{m_b} - 0.25 \]

\[ \varepsilon_{stab} = \frac{B_{avg} k_{avg}}{m_b \omega_b^2} = \frac{F_{DIST}}{m_b \omega_b^2} \]

\(\mu\) – tether – ballast mass ratio [·]

\(\varepsilon_{stab}\) – disturbance – stabilising torque ratio [·]

Dynamic stability analysis is required taking into account the librations of the tether and possibly all the tether oscillations and the in orbit variations of magnetic field, ionospheric plasma and librations, this is beyond the extent of this feasibility study and requires further research at a later stage.

**Deployment Dynamics**

The most critical phase for the experiment is the deployment. No slack is allowed in the tether during deployment \([\text{REQ-12}]\); a slack tether deviates from the tether equations of motion and describes a free motion. Worst case this free sub satellite motion results in a tether jerk that can rupture the tether. The ±5° absolute pointing error also needs to be maintained by the system. If the initial deployment tension is low enough the system can be deployed passively using an initial separation force (spring) \([\text{Carroll}]\). Maximum tip off rates \(\text{s}^{-1}\) \([\text{TBD 37}]\) need to be determined ensuring the tether does not entangle with the bus \([\text{Koss}]\). The resulting 3 phases of deployment are

1. Provide initial impulse to start separation
2. Distance is large enough to let the gravity gradient force continue separation
3. Brake or damp out energy at end of deployment

The deployment is initiated using a force \(F_{dep}\) acting in \(+z_{OR}\) direction, once the two masses are separated by a small distance the gravity gradient forces ensure that they will continue to separate making deployment an inherently stable operation. To allow tether deployment the systems friction needs to be overcome using a large enough ejection force if a passive deployment method is used. Initial deployment velocity required depends on inertia of the tether storage reel, friction of the rotating system and tether and the desired end speed of the ballast mass. If the initial deployment speed is too large the tension in the tether will become too large and the tether will have to be over-dimensioned. Too small initial velocity results in no full deployment of the tether. The goal is to minimise the rebounding of the tether at the end of the deployment, this is done by minimising the energy of the system when tether reaches its fully deployed length. Deployment can be performed using an open loop control system (passive) due to the inherent stability of tether deployment with the system being a damped for \(\frac{i}{l} > 0\) motion, for tether retraction the systems vibrations are amplified \([\text{Pascal}]\) as can be seen the in the following reduced set of differential equations \([\text{appendix 8}]\) for in plane motion during deployment when neglecting out of plane disturbance forces.

\[ \dot{\theta} + 2\left(\frac{I_{rot}}{m_i} \dot{\theta} - \omega_o \right) + \frac{3}{2} \omega_o^2 \sin 2\theta = \frac{Q}{m_i l^2} \]

\[ \dot{l} - (\omega_o^2 l^2 + \omega_o^2 l (1 - 3 \cos^2 \theta)) = \frac{Q}{m_z} = \frac{T}{m_z} \]

\(Q\) – generalised force or moment [N; Nm \(^2\)]
Assuming in plane angle and angular rates are negligible and no external forces are acting on the tether during short duration deployment the in plane motion of the deployment is

\[ \dot{\theta} + 2 \frac{j}{l} \omega_o + 3 \alpha \dot{\theta} = 0 \tag{3-25} \]

If \( l(t) \) is relatively fast and tether length \( l(t) \) is small the tether system will pitch backward and tumble, initial deployment speeds need to be sufficiently small to limit the coriolis term in equation (3-25) avoiding the system from tumbling [Zedd].

If in the end configuration the tether needs to be vertically stabilised energy dissipation during or after the deployment is necessary. The required end librations of the tether after deployment determines the amount of braking during deployment, energy that is not dissipated will end up in the in-plane libration motion of the tether or break the tether. The amount of energy to be dissipated \( E_{\text{diss}} \), discounting the friction in the system, has to be equal or larger than [Carroll]

\[ E_{\text{diss}} \geq \frac{1}{2} L_i T = \frac{3 \omega_o^2}{2} \left( m_e + \frac{1}{2} m_i \right) L_i^2 \tag{3-26} \]

For a 2500 m 80 mm wide tether with ballast mass of 0.83 kg 164 J of energy needs to be dissipated during deployment by the deployment system and the tether. The minimum time for deployment is related to the maximum allowable tether deviation from the vertical. A minimum time is required to allow the gravitational moment to bring the tether system into rotation at the orbital rate \( \omega_o \) [Beletsky], an estimation is \( \omega_o t > 2/3 \) being approximately 1/9 of the orbital period.

**REQ-19 Minimum Deployment Time** \( t_{\text{dep}} \)

\( t_{\text{dep}} > 651 \) [s] [TBC 8]

To assure tether integrity after deployment the maximum allowable end mass (EM) velocity \( v_{\text{EM, max}} \) needs to result in a peak tension level (jerk) smaller than the ultimate load of the tether at the end of deployment. Assuming that the aluminium substrate is the load carrier the maximum end mass velocity is calculated as [Beletsky]

\[ v_{\text{EM, max}} = T_{\text{ult}} \sqrt{\frac{L_i}{E_i A_i \left( m_e + \frac{1}{2} m_i \right)}} \tag{3-27} \]

A safety margin of 3 is added to the operating design strength of the tether to reduce the impact of tension jerks occurring during (low speed) deployment [Kruijff].
4 MEASUREMENT APPROACH

A measurement approach to obtain the experiment data required for achieving the scientific objectives of the EDT experiment is derived using the EDT performance characteristics obtained in the previous chapter and an overview of instrumentation and measurements performed on previous tether missions [Wijnans5b]. The measurement objectives are listed in section 4.1 followed by a discussion of optional measurement methods in section 4.2. In section 4.3 the instruments to be added as part of the EDT experiment onboard of Delfi-1 are selected and the amount of telemetry data produced and the power usage are estimated.

4.1 Measurement Objectives

The primary scientific objectives of the EDT experiment are

<table>
<thead>
<tr>
<th>REQ</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-20</td>
<td>Bare EDT</td>
</tr>
<tr>
<td>REQ-21</td>
<td>Tape EDT</td>
</tr>
</tbody>
</table>

Secondary objective is [TBC 9]

<table>
<thead>
<tr>
<th>REQ</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-22</td>
<td>Gas cathode</td>
</tr>
</tbody>
</table>

The functional breakdown of the EDT experiment from the first part of this study gives four distinct in flight experiment data sets during each phase of the experiment, storage, deployment, operational phase I and operational phase II with the gas cathode activated. A minimum experiment duration of two weeks [TBC 11] in which measurable effects are to be achieved by the tether has been set in part I of this study. Tether nominal operations are expected to be achievable during this period and by limiting this time also the risk of an untimely cut (rupture) of the tether similar to SEDS-2 can be minimised.

Storage Phase: Experiment Data Set 1

The objective in this phase is to collect data on the systems deorbit rate, attitude angles and accelerations to be used as a reference baseline measurement of the system without the EDT deployed. When the tether is stored the satellite is subject to aerodynamic forces and solar radiation pressure. These forces lead to slight changes in semi major axis and eccentricity. The satellite has a small ballistic coefficient compared to the tape tether and is subsequently less susceptible to both forces than with the tether deployed. Using equation (2-23) the aerodynamic drag force on the satellite can be determined by measuring variations in orbital period, satellite velocity or semi major axis. Largest uncertainties are in the drag coefficient \( C_D \) and atmospheric density \( \rho \). The effect of aerodynamic drag has been estimated for the 9 months of operation of the Delfi-1 prior to EDT deployment in appendix 10; table a10- 1. Results were derived assuming atmospheric density as a constant. For low altitudes (750 km and less) the change in orbital period is in the order of seconds and the SMA varies from 0.25 km to 0.82 km for average aerodynamic drag. For higher altitudes the effect of aerodynamic drag is reduced. Accelerations on the satellite range from 4e-10 ms\(^{-2}\) to 1e-7 ms\(^{-2}\) depending on atmospheric density and relative velocities of the satellite to the atmosphere.

Deployment Phase: Experiment Data Set 2

Goal is to determine the length of tether successfully deployed and the deployment profile. Tether deployed length, velocity and tension are measurements required to determine the deployment profile and verify the velocity of the tether at ejection point \( (v_{dep}) \) is the same as the velocity at the end mass \( (v_{EM}) \) verifying the no slack condition during deployment [Heijning]. Measuring tether tension during deployment has been done on previous tether missions. Required measurements during tether deployment are derived from [Heijning] as

- Deployed length \( L_{dep}[0 \text{ m} – 2500 \text{ m}] \)
- Deployment velocity of tether \( v_{dep}[0 \text{ m/s}^{-1} – 3/5 \text{ m/s}^{-1}] \)
- Deployment tension \( T_{dep}[0 \text{ N} – 5 \text{ N}] \)
Operational Phase Part I: Experiment Data Set 3

The goals for this phase are to determine if the bare tether can

1. Induce a bias with respect to the surrounding plasma potential
2. Generate a current without the use of separate anode (or cathode)
3. Produce a Lorentz force acting (on average) in opposite direction of the satellites velocity
   - Deorbit rate \([da/dt]\]
   - Tether and system attitude dynamics and librations

It is important is to distinguish between the effects of Lorentz forces and other secondary (drag) forces determining effects of \(F_\text{L}\) with a sufficiently high signal to noise ratio to prove the bare tether propulsion concept. With the aerodynamic drag having similar effects on the deorbit rate of the system a method of filtering the data is required, for example by looking at the force excitation frequencies and modulation of the measured signals. The tether and satellite oscillation frequencies can be derived from onboard accelerometer data using Fourier transforms [Kruijff]. Solar Radiation pressure can be estimated using solar panel performance data from the Delfi-1 power system.

The drag force of the tether on the system will have the largest effect on the semi-major axis and orbital velocity. These can be derived from the satellites ephemeris data giving position and velocity as a function of time. Using the tether dimension range of \(L - 250\) m, \(w - 5\) mm and \(L - 2500\) m, \(w-80\) mm the minimum expected deorbit performance is calculated for the 1000 km, 85° orbit. The results are shown below.

<table>
<thead>
<tr>
<th>Time between measurements</th>
<th>(\Delta\text{SMA range [m]})</th>
<th>(\Delta V \text{ range [ms}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Station contact</td>
<td>Average 247 min [slr112]</td>
<td>0 – 190</td>
</tr>
<tr>
<td>Per orbit P_{orb}</td>
<td>97 -105 min</td>
<td>0 – 75</td>
</tr>
<tr>
<td>Two weeks</td>
<td>14 – 15454</td>
<td>0.007 – 7.7</td>
</tr>
<tr>
<td>3 months</td>
<td>85 – 91833</td>
<td>0.04 – 46</td>
</tr>
</tbody>
</table>

With the amount of deployed tether length and mass distribution of the system known the tether tension at suspension point can be used to determine tether dynamics and angles, giving an indication if the tether is within nominal operation range and possibly estimations for current levels aiding in distinguishing between aerodynamic and Lorentz forces. As shown in appendix 8 in equation (A8-10) the tension in the tether is a function of the in plane \(\theta_t\) and out of plane angle \(\phi_t\) of the tether. For nadir-zenith oriented (hanging) tethers [Pearson] determined that EMF variations will give an indication of the out-of-plane dynamics, with the \(2\omega_o = 2932\) s period of the OOP libration also seen in the induced EMF and the resulting tether bias variations at the suspension as shown below for a 1000 m tether with an end mass of 3 kg.

Figure 4.1: OOP angle, tether bias and EMF variation in orbit [ETBSim results]

When looking at the in-plane dynamics additional measurements of tether accelerations or tension are useful [Pearson], this can be seen in the linearised equations of motion (A8-11) for the tension of the tether with main variable being the in plane angle \(\theta_t\). With the deployed tether length and the mass distribution of the system known the tether tension at suspension point can be used to determine tether accelerations using system librations measured with a 3-axis accelerometer [Zedd]. The ATEx and TSS experiments also used pitch and roll data of the main satellite to complement the tension and acceleration data [Cosmo].
EDT Tension at Suspension

Assuming a uniform tether consisting of 15 µm thick aluminium tether enforced over 25% of the width with a Kapton substrate of 6 µm the tension in the tether is calculated using equations (2-17) and (2-18). Tension jerk due to slack unstable tether motions is not considered to be in the tension measuring range as the tether is already considered unstable and out of its operational range at this point. The resulting accelerations due to tension on the Delfi-1 satellite are shown table 4.2.

Table 4.2: Range tether operating tension at suspension $m_b - 0.83$ [kg]

<table>
<thead>
<tr>
<th>Tether Dimensions</th>
<th>$m_b$ [kg]</th>
<th>$z_{c.m.}$ [m]</th>
<th>$T_{c.m.}$ [N] (2-19)</th>
<th>$a_{sc}$ [g]</th>
<th>$T_{susp}$ [N]</th>
<th>$a_{sc}$ [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 m 5 mm 21 µm</td>
<td>0.053</td>
<td>4</td>
<td>7.39e-4</td>
<td>1.73e-6</td>
<td>6.01e-4</td>
<td>1.41e-6</td>
</tr>
<tr>
<td>1500 m 40 mm 21 µm</td>
<td>2.6</td>
<td>66</td>
<td>1.09e-2</td>
<td>2.55e-5</td>
<td>9.99e-3</td>
<td>2.34e-5</td>
</tr>
<tr>
<td>2500 m 80 mm 21 µm</td>
<td>8.5</td>
<td>240</td>
<td>4.39e-2</td>
<td>1.03e-4</td>
<td>3.60e-2</td>
<td>8.43e-5</td>
</tr>
</tbody>
</table>

System Attitude Dynamics

Attitude angles and angular rates of the Delfi-1 bus during operation can be obtained from the ADCS system. As the tether is designed to allow the bus to maintain a ±5° APE effects of the EDT on the SC attitude are minimal. The maximum equilibrium angle of the system for steady state torque balance increases by 0.8° to 1.06° due to tether deployment of a $L_t - 1500$ m w - 40 mm $m_b - 0.83$ kg EDT system [TN.4122.19] it has to be determined if this is measurable by the onboard ADCS [TBD 19]. As the attitude angles of the system have been derived for the static torque balance extremes dynamic attitude analysis of tether and satellite system in orbit is required to give a better indication of the systems angles and if the ADCS system of Delfi-1 will measure effects of the tether when deployed.

Operational Phase Part II: Experiment Data Set 4

The same measurements are performed as in phase I with the gas cathode activated, taking an increase of the sampling rate by a factor 5 [REQ-23] [TBC 10] into consideration during this phase. The current and bias distribution will alter depending on the amount of gas released and the degree of ionisation of the gas Priority measurements are the GPS with Lorentz drag force increasing by a factor 10-100 depending on current levels occurring and the tether bias giving a direct indication of $I_{gas}$ effect. Also tether tension, attitude of the satellite can show effects of higher currents in the tether.

EDT Experiment Measurements Overview

Based on the previous chapters and this section an overview of the parameters that can be measured is shown table 8.1. The expected values for the Delfi-1 orbit range are given including the required resolution. An initial estimate of the measurement frequencies is also given.

4.2 Measurement Methods

In this section options for obtaining the proposed measurements of the previous section are discussed and the attainability of these measurements is determined using data from previous tether experiments and the capabilities of various instruments currently available.

4.2.1 Orbit Determination

Orbit determination is performed by combining observations (tracking data) with a theoretical model (orbit propagation model) giving solutions for the orbital elements and auxiliary parameters describing uncertainties in the model. Due to errors and uncertainties in both the model and the observations ephemeris orbit determination is best applicable over a short period of time. Performance requirements for the orbit determination are based on a minimal two week mission requiring an accuracy of single point position and velocity solutions of 14 m and 7e-2 to 1 ms$^{-1}$ depending on tether performance and dimensions, see table 4.1. Options being considered for determining the orbit of the system are 1) ground based tracking system or 2) onboard orbit determination using GPS [Wijnans$^5$].
Ad 1) The Delfi Doppler Tracking System (DDTS) developed for the Delfi-1 satellite, yields the following minimum prediction accuracies of individual orbit parameters [SLR 84]. These can be considered to be typical for most ground based tracking systems.

Table 4.3: DDTS allowable individual orbit parameter errors [SLR 84]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>±2 km</td>
</tr>
<tr>
<td>RAAN</td>
<td>±2°</td>
</tr>
<tr>
<td>i</td>
<td>±1 arc perigee</td>
</tr>
<tr>
<td>±2°</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>±0.005</td>
</tr>
<tr>
<td>τ</td>
<td>±30 s</td>
</tr>
</tbody>
</table>

The orbital elements propagation model will need to incorporate the amount of aerodynamic drag and Lorentz drag force acting on the system with the EDT deployed, both highly subject to modelling uncertainties initiating errors in the orbit determination. An orbit altitude change of at least 4 km is necessary when using the DDTS to allow for a maximum error in satellite position of ±2 km in two subsequent measurements, a similar order of deorbit is required when using the two line elements tracking data. This limits tether length-width to the heavier systems being considered and reduces the applicable orbit range to low inclination and altitudes where the aerodynamic drag is comparable to Lorentz drag to obtain a measurable amount of deorbit.

Ad 2) Real time orbital position data can be obtained using a GPS receiver combined with an onboard computer eliminating the need for tracking stations and intensive computational orbit determination. Real time navigation data gives information about the deorbit behaviour of the tether-satellite during multiple points in orbit depending on the tether performance and accuracy of the GPS receiver. This can then be coupled to other in orbit variations affecting deorbit performance of the system. The method of real time orbit determination is less subject to modelling errors and uncertainties pertaining to the EDT effect on orbital elements than with method 1. The use of highly accurate orbit determination models is less critical compared to ground station tracking systems [Wertz]. Single frequency receivers use less power compared to dual receivers and can obtain a typical accuracy of 10 m for single point position solutions as shown in table 4.4 for a small GPS receiver [SSTL] which is considered sufficient for the EDT experiment deorbit range. If at a later stage a more precise orbit determination is required it is possible to include a Kalman filter to process the raw GPS data increasing computing power onboard or transmit the raw data to the ground for processing.

Table 4.4: GPS SGR-05U/P accuracy [SSTL-27433]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical (95%)</th>
<th>Max (95%)</th>
<th>SA turned on DoD Typical (95%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Position</td>
<td>10 m</td>
<td>20 m</td>
<td>50 m</td>
</tr>
<tr>
<td>Orbital Velocity</td>
<td>0.15 ms⁻¹</td>
<td>0.25 ms⁻¹</td>
<td>2 ms</td>
</tr>
<tr>
<td>Time</td>
<td>0.5 µs</td>
<td>1 µs</td>
<td>1 µs</td>
</tr>
</tbody>
</table>

An onboard GPS receiver (single frequency) used to determine the orbital position and velocity has a higher accuracy than the DDTS and allows for an increased frequency of orbital position data for use in tether performance models compensating for major uncertainties as to tether performance, aerodynamic drag and solar radiation pressure effect on the orbit.

For a minimum 2 week period in which the experiment has to produce measurable data a GPS receiver is required for most of the tether dimensions and orbit range being considered. The proposed approach for determining the deorbit performance of the EDT experiment is to use an onboard GPS receiver. The obtainable accuracy of a GPS receiver of 10 m to 20 m indicates that a 20 m-40 m change SMA is required to determine deorbit of the system, if selective availability (SA) is turned on the deorbit requirement is increased to 100 m. Taking into account uncertainties in the amount of current collected by the system and the aerodynamic drag force generated by the tether a design margin of a factor 2 [TBC 16] is included on the required deorbit of the system to obtain a measurable deorbit by the GPS receiver a 2 week period of operation.

REQ-20 Bare EDT Demonstration of EDT by a de-boost ΔSMA ≥ 80 – 200 [m] of the Delfi-1 satellite using a passive bare electrodynamic tether during a 2 week operational period
To ensure the deorbit is in part due to the induced Lorentz drag force a minimum amount of $F_L$ is required whereby the ratio $F_L/F_D$ is currently estimated to be at least 50% [TBC 17], see figure 3.2, by tether design. Further study is required into a filtering approach of the GPS orbit data to obtain a proof of concept for the operation of a bare EDT for propulsion.

**REQ-24 Ratio of $F_L$ over $F_D$ [TBC 17]**

$$\frac{F_L}{F_D} \geq 50\%$$

Designing the tether to produce measurable velocity changes is not required, this would result in increased tether dimension requirements compared to the deorbit requirement and have not been used as a system design requirement. If at a later stage velocity changes are required and the GPS receiver accuracy is not sufficient for the tether design performance an accelerometer can be used limiting the mass of the final system or the raw GPS data can be processed on the ground obtaining more accurate velocity solutions [Montebruck]. An option to use the DDTS as a back up system for the 3 month experiment duration requiring at least a deorbit of 4 km constrains the tether dimensions to longer lengths with increased micrometeoroid and orbital debris (M/OD) risks and most likely out of budget and is subsequently added as a wish but not a design requirement for the system. A direct comparison of bus accelerations induced by the tether and compared with accelerations during the EDT storage phase can also be performed using an accelerometer. Due to small forces and acceleration levels of bus and tether a high resolution accelerometer is will be required. Viability of using these additional (backup) systems will be studied at a later stage in the development of both satellite and experiment.

The release of the neutral gas shall ideally sustain a current producing measurable effects on the deorbit rate of the system using the GPS receiver as current cannot be measured of the tether directly with the gas cathode located at the lower end of the tether and no telemetry capabilities between bus and end mass are available in the baseline design description.

**REQ-25 Deorbit Performance Gas Release**

Produce a measurable effect in deorbit by the GPS receiver during gas release of the cathode deorbit of 20 m [TBC 18] during gas release time and subsequently also produce a measurable effect on the bias distribution of the tether.

**REQ-26 GPS Performance and Integration Requirements**

- High dynamic environment ability
  - operational velocity 7531 [m s\(^{-1}\)]
- Accuracy
  - real time position < 20 [m]
  - velocity 0.06 – 1 [m s\(^{-1}\)]
- Single Frequency Receiver
- Time to first fix (TTFF) cold and warm [TBD 21]
- Time offset [TBD 21]
- Number of channels > 4
- Output frequency 1 Hz [TBC 19]
- Output data
  - Position Cartesian ECI
  - Velocity Cartesian ECI [TBC 19]
  - Time signal
  - Raw Data [TBC 19]

Candidate payloads for the Delfi-1 mission consist of a dual GPS receiver and a star sensor GPS fusion experiment [DES.4120.01], at this point it has been decided not to depend on other experimental payloads as primary measurement systems for the EDT experiment also at this stage there is no certainty as to which payloads will fly onboard the same bus so the EDT experiment will initially be designed as a self-sustaining experiment also having flexibility to fly on another platform if required. At a later stage the use of other payload as additional sensors for the EDT experiment can be re-examined when more information is available about the other payloads a risk-benefit evaluation can be performed.
4.2.2 Tether & SC Attitude Dynamics

During the deployment phase determine the deployment profile and during the operational phase give an indication of tether angles by measuring the tension at the suspension point of the tether. The dynamics of the tether-satellite system as a whole can be derived from attitude angles and accelerations of the Delfi-1 satellite.

Tether Deployment Profile

A turncounter and a tension sensor are used to determine the tether deployment profile. Length and velocity during deployment can be derived from counting the number of turns and the turn count rate of the reel, as done onboard the SEDS and ATEx experiments [Cosmo]. The relationship between the amount of deployed tether, exit velocity $v_{dep}$ and number of reel turns needs to be determined during the winding of the reel. This data needs to be compensated for differences in tether temperature and tension during deployment compared to winding conditions [Carroll]. The angular displacement sensor is not part of a feedback loop as initial deployment system design is a passive open loop deployment; the accuracy is determined by the data required on deployment performance. Using the deployment profile [Deployment Profile Determination v1.0] the velocity of the reel was determined for a $L_t - 1000$ m, $w - 30$ mm and $t - 17.5$ $\mu$m thick tether deployed of a 20 mm inner diameter reel. The turn counter can be set up to generate 1, 2 or 4 pulses per turn.

REQ-27 Turn Counter Performance Requirements
- Resolution # counts per turn $1 - 2 - 4$ [TBD 22]
- Rotational speed $21-98$ [RPM] [TBD 22]

REQ-28 Calibration Data Deployed Length

Measure the temperature $T_t$ and tension $T$ of the tether during deployment to calibrate the amount of tether deployed for each turn for deployment conditions required for post processing of the number of turns to tether length deployed.

Tether Tension Measurement

Options for obtaining the tether tension
- Direct application of a (bonded) strain gauge onto the tether at the suspension point limited to operational tensions
- A tension transducer integrated with the deflection roller of the deployment system [Heijning]
- Accelerometer onboard SC measuring accelerations on the SC due to tether tension

A bonded strain gauge on the tether will be critical in integration of the sensor on the tether which is expected to have a large temperature operational range in orbit. The sensor will have to have self-temperature compensation, use a Wheatstone bridge or be calibrated using secondary temperature measurements. Bonded foils have a large contact area for accurate measurements however they have limited operating temperature ranges, low output signals and a limited fatigue life. Bonded semi conductors are also extremely sensitive to temperature but have a better fatigue life [Ekola]. Adhesives have limited temperature ranges, having glass transition temperatures around $-10^\circ$C to $-30^\circ$C [Conely], operational temperatures of the tether can reach $-150^\circ$C [Kruijff]. Temperature variations can also result in a non zero offset of the sensor [Ekola]. Storage of 9 months onboard could potentially degrade the adhesive due to outgassing and temperature variations. Physical integration of a strain gage and measuring the tether tension will have to be tested as to viability of this method for obtaining operational tension loads on the tether. The operational performance requirements for the strain gage are listed in table 8.1.

In the packaging, textile and printing industry a multitude of tension measurement devices are available based on the principle of the wire, tape or foil moving over rollers and using a load cell to measure the tension. This method of measuring tension in the tether was used on the SEDS, ATEx and YES2 missions.
The deployment system designed by [Heijning] uses a (fixed) roller to deflect the tether by 90° in the desired deployment direction with the reel mounted parallel to the nadir panel of the bus shown below. Obtaining tether tension directly of this roller using a tension transducer will allow for a combined system for both deployment and operational tension measurements depending on load cell requirements for each operational phase.

![Figure 4.2: Tether deflection roller [Heijning]](image)

Performance requirements for the tension transducer are shown in table 8.1. Additional requirements are

- Overload capacity 300% allowing up to 15 [N] [TBC 20]
- Fixed idle roller

Measuring the acceleration on the bus combined with the known mass distribution of the system the tension in the tether can be determined as accelerations on the bus will be predominantly due to tether forces, see section 2.3.1. Accelerations on the bus due to tether tension range from 2 µg to 120 µg depending on tether dimensions and ballast mass.

\[
a_w = \frac{T_{\text{sep}}}{m_w + m_{\text{GBL}} + m_{\text{eq}}} \tag{4-1}
\]

Performance requirements for the accelerometer are listed in table 8.1. Standard micro-chip accelerometers have resolutions in the order of µg’s and input ranges of mg, for the shorter tethers with low end mass the tension levels are extremely low and to be measured as accelerations on the bus requires highly sensitive accelerometers suited to measuring onboard vibrations.

Based on ease of integration and allowing simultaneous deployment tension and operational tension measurements these are ideally to be performed by integrating load sensors with the tether deflection roller. Range and resolution requirements for the deployment and operational phase are however of a different magnitude, using one sensor for both sets could limit performance during operational phase. It needs to be determined if the tension transducer can operate at various ranges and resolutions. The tension meter onboard the SEDS experiment was capable of operating at ±0.1 N 1 N and 10 N with resolutions of 0.83 mN, 8.3 mN and 83 mN [Cosmo]. If this is not possible the measurements of tension for each phase need to be performed by separate instruments.

**ADCS Sensors Delfi-1**

SC attitude information can be derived from the ADCS system, piggybacking on the available data. A three axis fluxgate magnetometer has been proposed as primary attitude determination sensor for the Delfi-1 satellite combined with an experimental payload consisting of a nano-sensor package [Kalies; Crichton]. The magnetometer is used to determine Delfi-1’s attitude in space by comparing the measurements with known data of Earth’s magnetic field. A secondary sensor for attitude determination is required to determine the attitude completely [Pisacane²], a solar panel based sun sensor has been proposed for Delfi-1. No data on the accuracy of the attitude determination system is available. The largest component of the noise in the measurements is due to errors in the magnetic field model with errors in the model varying from 0.5° at the equator to 3° at the poles [Wertz]. For this study it has been assumed that the attitude angles can be determined with an accuracy of at least ±1° per axis [TBC 21] in combination with the solar panel based sun sensor (0.005°to 3°). At a later stage research if the experimental nano-sensor package can be activated during the EDT experiment providing additional data on attitude and accelerations of the bus. The nano-sensor package consists of three 3-axis magnetometers, three 2-axis accelerometers and three rate gyroscopes [DES.4120.01].
A 3-axis accelerometer can also be used to determine the satellites oscillation frequencies, their amplitude and phase by the use of Fourier transforms [Kruijff]. It still needs to be determined if for the low tension range of the EDT design configurations the accelerations are measurable.

REQ-29 Pitch and Roll Attitude Angles Delfi-1
The EDT requires access to data from the ADCS system onboard Delfi-1 consisting of the systems attitude angles during storage, deployment and operational phase (and possibly termination phase) of the EDT experiment.

4.2.3 Other Tether Measurements

Tether Bias Measurement
Goal is to determine the bias of the tether with respect to the plasma as this is an indicator of the passive tethers capability to collect current from the ionosphere. Calculating the induced EMF of the tether will have an unknown margin of error as it is not possible to know the exact amount of effective tether length as the shape of the tether (and angles) in orbit will not be known precisely. For the high inclination orbits of the Delfi-1 orbit range the out of plane Lorentz force component can be substantial, see section 2.3.2, affecting the EMF. The induced EMF can be determined in two ways:
1. Direct measurement of the bias at the tether suspension point
2. Calculation using inputs:
   - Magnetic field strength measurements
   - Orbit determination

The bias of the tether at the suspension is a function of orbit, tether angles and length and the location of the zero bias point which varies with the local plasma environment see section 2.1.2 and 0. Comparing the measured voltage of the tether at the suspension with calculated values for the induced EMF will give an indication of current length of the tether (severance, large angles). The bias of tether to the plasma at the anode end of the tether varies from +0.085 V to +5.4 V for EMF extremes and tether lengths 250 m – 1500 m. With the gas cathode activated the bias distribution will alter and can exceed the required 10 V potential differential to the bus. In orbit variations of the induced EMF vary from 10 µV to 10 mV per second.

Tether bias measurement requirements are listed in table 8.1, adding a margin of two during operational phase to take into account any additional charging effects in the auroral and polar region and four for gas cathode operational phase. The required frequency of the measurement depends on the final use for tether dynamics analysis 8 Hz [Cosmo] and possible correlation to the magnetic field data or having a basic knowledge of the bias at tether end 1 Hz.

Tether Temperature
The tether temperature measurement is required for the deployment profile determination from the amount of reel turns counted for calibration purposes. Not considered an essential measurement for tether performance but seen as additional data at a relatively small cost. Temperature sensor requirements are listed in table 8.1.

4.2.4 In Situ Environmental Measurements
The magnetic field strength, direction, plasma density and temperatures are environmental parameters that can be used for estimation of current collection to the EDT in orbit. No direct current measurement can be taken of the tether as due to passive floating operation the current at both ends is zero, see figure 2.5. Combined with bias measurements, deorbit performance and tether tension levels an indication of the amount of collected current can be made. To estimate the effects of solar radiation pressure the solar panel based sun sensor of the ADCS and data from the EPS on solar panel performance can be used giving an indication of solar angles and intensity.

REQ-30 Sun Sensor and EPS data Delfi-1
The EDT requires access to data from the ADCS sun sensor and performance data of the EPS onboard Delfi-1 to derive the solar angle in orbit and estimate the solar intensity during the operational phase (and possibly termination phase) of the EDT experiment.
Magnetic Field Strength and Direction

Magnetic field strength measurement range is ±35 µT and a resolution of in the order of 10 nT [TBC 22], see table 8.1, depending on the rate of change of the magnetic field and the sample rate of the measurement. It is assumed the magnetometer operates at a 10 Hz frequency for attitude determination.

REQ-31 Magnetic Cleanliness [TBC 23]

The DC magnetic field generated onboard the Delfi-1 bus < 20 [nT] at the location of the magnetometers [Cosmo; TSS-S data] or the output data of the magnetometer has to be calibrated for ambient magnetic fields.

Plasma Diagnostics

Plasma diagnostics can be performed using an electrostatic sensor, a Langmuir Probe (LP), as done with the TSS-1R mission and onboard the Astrid-2 satellite [Cosmo; Holback]. An electrode is electrically in contact with the plasma and biased over a range of voltages, the sweep bias. At negative potentials the probe attracts ions from the surrounding plasma; when it is biased at a positive potential, it attracts electrons. A LP can be operated with a fixed bias, LP (n_e), or dynamic voltage sweep; a swept bias, LP (n_e, n_i, T_e, V_p) [Aase]. The current collection of the probe over a sweep bias is measured and the current-voltage (I-V) characteristics of the probe are acquired, this is outlined in more detail in appendix 10. The analysis of the I-V curve characteristics can provide the following plasma parameters [Wijnans^5]

- Plasma density n_e
- Electron temperature T_e
- Plasma potential V_p

This will allow calculation of the Debye length and characteristics of the local plasma environment and subsequently aid in estimating OML current levels. The plasma potential can be used to determine the bias of the tether to the local undisturbed plasma when combined with the tether bias to the satellite ground measurements. LP I-V acquisition is defined below based on [Kruijff] and using the EDT Environment tool [TN.4122.12] describing the ionospheric plasma for the Delfi-1 orbit range.

- Floating voltage of the probe is close to plasma potential being a few \( k_B T_e/e [V] \) negative to plasma potential, with \( \frac{k_B T_e}{e} \approx 0.24 - 0.28 [V] \) for orbit altitudes being considered
- Acquisition of I-V curve should be carried out with a resolution better or of same order than \( k_B T_e/e \) to maintain a good definition of the exponential part of the I-V characteristic used to determine \( T_e \)
- Electron and ion saturation regions are satisfactorily defined if acquisition is carried out with voltage span in the order of 10 [V]

Dynamic requirements need to be derived for all \( v_{orb}, n_o, T_e \) changes, the ionospheric polar and auroral region influences. More research concerning the ionospheric plasma in the auroral and polar regions is required to derive more accurate operational requirements for the LP. As shown in appendix 10 equations (A10-3) to (A10-5) the LP current is a function of the potential difference between plasma and probe. The current levels as a function of altitude and probe radius are given below.

Table 4.5: LP current levels for 650 km and 1000 km orbits

<table>
<thead>
<tr>
<th>r_p [m]</th>
<th>Plasma density n_e [m^-3]</th>
<th>Ion Saturation Region I_e(-25 V) [A]</th>
<th>Transition Region I_e(0 V) [A]</th>
<th>Electron saturation Region I_e(+25 V) [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00E-04</td>
<td>2.50E+11</td>
<td>1.63E-09</td>
<td>1.03E-08</td>
<td>1.08E-06</td>
</tr>
<tr>
<td>5.00E-03</td>
<td>6.00E+10</td>
<td>7.63E-08</td>
<td>2.65E-07</td>
<td>2.43E-05</td>
</tr>
<tr>
<td>8.00E-03</td>
<td>2.50E+11</td>
<td>4.16E-07</td>
<td>2.65E-06</td>
<td>2.77E-04</td>
</tr>
<tr>
<td>8.00E-03</td>
<td>6.00E+10</td>
<td>1.95E-07</td>
<td>6.79E-07</td>
<td>6.23E-05</td>
</tr>
<tr>
<td>1.00E-02</td>
<td>2.50E+11</td>
<td>6.51E-07</td>
<td>4.14E-06</td>
<td>4.33E-04</td>
</tr>
<tr>
<td>1.00E-02</td>
<td>6.00E+10</td>
<td>3.05E-07</td>
<td>1.06E-06</td>
<td>9.73E-05</td>
</tr>
</tbody>
</table>
REQ-32 Langmuir Probe Performance

- $T_e$ Range 2200 – 3200 [K]
  - Accuracy ±10% [Cosmo]
  - Resolution 50 K [Cosmo]
- $n_0$ Range 3e10 – 2.5e11 [m$^{-3}$]
  - Accuracy < ±10%
  - Resolution [TBD 23]
- Resolution I-V acquisition 0.1-0.2 [V] [TBC 24] [Krujff]
- Sweep voltage estimated range ±25 [V] incl. margin [TBC 24] [Krujff]
- Current levels range from 1.6e-9 to 2.8e-4 [A]

The wide range of current levels requires auto-range control in the ammeter electronics of the LP and the application of logarithmic data compression to the digital conversion of the data [Krujff]. Space charging of the ground (SC chassis or tether) will induce an additional voltage polarisation that will need to be taken into account when deriving the actual bias of the probe to the plasma [Krujff]. Grounding the LP to the SC chassis single point ground (SPG) which will float near plasma potential, see appendix 4, will simplify this as the tether has a variable voltage and will complicate the dynamic range of the voltage sweep.

REQ-33 Langmuir Probe Reference

The LP will be referenced to the SPG of the spacecraft chassis

4.3 Instrument Selection

EDT instrumentation is the science data acquisition part of the TLM system that provides all required sensors and data interfaces to and from the CDHS of Delfi-1, consisting of housekeeping data, commands and scientific data. Requirements and constraints are located in EDT System Requirements Specification [SPC.4122.01-02] listed in the annex of this report and EDT Technical Budgets [TN.4122.08]. Some requirements and design drivers for the TLM system are

- Mass 1 [kg] design target 0.8 [kg]
- Power 4 [W] design target 3 [W] solar part orbit and 0.66 [W] target 0.5 [W] eclipse
- Data rate < 210 [bps] [TBC 25] design target 160 bps
- The TLM shall use a maximum sample size of 8 [bits]
- Low volume, 4 PL modules including antenna modules, see section 5
- Location of all sensors at satellite end
- Onboard operating temperature range [-20°C +55°C]
- Radiation dose > 5 [kRad]
- EPS interface 28 [V]
- Interface RS-485 standard connection to the bus 2 per PLM
- Data format digital signals to the CDHS
- EMC compatibility with de Delfi-1 bus and no potential bias exceeding 10 [V] between component and bus ground
- Low cost (COTS)

For larger instruments volume, mass and power requirements are expressed in payload modules (PLM). Use onboard Delfi-1 sensors where possible with the design drivers being low volume, power use and cost.

Angular Displacement Device (TC)

In appendix 10 an overview of angular displacement devices is given [Jongkind]. The simplicity and achievable resolution and accuracy at a low data rate make an incremental encoder a suitable device for counting the number of turns of the reel during deployment. Incremental encoders are nearly always applied for velocity measurements [Jongkind] and were also used on previous missions [Cosmo; Krujff$^2$; Zedd]. The deployment is uncontrolled once initiated and will continue during power failures subsequently power loss to the encoder will always result in loss of a number of turns counted. Using an absolute encoder retaining the last position is not necessary.
Various methods of obtaining encoder output are available using mechanical, optical, magnetic or capacitive transducers. Optical is used when high resolution and accuracy measurements are required. Optical encoders are more robust and suitable for higher rotations per minute (RPM) systems. Magnetic encoding simplifies the system; no shaft and sensor are required; the system is based upon either the Hall effect [Honeywell SR16C-J6] or variable reluctance and has an analogue output signal [AN9]. A Digital Vane Sensor (DVS) was used to measure rotations of the reel axis for the development and testing of the Tether Deployment System (TDS) by [Heijningen] on the axis of the reel. The magnetic field of the vane sensor created small shocks in the rotation of the reel and a torque on the reel axis a recommendation was made to use an optical sensor to measure the rotational speed of the reel axis [Heijningen]. Incremental encoders are generally cheap, meet environmental requirements and are characterised as being low mass, volume and power devices so are not expected to be design critical in their selection. An optical encoder for example the [HEDS 9700] and [GIO 24] is currently selected as possible options for the TC. The resolution of an optical encoder is determined by the number of bits output, 2 quadrature outputs and a single gated index are available. Assuming a single pulse per revolution is sufficient resolution a 2 Hz measurement frequency is required as at 100 RPM’s the system will generate 1.6 pulses per second.

Table 4.6: Data rate output digital turn counter [Manual #: 940-0D015]

<table>
<thead>
<tr>
<th>Pulses per revolution</th>
<th>Marker pulses per revolution</th>
<th># Output bits per revolution</th>
<th>Max pulses per second</th>
<th>F_s [Hz]</th>
<th>Data rate [bps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1.6</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4 + 2</td>
<td>3.2</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>8 + 4</td>
<td>6.4</td>
<td>7</td>
<td>84</td>
</tr>
</tbody>
</table>

GPS Receiver (GPS)

In the previous section the performance requirements for the GPS system were given combined with integration requirements determined using the TLM mass and power budget aiming for
- mass < 150 [g]
- volume < 1 PL < 1 APL
- power < 1 [W]

In table a10- 2 of appendix 10 a selection of GPS receivers is shown, both the SGR-05P [Unwin; SSTL] and the PHOENIX-S [Gill] meet the requirements stated in section 4.2.1 with the PHOENIX-S having a mass, dimension and slight power advantage. The temperature range of both receivers slightly falls short of the +55°C requirement both achieving a maximum of +50°C, the PHOENIX does have storage capabilities up to +70°C. The COTS SGR-05U does not meet the minimum operating temperature requirements.

Both receivers have an output frequency of 1 Hz and are capable of user selectable output, data rates can be adjusted to meet the requirements for the EDT payload. Available data from the receiver consists of time, position, velocity, raw data, position solution residuals, channel tracking status etc. Both receivers require a Universal Asynchronous Receiver/Transmitter (TTL-UART) to RS-485 converter to interface with the CDHS. Multiple data arcs, depending on expected tether deorbit performance and actual data output of the receiver, can be obtained in orbit allowing correlating the deorbit performance with changes in magnetic field, plasma and eclipse conditions [TBC 26].

The maximum number of useful orbit determinations per orbit depends on the time in which the system is expected to deorbit by an amount of at least 10 m. For a 1500 m - 40 mm tether a maximum of 6-10 data arcs are useful at maximum deorbit performance. For the EDT experiment the data rate from the GPS is required to be < 100 bps limiting the total amount of data to 586400 bits per orbit. Depending on the data output of the receiver the duration and number of data arcs can be determined for the expected performance of the tether.
Mode of operation of the SGR-05 is intermittent to prevent errors due to latch up and single event upsets (SEU’s) and reduce the total data rate and power use. The Delfi-1 CDHS is required to perform checks as to nominal operation of the receiver, the SGR-05 receiver has inbuilt sanity checks as well resetting if no signal is detected for over five minutes and no position fix is acquired for 20 minutes. This protects the system from single event upsets (SEU’s) micro latchups and single event latchups (SEL’s) by resetting the system when required [Unwin].

REQ-35 Command & Health Data GPS  
The CDHS is required to perform checks on the operation of the GPS system and be able to reset the GPS system if required

REQ-36 GPS Antenna Placement  
The antenna module containing the GPS antenna is required to have a clear view of space and needs to be attached to the zenith panel of the satellite.

Tension Transducer (TEN)
A tension transducer is used translating a change in force to a measurable voltage output, with the tether being a narrow web a single load cell is sufficient for performing the measurement. Critical for this instrument is finding a transducer capable of the low tension force range, resolution and sensitivity required for the EDT Experiment. Available load cell types are

- Strain gauges
- Linear Variable Differential Transducer (LVDT)
- Magneto – elastic

Linear Variable Differential Transducer [Jongkind] for high accuracy in linear displacement measurements, but has moving parts and requires signal conditioning, an input voltage and have a higher mass and complexity compared to strain gages. They are capable of operating at a variable force rating. The LVDT however requires approximately 6-15 times more movement to create a signal compared to strain gages [Dover Flexo], the same seems to be the case for the magneto-elastic load cells [TBC 27]. Strain gage transducers are widely used due to their simplicity, low mass and accuracy. All load cells types are affected by ambient temperature variations [Ekola] this needs to be taken into account especially for wide temperature ranges, thermal analysis of the roller and tether connection is required to determine the temperature variations that the load cell will be subjected to.

The load rating of the transducer is determined by strength of the roller, roller weight does not contribute to the net force acting on the load cell near the c.m. of the system so the entire output is due to the tension of the tether acting on the roller. In appendix 10 the load ratings for deployment and operational tension forces calculation is shown, for deployment tension it is 1441 g and 0.17 g - 10 g during the operational phase depending on tether dimensions. Sensor load ratings as low as 3 g have been found [tensionmeters] more research is required if the low operating tensions can be detected using a tension transducer. A bonded silicon (semiconductor) strain gage is currently selected for its higher electrical output, increasing their sensitivity compared to foil gages. They are also less susceptible to temperature effects compared to foil gages according to [Dover Flexo]. A temperature compensated load cell using a Wheatstone bridge to obtain a measurable output. The output is a voltage proportional to the amount of tension in the tether; the signal passes the load cell amplifier and is sent to the CDHS in a digital format using the analogue to digital converter (ADC) of the PLM. To achieve the resolution of the tension measurements listed in table 8.1 derived from [Cosmo] based on data from the SEDS mission require a sample size of 7 bits. Depending on the required measurement frequency (1 Hz – 8 Hz >> Nyquist frequency [Cosmo]) the instrument data rate to the ADC ranges from 7 bps to a maximum of 56 bps.

Accelerometer (ACC)
Used for determining the tension in the tether during deployment and operational phase and measuring oscillation frequencies of the satellite requiring highly sensitive accelerometers. Capacitive accelerometers are required for the high sensitivities required for the EDT experiment [Jongkind]. In appendix 10 overview of accelerometers used on other satellites is given that fit the performance requirements of the EDT experiment.
With the high resolution and sensitivities required for the lower range of tether tensions a very sensitive accelerometer is required to measure the onboard vibration environment. An initial data rate estimate for a 3-axis accelerometer at 8 Hz measurement frequency for 8 bits measurement sample size results in 192 bps [TBC 28] data rate the entire budget for the experiment when used continuously. More research on signal amplification and filter technology to obtain the required range, resolution and sensitivity for measuring tether tension and satellite oscillation frequencies is required. Due to the low mass of the tether being designed this will be a challenge on multiple fronts, at this point the accelerometer is not considered to be a dependable instrument for determining the bus oscillations and the dynamics of the tether due to the limited data rate budget available. Operational tension of the tether due to the small forces involved requires a very high resolution accelerometer, at the lower measurement frequencies available it needs to be determined if this is a useful measurement. The accelerometer whether a microchip or a separate device will not put a strain on the volume and mass budgets for the experiment.

**Tether Bias Sensor (TBM)**

To measure the potential difference between the SC chassis ground and tether upper termination the tether termination needs to be isolated from satellite ground. Add a Zener-diode (5.6V) or a transient voltage suppression (TVS) diode to clamp the potential between tether and SPG to a maximum level of ±10 V between tether and SC parallel to the voltmeter to ensure REQ-1 is met taking into consideration higher charges occurring of both satellite and tether in the polar and auroral regions of the ionosphere and during gas discharge on bias distribution along the tether. Voltage spikes are diverted (short circuited) to the ground. To protect the TVS from high current levels a resistance can be put in series with the TVS or Zener diodes as shown in figure 4.3. This will not enable tether biases exceeding 10 V for instance during gas cathode operation to be measured apart from showing a gap in voltage measurement data however.

![Figure 4.3: Tether bias measurement and surge protection circuit](image)

A sample rate of at least 1 Hz [TBC 29] measurements for bias and 8 Hz to be able to deduce tether in plane and out of plane oscillations [Cosmo] is required. A signal range of ±0.17 V – ±10 V needs to be converted to 0 and 4 V signals for CDHS using a voltage divider and subsequently converted to digital signal using the payload module ADC. Maximum range ±10 V during the gas cathode operation phase at a resolution 10 mV for the bias measurement requires 2000 numbers, 11 bit sample sizes. To limit the sample size the resolution available is 0.05 V this is sufficient to measure bias fluctuations in orbit at a 1 Hz sampling rate. If parallel redundancy by a factor of 2 is applied the data rate for the tether bias sensor is 16 bps, preference is switching redundancy to reduce power and data rate, this however increases the complexity of the system.

**REQ-37 Tether Bias Measurement Performance**
- Range ±0.17 – ±10[V]
- Resolution 0.5 [mV] – 0.05 [V]
- Tether electrically isolated from sc chassis
- Frequency 1 [Hz] [TBC 29]

**Temperature Sensor (RTD)**

In appendix 10; table a10- 5 an overview of types of temperature sensors is given. Previous missions have shown a tendency for the use of thermistors (thermally sensitive resistor) [Wijnans5b] being both accurate and very sensitive to temperature changes with high repeatability. They also have a resolution better than thermocouples and resistive temperature detectors (RTD) [Jongkind]. Based on long storage and operational period an RTD sensor is chosen based on its stability and repeatability of measurements over longer periods of time. The (platinum) RTD seems practical if EDT experiment operates the full three months also having a minimum of calibration errors and being slightly more rugged when compared thermistors. RTD’s are sensitive to strain and shock but unlikely that tether strain and shock are large enough to affect the accuracy of the RTD.
The leads of the sensor are fragile contacts but should be possible to integrate with the reel, possibly use 2 for redundancy either parallel or standby depending on power and data rate budgets [Reijns]. Testing the integration of the temperature sensor is required for the entire deployment and operational phase loads with adequate safety margins. Thermal EMF errors are produced by the EMF adding to or subtracting from the applied sensing voltage, primarily in DC systems, will be introduced due to integrating the RTD onto the biased tether [TBC 30]. Option is grounding the RTD or thermistors to the tether eliminating any bias between them. Thin film RTD platinum Honeywell HEL-700 Series or HRTS-5760 Series are examples of RTD’s operating in the required temperature range.

Using a different type of sensor will have minimal impact on the systems budgets, not a critical component. Data rate for the temperature sensor depends on the range and resolution required. For a range of 300° and a resolution of 1° requires 300 numbers; 9 bits are required not available by the CDHS. Limiting the resolution to 2° results in 150 numbers and 8 bit sample size is sufficient. Data rate 8 bps and if redundant parallel system is chosen it is increased to 16 bps.

REQ-38 RTD Temperature Sensor Performance
- Range ±150 °C
- Resolution 2°C
- Frequency 0.1 Hz

Magnetometer (MAG)
The Delfi-1 satellite is equipped with a 3-axis fluxgate magnetometer used for the ADCS. Either a ZARM FGM or a Billingsly TFM100G2 is being considered [Steindl]. Expected performance is
- Range ±64 to ±100 [μT]
- Sensitivity 100 [μV/nT]
- Accuracy 0.64 [μT] to 0.75 [μT]

The EDT experiment will make use of the onboard magnetometer data output for magnetic field measurements to minimise the volume, mass and cost of the experiment. Magnetic field measurements will be coupled to tether voltage measurements giving an indication of tether angles. If the required data rate from the magnetometer is increased due to the EDT experiment the data rate and power increase will be budgeted to the EDT experiment. At this point it is assumed the experiment makes use off the available ADCS data.
- power < 1[W]
- data rate < 100 [bps]

Langmuir Probe (LP)
A LP is proposed to obtain nₑ, Tₑ and Vₑ. Langmuir probe configurations have been studied in [Wijnans⁵] consisting of
- Single probe system biasing the electrode relative to the chassis (SPG)
- Hot single probe; discrepancy between heated and unheated characteristics sensitive indicator Vₑ
- Dual probe system biasing the electrode relative to a second electrode instead of the sc chassis
- Triple probe system 2 electrodes biased with a fixed voltage and the third one floating

Previous experiments tend to use a dual probe configuration with the electrode biased relative to the second and neither very far above floating potentials. Limitations as to surface mounting area and volume restrictions of the payload could limit the LP to a single probe configuration. To measure the undisturbed plasma environment the placement of the LP needs to be outside the sheath and the wake of the satellite [Aase]. Due to passive tether operation having floating potentials near the plasma the sheath size at the satellite end due to the upper termination of the tether is limited. A separation distance in the order of ∼10 cm from the tether-SC should be sufficient (sheath size ≈ 6 λₑ [Beletsky]) to have the probe measure undisturbed plasma environment with Debye lengths varying from 7 to 16 mm for Delfi-1 orbit range, see figure 2.4. The ram and wake structure occurring due to the system moving at mesosonic speeds also impacts the distance from the SC for reaching undisturbed plasma, the dimensions of this structure need to be determined.
REQ-39  **LP Configuration Requirements [preliminary]**

- Deploy the sensor head(s) with a deployable boom of 10 [cm] [20 incl. design margin] from the spacecraft; $L_o > 0.1-0.2$ [m]
- Probe location a function of ram – wake effects [TBD 24]
- Not mounted on a surface directly in sun
- Disturbance RF antenna's and tether
- Power < 2 [W]
- Dimensions
  - Probe dimensions <1 antenna module
  - Electronics dimensions <1 PL module

For plasma diagnostics ideally the SC has either a positive or a floating ground as it will cause less disruption to the local plasma environment [Tribble]. At this stage it is unknown if Delfi-1 bus has a negative ground due to power system constraints, this is usually the case [Tribble]. The Delfi-1 satellite is assumed to be an unbiased object at this point; the floating potentials for the satellite are in the order of -0.9 V to -1.3 V (section 2.2.3).

REQ-40  **Grounding**

The Delfi-1 bus shall preferably have a positive or floating ground

In [Wijnans] a number of Langmuir probes are given characterised by single probe properties giving an estimate for a single probe configuration. Based on the LINDA probe [Holback] and the proposed LP in [Kruijff] an assumption of the expected properties of a single LP are given below.

**Table 4.7: Assumed single LP properties**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LP Boom Probe</td>
<td>0.08-0.2</td>
<td>200 - 665</td>
<td>10 – 30</td>
</tr>
<tr>
<td>Electronics &amp; data processing</td>
<td>0.2</td>
<td>2</td>
<td>178 x 122 x 20</td>
</tr>
<tr>
<td>Harness</td>
<td>0.02-0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.3-0.6</strong></td>
<td><strong>2</strong></td>
<td><strong>1 APL 1.5 PL</strong></td>
</tr>
</tbody>
</table>

It might be possible to develop a specific LP for this experiment in house reducing the cost as was done for a sounding rocket mission by [Aase]. More research into the technology of performing the required measurements is required to ascertain if this is a viable option. The theory is well established and the required components for building a probe are widely available so it would be a case of putting it into practise. A single (hot) probe set up used to determine the $V_p$ seems suitable for in house development. A single (hot probe) also seems most viable in a practical sense due to mass, volume (electronics) and power constraints for the PL as a single probe will already strain the available budget as can be seen in table 4.10. The expected data rate of a single Langmuir probe is estimated using [Kruijff], a single I-V data point consists of 8 bits and 256 data points are required for one I-V curve. An additional 2 bits for calibration and are required for each data point [Kruijff]. With one I-V curve per minute the data rate for 1 LP totals to 2560 bits per minute or 43 bps.

**Instrument Data Output**

![Figure 4.4: Science Data from EDT to CDHS](image-url)
Data output signals consist of digital and analogue shown in figure 4.4. Digital data output can be sent directly to the CDHS and analogue signals are converted to digital signals using the analogue to digital converter (ADC) of the PLM [DES.4120.01] before interfacing with the CDHS.

Estimated science data rates for each instrument are given in table 4.8. Results show total data rates range from 144 – 269 (186–336 incl. 20%) bps excluding the accelerometer from the current TLM configuration with the magnetometer considered to be part of the ADCS data rate and a tether tension measured using a load cell. Housekeeping and calibration data are incomplete at this point but at the low data rates expected these will be a limited part of the data rate budget. Including a design margin of 20% the high frequency measurements (8 Hz) used for determining bus and tether oscillations are considerably out of budget and might exceed current data rate estimates as some measurements possibly have to operate at an increased increasing the data rates even further. The LP is considered to be sensitive to noise, take measures to reduce system noise in design of harnessing and grounding of the instrument.

REQ-41 EMC Instrumentation
Noise quiet conditions during LP operation at EOL of Delfi-1 mission, Delfi-1 platform transferred into science quiet platform. Also possibly a number of instruments could require quiet platform conditions due to low-level signals generated [TBD 26]

REQ-40 EMC EDT Tether
Set up experiment (electronic connections) so failure of onboard electronics will not influence operation of tether. Isolate tether termination from satellite ground [TBC 31].

| Table 4.8: EDT instrumentation preliminary TLM listing |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Sensor** | **Type** | **Telemetry** | **Quantity** | **Sampling Rate F_s [Hz]** | **Sample Size [bits]** | **Data Rate [bps]** | **Remarks** |
| TC | D | # turns | 1 | 2–4 | 2–4+2 | 4–24 | TBD 22 |
| TEN | A | voltage | 1 | 1 – 8 | 7 | 7–56 | high frequency not in budget |
| ACC | A | voltage | 3 | 1 – 8 | 8 | (24 – 128) | high frequency not in budget |
| TBM | A | voltage | 2 | 1 – 8 | 8 | 8 – 64 | |
| LP | D | current | 1 | 1/60 | 8 | 50 | |
| D | range voltage | 1 | 1/60 | 8 | 0.13 | |
| RTD | A | temperature | 2 | 0.1 | 8 | 1.6 | |
| GPS | D | Orbit Determination | 3 | 1 | 8 | 24 | output data required |
| D | Orbit error | 1 | 1 | 8 | 8 | |
| D | Time stamp | 1 | 1 | 8 | 8 | |
| D | Rest string | 4 | 1 | 8 | 32 | |
| MAG | A | Magnetic field | 3 | 10 | 8 | (240) | ADCS |
| **Calibration Data** | | | | | | | |
| TC | D | Null point | 1 | 1/60 | 8 | 0.13 | TBD 25 |
| TEN | A | temperature | 1 | 1/30 | 8 | 0.3 | TBD 25 |
| TBM | A | TBD 8 | 2 | 1/30 | 8 | 0.5 | TBD 25 |
| LP | D | TBD 8 | 1 | 1/60 | 2 | 0.3 | TBD 25 |
| **Housekeeping Data** | | | | | | | |
| GPS | A | voltage | 1 | 1/60 | 8 | 0.13 | TBD 25 |
| A | temperature | 1 | 1/60 | 8 | 0.13 | TBD 25 |

**Risk Analysis Instrumentation**
Instrumentation does not have a critical impact on the Delfi-1 satellite operations, the GPS, TBM and turn counter are critical instruments for performing the scientific objectives and failure of these instruments will have an experiment critical impact.

---

5 All instrument data rates-power and dimensions are [TBC 30]
6 Calibration & Housekeeping Data Incomplete [TBD 8]
Risk mitigation for loss of the GPS is to use ground station tracking as a back up system, this will impose requirements on the tether design it needs to be determined if this is a viable option within the Delfi-1 bus constraints. The tether bias measurement will be designed parallel or standby redundant depending on CDHS capabilities and final mass, power and data rate budgets.

Table 4.9: Risk map instrumentation

<table>
<thead>
<tr>
<th>Feasible in Theory</th>
<th>TEN</th>
<th>ACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Laboratory Model (verified simulation)</td>
<td>LP</td>
<td>TBM</td>
</tr>
<tr>
<td>Based on Existing Design</td>
<td>RTD</td>
<td>TBM</td>
</tr>
<tr>
<td>Extrapolated from Existing Flight Design</td>
<td>TC</td>
<td>GPS</td>
</tr>
<tr>
<td>Proven (flight) Design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criticality</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Overview of Instruments Selected

An overview of the instruments selected and their characteristics is given below with the TLM system requirements listed in the annex of this report.

Table 4.10: Selection of instruments EDT experiment

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
<th>Mass [g]</th>
<th>Dimensions [mm]</th>
<th># PLM</th>
<th>Power [V]</th>
<th>Data rate [bps]</th>
<th>Budget Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn counter</td>
<td>HEDS-9700 GIO-24K</td>
<td>125</td>
<td>15-25 x 30</td>
<td>0.2</td>
<td>0.15 - 0.5</td>
<td>4-24</td>
<td>OK</td>
</tr>
<tr>
<td>Tension Transducer</td>
<td>Silicon strain gage</td>
<td>125 [TBC 32]</td>
<td>26 x 44 x 92</td>
<td>0.2</td>
<td>0.5</td>
<td>7</td>
<td>OK</td>
</tr>
<tr>
<td>Tether Bias Measurement</td>
<td>DC-DC; voltage divider to 0-4 V signals (2)</td>
<td>100</td>
<td>2 x 20 x 20 x 20</td>
<td>0.2</td>
<td>0.4</td>
<td>16</td>
<td>OK</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>RTD (2) platinum</td>
<td>30</td>
<td>20 x 20 x 20 x 20</td>
<td>0.2</td>
<td>0.2</td>
<td>1.6</td>
<td>OK</td>
</tr>
<tr>
<td>GPS</td>
<td>SGR-05U/P</td>
<td>70</td>
<td>70 x 45 x 10</td>
<td>0.4</td>
<td>0.8</td>
<td>72</td>
<td>OK</td>
</tr>
<tr>
<td>antenna</td>
<td></td>
<td>12-50</td>
<td>13 x 13 x 40 169 mm²</td>
<td>&lt;&lt; 1APL</td>
<td>0</td>
<td>0</td>
<td>OK</td>
</tr>
<tr>
<td>Langmuir probe⁶</td>
<td>Concept Incl. electronics</td>
<td>300-600</td>
<td>178 x 122 200 boom d Erotic 30</td>
<td>1.25</td>
<td>2</td>
<td>50</td>
<td>Cost Power Dimension</td>
</tr>
<tr>
<td>Total specification</td>
<td>782-1120 g</td>
<td>624519 mm³</td>
<td>1 APL 2-3 PL</td>
<td>4.05-4.4W</td>
<td>151-171bps</td>
<td>Data Rate</td>
<td></td>
</tr>
<tr>
<td>Accelerometer</td>
<td>QA 200/300 3-axis</td>
<td>71</td>
<td>25 x 15</td>
<td>0.1</td>
<td>0.48</td>
<td>48-256</td>
<td>Data Rate Performance NO GO currently</td>
</tr>
</tbody>
</table>

The data shows that the selected instrumentation is within budget for the low mass estimate but exceeds the mass budget for the higher bottom up estimate at a total of 1.33 kg. This includes a design contingency for each instrument based on current status of technical specification ranging from 10% for well defined systems like the GPS receiver and 20% for systems at a less mature state of development documented in [EDT Technical Specification]. This estimate however does not include the required housekeeping and command transfer hardware also part of the TLM system. A design effort will have to be made to ensure TLM remains within the set mass budget. The instrumentation uses a total of volume of 2-3 standard PL modules and less than 1 antenna module for LP and GPS is required. Including a bottom up 10%-20% design margin depending on maturity for each instrument the total power is 5.2 W, with the turn counter only operating during deployment a maximum of 4.6 W is used simultaneously. The Langmuir probe pushes the TLM system out of the power budget and also strains the mass budget considerably; with this instrument omitted the system is within the set power budget for simultaneous operation of all instruments during the solar part of the orbit.

⁶ Assuming parallel redundancy
⁷ Based on single probe data
A scheduling of measurements can be set up with intermittent operation of both the LP and GPS receiver. This will achieve peak power usage of 2.4 W and peak data rates of 114 bps for low frequency measurements leaving a margin of 46 bps for housekeeping data (HSK) and commands and ranges to 200 bps for high frequencies used on TEN and TBM not within the 160 bps design target. The power restriction during eclipse will limit the system to intermittent voltage and temperature, tension and possible GPS data if operated in low power mode [SSTL-27433].

Table 4.11: Instrument scheduling approach excl. design margins

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GPS</td>
<td>0.8</td>
<td>72</td>
<td>GPS</td>
<td>0.5</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>TC TEB RTD</td>
<td>1.3</td>
<td>33 - 82</td>
<td>not required</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3-4a</td>
<td>TBM GPS TEN RTD</td>
<td>1.9</td>
<td>114 - 170</td>
<td>TBM RTD</td>
<td>0.6</td>
<td>17.6 - 74</td>
</tr>
<tr>
<td>3-4b</td>
<td>LP TBM</td>
<td>2.4</td>
<td>66 - 122</td>
<td>GPS</td>
<td>0.5</td>
<td>72</td>
</tr>
<tr>
<td>3-4c</td>
<td>TEN GPS</td>
<td>1.7</td>
<td>95 - 200</td>
<td>TEN</td>
<td>0.5</td>
<td>7 - 56</td>
</tr>
</tbody>
</table>

Another option is to limit the instrumentation to priority instruments only to determine if the tether is deployed, inducing a bias and increasing the deorbit rate of the satellite. These consist of the turn counter, tether bias measurement and the GPS receiver combined with available data from the ADCS and EPS on magnetic field strength, system angles and solar angle and intensity. Instrumentation including 10%-20% design contingency, see EDT Technical Specification document, is then limited to 424 g mass, 2 W and 134 bps.

During operational phase II when the gas cathode is activated the sampling frequency is assumed to increase by a factor 5 for the TBM and the TEN increasing the data rate by 110 bps including a 20% margin assuming the resolution of the instruments is not altered and the bias measurement instrument is parallel redundant. During this phase instrumentation is subsequently limited to the TBM, TEN and GPS.

**Calibration Requirements**

**REQ-42 Calibration EDT Instrumentation**

All instruments are required to be calibrated pre-flight for entire expected operating range. During storage and operational phase in flight recalibration will be applied to instruments sensitive to degradation by using known inputs and requiring to be calibrated before operation.

**TLM Interface CDHS**

The Telemetry System consisting of EDT Instrumentation and hardware providing the required housekeeping data and commands to and from the CDHS of Delfi-1. The functions of the TLM are to provide data acquisition – processing and transmission to and from the CDHS.

The EDT shall interface with the Delfi-1 CDHS with the TLM system [REQ-43]

1. The TLM shall be able to provide status and health checks to the CDHS
2. The TLM shall be able to receive commands from the CDHS
3. The CHDS shall initiate deployment (HDRM and TES)
4. The TLM shall acquire all experiment data and deliver it to the CDHS
5. The experiment shall be terminated when signalled by CDHS

Housekeeping data consists of temperatures, power supply voltages and currents of main equipment of the EDT experiment providing health checks of the payload also consisting of individual digital bits representing operational status of equipment indicating that a particular functional mode is either selected or deselected.
The GPS receiver data is also sent to the CDHS allowing it to perform a secondary health check on the GPS orbit determination. Any significant and permanent change in bias voltage at suspension or indications from tension measurements can determine if librations are out of control (slack criteria) or if a tether break up event has occurred ending the experiment. During the termination phase (after three months operation or off nominal tether librations) housekeeping data consists of bias and tension measurements to monitor the status of the tether. It can be decided to cut the tether to minimise its area lifetime in orbit depending on the results of risk analysis comparing the collision risk of the combined tether and satellite and the separated (untrackable) tether when cut [TBD 27]. Cutting the tether when librations exceed stability limits can also be performed to mitigate the risk of Delfi-1 failure due to the tether. Commands primarily consist of activation signals for each operational phase and instrument scheduling commands.
5 EDT SYSTEMS DESIGN

In this chapter some of the EDT systems are designed in more detail. The EDT experiment consists of the electrodynamic tether (TET), the tether deployment system (DEP), the tether end mass (EM), telemetry system (TLM) and a power and structure system (EPS-STS). A more detailed systems breakdown is provided in figure 6.2 of chapter 6. This systems definition, together with the design budgets and constraints developed in part I of this study result in the following technical budgets for the experiment:

- Dimensions/Volume: The EDT shall remain within 50%-65% of total PL volume. The payload platform is designed to hold 13 standard payload modules (PLM), 7 double sized PLMs and 8 antenna modules and an envelope of 410 x 410 x 140 mm [(x_L) x (y_L) x (z_L)]
- Mass < 6 kg [REQ-44]
- Power < 6 W and < 1 W during eclipse [REQ-45]
- Data rate < 210 bps (design target is 160 bps) [REQ-46]

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT Payload EDT</td>
<td></td>
<td>6.0</td>
<td>4.6</td>
<td>6</td>
<td>4.62</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>Deployer</td>
<td>DEP</td>
<td>1.0</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Telemetry</td>
<td>TLM</td>
<td>1.0</td>
<td>0.8</td>
<td>4</td>
<td>3.1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Power</td>
<td>EPS</td>
<td>0.6</td>
<td>0.5</td>
<td>2</td>
<td>1.5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Structure and Harnessing</td>
<td>STS</td>
<td>0.7</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Tether</td>
<td>TET</td>
<td>1.6</td>
<td>1.3</td>
<td>0</td>
<td>0</td>
<td>DEP</td>
<td>DEP</td>
</tr>
<tr>
<td>Gas cathode</td>
<td>GAS</td>
<td>1.0</td>
<td>0.8</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>End mass [Heijning]</td>
<td>EM</td>
<td>0.83</td>
<td>0.66</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The table provides data as specified and as target data. The latter are consistent with the 23% design margin used for the Delfi-1 satellite in the conceptual design phase [SLR 156]. At this stage in the design the intention is to achieve the target data for each system. In this chapter a more detailed design will be performed of the tether consisting of material choice including environmental affects, load and thermal analysis and payload constraints. The neutral gas cathode operation and design will also be addressed. All requirements derived for each EDT system this thesis work are listed in an annex of this report listing the EDT System Requirement Specification [4122.SPC.01-02]

5.1 ED Tape Tether

The preliminary design of the tether conducted in the first part of this study indicated a thin and wide foil would be optimally suited for collecting current and have increased survivability and favourable drag properties when cut. To protect the tether from ripping the foil will be enforced along its length. Initial tether design will focus on this concept with tether width dimensions varying from 5 - 80 mm and lengths from 250 - 2500 m. The two main functions of the tether are to remain intact during the deployment and operational phase allowing sufficient bias to be generated and current collection and conduction to occur. The tether subsequently needs to maintain its desired properties during storage, be deployable, survive deployment and operational mechanical and electrical loads, survive the environment and remain within nominal dynamics range during the experiment.

In table 1.1 the environment the tether is exposed to is summarised [ECSS3], the effects on the tether design are listed below combined with design drivers and constraints:

- Mechanical Loads [Dynamic & Static, Handling]
- Electrical Loads
- Thermal Environment, Cycling and Loads
- High Vacuum (contamination)
  - Outgassing
- Atomic Oxygen (AO) Erosion and Oxidation
- Plasma environment Sputtering
- Ionising Particle & Ultra Violet (UV) Radiation
- Micrometeoroid & Debris
- Electrical Charge & Discharge
- Moisture Absorption and Desorption (polymers) during storage
- Galvanic Compatibility Reel and Tether
- Corrosion (storage; pre launch)
- Combined Environment and Loads [Stress Corrosion (metal); cracking; thermo-elastic behaviour [TBD 29]
- Storage affects on tether material and deployability including cold welding [TBD 30]
- Constraints Mass and Storage Dimensions
- Design drivers
  - Simplicity
  - Availability
  - Cost

In this section possible materials for the tether are discussed. The conducting tether requires a material with good conductive properties able to withstand oxidation, surface erosion and sputtering. Other materials of importance consist of materials to enforce the tether, adhesives and coatings. Following the review of possible materials, the effects of electrical and mechanical loads on the design are discussed in section 5.1.2. Since the temperature of the tether material influences the conductive and mechanical properties of the tether a thermal analysis is performed to determine tether temperature extremes in orbit. This analysis is described in section 5.1.3. In the next section it is shown how tether dimensions affect its severance probability in the micrometeoroid and orbital debris environment. Finally the effect of constraints of both mass and storage on the tether design are discussed.

5.1.1 Tether Configuration & Materials

The tether consists of the conductive tape, an enforcing substrate and adhesive and a protective coating. In this paragraph the design configuration of the tether and a review of potential materials for each tether component are outlined. Also the effects of the space environment on these materials is discussed including protective measures where required.

Tether Conductive Material

In line with findings of [Jainandunsing; Kruijff; Beletsky] and part I of this study aluminium is selected as the conductive tether material. Compared to other materials aluminium has a relatively low density, high specific conductivity, good availability and low cost combined with excellent mechanical properties. An overview of various materials and their properties can be found in appendix 11; table a11- 1. Aluminium foil can be produced as thin as 4.32 µm; in comparison over the counter household foil is 15.2 µm thick. A bare aluminium tether can be relatively rigid potentially causing problems during deployment therefore an initial mechanical part can be desirable to achieve good deployment [Kruijff]; also increasing the stability of the EDT by increasing the stabilising gravity gradient torque. Integrating a tape tether with a mechanical part needs to be verified by tests. Also friction of the tether will have to be taken into account during deployment and is expected to increase after being stored on the reel in space for a year.

A rolled-annealed foil is initially chosen based on the ductility and flex life endurance. Aluminium alloys 1000 series (99% pure aluminium) and 8000 series (nickel and iron) have the highest electrical conductivities both considered to be conductor alloys [Harper, Matweb]. These alloys have a lower strength compared to other alloys but this is not expected to be critical for the tether design, see part I of this study. In section 8; in the annex of this report listing EDT system requirements the requirements for the conducting tether material are listed as [REQ-47].

Tether Design

When the aluminium foil is fractured or ripped at the edges the smallest strain on the tether can sever it, to ensure the electrodynamic function of the tether it must remain intact. To provide rip stop protection the foil needs to be enforced preventing the tether severing due to operational forces and micrometeoroid or debris grazes at the edge of the tether.
The two main options being considered for enforcing the bare aluminium foil are
1. Laminated to a substrate (adhesive tape)
2. Coated to a substrate (adhesiveless)
   - Cladding or electrolytic plating
   - Sputter or Vacuum Deposited (Metalised Films)

A plastic film coated with aluminium only collects current on one side but is not as rip sensitive as
bare aluminium foil, clad coatings of 25 µm -2500 µm thick aluminium on a substrate are available [Harper]; this is a form of laminate that has good ductility properties and a tether with a thin conductive outer layer is less susceptible to self-field effects [Sanmartin4], see section 2.1.2. Vacuum deposited coatings have aluminium coatings on a substrate with a thickness in the order of angstroms and are subsequently not applicable as the resistance is too high, see section 2.2.1. The other option is to laminate a substrate film onto the aluminium foil; solar sails use Kapton® tapes joined to the rear surface providing rip stop protection for the sail.

Initial design will focus on the most efficient design for collecting current; a bare conducting foil tape enforced with a plastic substrate on one side over part of the width of the bare tether providing rip stop protection, maximising the available A_{coll}. With aluminium laminated to a plastic substrate the adhesion and differential expansion due to stress and temperature between the plastic and metallic layers are of importance, similar coefficients of thermal expansion (CTE) and Poisson’s ratio υ of laminated materials are advisable [Harper]. There are multiple configurations conceivable for an aluminium foil with a rip stop protection laminate. For initial design purposes it is assumed a % of the bare aluminium width w_c is laminated with the enforcing material. At a later stage in the design the most efficient configuration of the laminate on the bare tape can be determined taking storage volume, deployability of the tether, stiffness/viscosity properties, mass and rip stop functionality into consideration whilst adhering to the low cost, simplicity and availability requirements for the EDT design. The components of the ED tape tether, their functions and environment the components need to withstand are shown below.

Table 5.2: Components of the TET

<table>
<thead>
<tr>
<th>Component TET</th>
<th>Functions</th>
<th>Environmental effects on component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductive</td>
<td>collect and conduct current and generate bias, mechanical and electric loads</td>
<td>Oxidation &lt; 700 km, Thermal</td>
</tr>
<tr>
<td>Enforcement</td>
<td>Rip stop protection, deployability, thermal control</td>
<td>Thermal, UV and Particle Radiation, AO erosion &lt; 700 km, Sputtering, Outgassing</td>
</tr>
<tr>
<td>Adhesive - Clad</td>
<td>Mechanical</td>
<td>Thermal, UV and Particle Radiation, AO erosion, Outgassing</td>
</tr>
<tr>
<td>Coating</td>
<td>Protection against oxidation, AO erosion and thermal control</td>
<td>Thermal, UV and Particle Radiation, AO erosion &lt; 700 km, Sputtering, Outgassing</td>
</tr>
</tbody>
</table>

In the next section the effects of the space environment of tether materials and design is discussed.

Oxidation, Surface Erosion & Sputtering

Below 700 km the ionospheric plasma region consists mostly of AO being chemically reactive causing oxidation or erosion of materials to occur. For orbit altitudes above 700 km [Pisacane] hydrogen H becomes the dominant ion species, see appendix 3; figure a3-5, and AO effects become negligible. The bare aluminium tether is subject to oxidation limiting current collection. This may require a protective coating that is conducting and oxidation resistant to prevent this from occurring [Sanmartin]. This coating should also protect the bare tether from oxidising during ground storage [TBC 34].

Chemical reactions of AO erode polymer materials like Kapton®, the erosion yield E and material loss is calculated using the following relationships determined by test samples [Pisacane]

\[ E = \frac{\Delta m}{A \rho F} \quad d = \frac{\Delta m}{A \rho} = EF \]  
(5-1)

A  – surface area test sample [cm²]
E  – erosion yield (AO atom) [cm³]
F  – atomic oxygen fluence (AO atom) [cm²]
Δm – mass loss [g]
ρ – density of test sample [gcm⁻³]
d – depth of material loss [cm]

For a three month mission duration a Kapton® or Mylar® layer will erode approximately 0.5 µm on the ram surface for worst case 650 km altitude and mean solar conditions, see table 5.3. The substrate will have to be protected from AO erosion for the lower part of the Delfi-1 orbit range with AO effects reduce rapidly with increasing altitude, see figure a11-1a. A thin coating with a thickness of 650-700 angstroms Al₂O₃ or SiO₂ or TOR™ can be used to protect the material as shown in figure a11-1b and table 5.3 [Pisacane; Schuler]. Alternatively a design margin on material thickness can be incorporated. Solar activity has a significant influence on the fluence of AO atoms, final launch dates will confirm whether the mission takes place during a solar max or min period.

Table 5.3: Erosion three months mean solar flux F_{10.7} – 150 [NRLMISE-00; SPENVIS]

<table>
<thead>
<tr>
<th>Material</th>
<th>Erosion Yield E [cm³]</th>
<th>d_{front} [cm]</th>
<th>d_{back} [cm]</th>
<th>Fluence F_{front} = 2.22×10¹⁹ [cm⁻²]</th>
<th>Fluence F_{back} = 4.47×10¹¹ [cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton</td>
<td>2.00-24</td>
<td>4.43×10⁻⁵</td>
<td>8.94×10⁻²³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂, 650 A on Kapton</td>
<td>0.0e-24</td>
<td>1.77×10⁻⁸</td>
<td>3.57×10⁻²⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mylar</td>
<td>2.30×10⁻²⁴</td>
<td>5.09×10⁻⁵</td>
<td>1.03×10⁻²²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al coated Kapton</td>
<td>0.01×10⁻²⁴</td>
<td>2.22×10⁻⁷</td>
<td>4.45×10⁻²⁵</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al coated Kapton</td>
<td>0.10×10⁻²⁴</td>
<td>2.22×10⁻⁶</td>
<td>4.45×10⁻²⁴</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sputtering occurs when impacting ions remove surface material on the negatively biased section of the tether; this is a slow process due to the low density of plasma [Sanmartín] but can be of importance when thin films or deposited type coatings are used as conducting material for the EDT. The impact energy of the colliding particle has to be larger than the energy of the atomic bond of the material surface atoms to sever atoms from the material. The energy per particle for the main particles in orbit are shown in table 5.4, thermal energies of the particles are small and neglected. The surface binding energy of aluminium is 2.95 eV [Pisacane].

Table 5.4: Orbital impact energies circular orbits [Pisacane]

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>𝑣_𝑖 [m/s]</th>
<th>O⁺, O⁻ [eV per particle]</th>
<th>H⁺, H⁻ [eV per particle]</th>
<th>He⁺, He⁻ [eV per particle]</th>
<th>N⁺, N⁻ [eV per particle]</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>7558</td>
<td>4.72</td>
<td>0.3</td>
<td>1.18</td>
<td>4.12</td>
</tr>
<tr>
<td>800</td>
<td>7452</td>
<td>4.58</td>
<td>0.29</td>
<td>1.15</td>
<td>4.61</td>
</tr>
<tr>
<td>1000</td>
<td>7350</td>
<td>4.46</td>
<td>0.28</td>
<td>1.12</td>
<td>3.90</td>
</tr>
</tbody>
</table>

Charging of the tether will increase the kinetic energy of the particles to approximately the bias of the tether [Tribble]. For the maximum induced EMF of 62 Vkm⁻¹ and a tether of 2500 m the resulting bias of approximately -150 V [appendix 5; table a5-2] will increase the impact energy of O⁺ ions to 155 eV instead of 5 eV exceeding the sputtering threshold. Sputtering yields for aluminium and silicon at 100 eV impact energy are shown below.

Table 5.5: Sputtering yields 100 eV [Tribble]

<table>
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<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.026</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
</tr>
<tr>
<td>Si</td>
<td>0.029</td>
<td>0.002</td>
<td>0.023</td>
<td>0.046</td>
</tr>
</tbody>
</table>

The total flux of ablated material is calculated as [Tribble]

\[ \phi(s) = \sum \int \frac{1}{E} \phi(E) \phi(E) dE \]  

\( \phi_s \) – sputtered particle flux [atoms/m⁻²]
\( \phi_i \) – flux incident particles energies E·dE [atoms/m⁻²]
Table 5.6: Number density and flux of incoming particles

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>O⁺ [m⁻³]</th>
<th>H⁺ [m⁻³]</th>
<th>He⁺ [m⁻³]</th>
<th>N⁺ [m⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>1.8e11</td>
<td>6.58e10</td>
<td>7.13e9</td>
<td>2.12e9</td>
</tr>
<tr>
<td>1000</td>
<td>2.5e10</td>
<td>1.16e11</td>
<td>1.91e10</td>
<td>5.44e8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>O⁺ [m⁻²s⁻¹]</th>
<th>H⁺ [m⁻²s⁻¹]</th>
<th>He⁺ [m⁻²s⁻¹]</th>
<th>N⁺ [m⁻²s⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>1.36e15</td>
<td>4.97e14</td>
<td>5.39e13</td>
<td>1.6e13</td>
</tr>
<tr>
<td>1000</td>
<td>1.84e14</td>
<td>8.51e14</td>
<td>1.41e14</td>
<td>4.00e12</td>
</tr>
</tbody>
</table>

Assuming all incoming particle flux is beyond the sputtering energy threshold and constant throughout the orbit using the 100 eV yields from Table 5.5 an amount of 0.087 µm aluminium is sputtered during the three month experiment duration due to impacting AO at an altitude of 650 km. Summation of the sputtering flux for all incident particles for the duration of the three month experiment leads to a combined material loss of 0.104 µm of aluminium being negligible for a tape thickness in the order of 10-20 µm.

Outgassing

Outgassing requirements for the EDT materials are taken directly from the Delfi-1 outgassing requirements. These state the maximum amount of material and contaminants a material used onboard Delfi-1 may produce due to outgassing effects in space.

REQ.4200.52 Total Mass loss TML

To limit damage to the spacecraft due to out-gassing effects, materials used on the spacecraft shall have a total mass loss of less than 1%.

REQ.4200.53 Volatile Condensing Material CVCM

To limit damage to the spacecraft due to out-gassing effects, materials used on the spacecraft shall have a volatile condensing material of less than 0.1%.

In appendix 11, table a11-5 the TML and CVCM for Kapton® and a number of adhesives are listed, not all types of adhesive meet the requirements for Delfi-1. To limit the outgassing of the adhesive the tether can be baked out in vacuum after winding on the reel as done for the EDDE tether [Pearson]; further research is required to determine if this is necessary. Perforation the enforcement substrate will allow trapped air and outgassed products to escape preventing them from degrading the adhesive bond [Tomlin; ECSS³].

REQ-48 TET Enforcement

Perforate the enforcing tape to allow for evacuation of trapped gasses

The enforcement material and protective coating applied to the tether will have to be resilient to both AO erosion, sputtering, outgassing and UV-particle radiation effects. In the next section potential materials and the design for the enforcing substrate, protective coating and adhesives are outlined.

Enforcing Material

Functions of the enforcing material are

- Prevent severance of the tether due to operational loads and M/OD grazing the tether edge; the rip stop protection function preventing tears in the tether from propagating through the entire width of the tether ensuring $A_{min}$
- Deployability of the tether [TBD 28]
- Thermal control

With the tether consisting of aluminium foil laminated to a plastic substrate the material properties have to be similar so they deform in the same way preventing strain between the layers. For the EDT the operational tension levels are low, see figure 5.3, this is not expected to be a critical issue.
The main function of the enforcing film laminate is rip stop protection and can subsequently be made as thin as possible.

Films used for thermal control blankets and solar sails are initially considered practical materials to use for enforcing the tether. Available off the shelf adhesive tapes used in space commonly start at a thickness of 50 µm this is potentially too large if a single wound tether on reel is to fit on the payload platform, see figure 8.2. Another example of thin foils consisting of a plastic type substrate used in space applications are solar sails. Most solar sail substrates consist of 1 µm-5 µm aluminised Kapton® or Mylar®. Polyamides films like Kapton®, have high thermal stability, high strength and medium folding endurance. Kapton® polyamide films also have a low outgassing rate in vacuum, minimal UV-degradation and have been used extensively in space and have a good adhesion to metal films, tapes and adhesives. Thin film Kapton® is commercially available from 7.5 µm [DuPont™] thinner films of 2 µm have handling and manufacturing difficulties making them non commercial. Mylar® films of 0.9 µm are commercially available [McInnes]. The material used for the re-enforcement of the tether can also help to control the temperature of the aluminium tether. The enforcing material is required to have a high emittance factor $\varepsilon$ [Pearson], $\alpha/\varepsilon \sim 1$ [Kruijff], tether substrate requirements [REQ-49] are summarised in the EDT system requirements listed in the annex of this report.

**Adhesive**

Solar sails are usually comprised of individual elements of sail film which are bonded together using a suitable adhesive. Adhesives for load carrying structures shall have a high strength and peel strength properties. Characteristics of some adhesives are given in appendix 11, table a11-4. The properties of the adhesive must be similar to the substrate and is required to function at an initial tether temperature range estimate of ±150°C [REQ-50]. Generally adhesives are limited from -60°C to +250°C making them temperature critical for the lower temperature range of the tether. Silicone adhesives have the widest temperature range [Conely]. Acrylic film adhesives are often used for laminating Kapton® film layers of thermal heaters, having an upper temperature range of 150°C [Pisacane]. Adhesive requirements [REQ-51] are summarised in the annex of this report. The silicone adhesive NuSil [Conely; NuSil] could be a viable option having the following properties:
- Temperature range -115°C to 200°C (Proven to -140°C – 310°C)
- Outgassing TML 0.31% CVCM 0.01%
- 1.12 gm$^{-2}$ lighter than Kapton® per micron thickness

More research is required into the manufacturing of the tether, configuration and mechanical requirements of the laminate concerning flexibility when selecting an adhesive, for design purposes it is assumed a 1 µm -2 µm is required at this stage.

**Coating**

Functions
- Protect bare aluminium from oxidation < 700 km
- Protect enforcement material from AO erosion < 700 km
- Increase friction during deployment acting as a brake dissipating energy that would otherwise end up in $v_{EM}$ and IP librations, see section 3.3 [TBC 35]
- Thermal control of the tether [TBC 36]
- Protect from cold welding [TBD 30]

The bare tether needs to be coated to prevent oxidisation of the tether and possible cold (vacuum) welding of the tether when stored onboard Delfi-1. Exposure to oxygen or certain other reactive compounds produces surface layers which reduce the effective current collection area. Storage tests of the tether will have to be performed to ascertain the risk of cold welding occurring. The enforcing laminate requires protection from the AO environment for altitudes below 650 km-700 km [Pisacane]. The coating should have a large optical emittance to limit the heating of the tether and increasing the long-term stability of the tether librations (section 3.3), be conductive, resistant to atomic oxygen erosion for lower altitudes, have low outgassing and being resilient enough to survive the deformations during deployment. Thickness of protective film coatings 0.06 µm -0.07 µm thick for protection against AO erosion and oxidation effects [Conely]. Silica, alumina or organic coatings >1 µm thick can be used for thermal control purposes of the tether by increasing the emittance limiting maximum temperatures and subsequently resistance losses [Cosmo].
A section of coating will be used to increase the friction of the tether during the final stages of the deployment acting as a deployment control system (DCS) if required limiting the end mass velocity at the end of the deployment phase. The requirements for the tether coating material [REQ-52] are listed in EDT system requirements (annex).

The conductive (film) coating TOR-BPTM was developed for the bare electrodynamic tether of the ProSeds mission having a thermal control function [Kruijff; Triton] by Triton Systems Inc. The advantage of TOR films over SiO$_2$ films is that they have a similar thermal expansion to aluminium preventing premature delamination of the coating due to temperature variations [Schuler]. They however do not adhere to the outgassing total mass loss (TML) requirement <1% shown in appendix 11 listing the properties of TOR coatings. This protective coating could possibly be used as rip stop protection for the aluminium foil depending on method of appliance to the tether either as a film or as a resin [TBD 31]. More research is required on the properties of the protective coating film or resin, determine if it will be sufficiently conductive and potentially limit the maximum temperature of the tether if required. Determine if when applied as a thin film coating it will increase the tear strength of the tether acting as rip stop protection allowing the elimination of the enforcing substrate.

Adhesives and coating materials where found to generally have a lower temperature limit of -115°C, adding a margin of ±15 K [ECSS] on initial tether temperature calculations a required minimum temperature of -100°C is set for the tether.

\[ T_{\text{tet, min}} = \text{minimum operating temperature} = -100^\circ\text{C} \]

### 5.1.2 Electrical and Mechanical Loads & Design

Functional failures of the deployed tether can be divided into mechanical, electrical and out of bound tether librations. Mechanical failure, tether severance, due to loads acting on the tether or M/OD impact is a function of the cross sectional area of the load carrying component of the tether being either the conductive layer $A_c$ or the enforcing layer $A_{\text{sub}}$ and the material strength. Electrical conducting failure is a function of the cross sectional area of the conductive component $A_c$ and will determine the tether thickness and amount of tether width that needs to be enforced giving the minimal cross sectional area in case of tether tears occurring in the tape. Collection failures will be due to either tether severance decreasing the length and bias or insufficient $A_{\text{coll}}$ due to either tether severance or surface degradation. The tether is divided into a nominal, damaged but functional and non operational status:

- Tether nominal no cut; no tear cross sectional area $A_c$, current collection area $A_{\text{coll}}$ librations $< 20^\circ$
- Tether having a tear, no cut, resulting in the % of $A_c$ enforced results in a minimal area $A_{\text{cmin}}$, for conductive function intact and tension load carrier either conductive or enforcement layer, current collection area is assumed to remain $A_{\text{coll}}$, librations $< 20^\circ$
- Non operational; tether cut or librations severely enough to prevent sufficient current collection and conduction

Electrical current load carrying function will determine the conductive tethers thickness $t_c$ and width of the enforcing substrate $w_{\text{sub}}$ resulting in a minimal conductive cross section for an operational tether in case of the tether ripping or being grazed by M/OD and the minimum cross section at certain points along the tether length reduced to the enforced width of the tether.

\[ A_{\text{cmin,ELEC}} = w_{\text{sub}}t_c \]  

\[ t_c \] – thickness conducting material [m]  
\[ w_{\text{sub}} \] – width enforcing material [m]

Mechanical load carrying function has to be performed by the enforced width of tether with either the conductive layer or the enforcing layer with the stiffer layer carrying most of the load [Pisacane].
These loads are discussed in more detail below.

Electrical Loads

To ensure the tether can provide for its electrical conducting function the conducting section of tether will be dimensioned for a maximum current level rating. In section 2.1.2, table 2.1 the maximum induced bias for the EDT mission was determined to be 62 Vkm$^{-1}$ for a nadir-zenith oriented tether. Peak current levels occur due to ionospheric density variations are assumed to be a factor 2 over $I_{OML_{max}}$. Scaling gas currents with the 1.1 A generated by the TSS mission factors of 1 x to 51 x $I_{OML_{max}}$ are seen for the 250 m-2500 m lengths and 5-80 mm wide bare tethers having no enforcing substrate. The design current load $I_{max}$ for the tether consists of the following

- $I_{OML_{max}}$ continuously, equation (2-12)
- a margin for peak current loads 2 $I_{OML_{max}}$ [TBC 37]
- a margin for gas discharge current (assume saturated case) 2-10 [TBC 38]

Resulting in current loads a factor 4-20 times $I_{OML_{max}}$, values shown in figure 5.1 for an entirely bare tether inducing maximum current levels. With the tether enforced over part of the tape width the current collection area will be reduced resulting in lower $I_{max}$ levels.

\[
A_{c_{\text{min,MECH}}} = w_{sub} (t_c + t_{sub}) \quad (5-4)
\]

\[t_{sub} \quad \text{– thickness enforcing material [m]}\]

$A_{c_{\text{min,MECH}}}$

Figure 5.1: $I_{max}$ including margin peak and gas currents vs. $L_t$ for various $w_c$, $t_c$ - 15 µm

As can be seen above wider and longer tethers induce a higher current these dimensions being more critical for the current loads the tether will be designed to handle. The minimum cross section of conductive tether $A_{c_{\text{min}}}$ required for $I_{max}$ has been determined by the maximum voltage drop due to Ohmic resistance. To minimise voltage losses in the system maximising the effective tether length used for current collection the voltage losses due to tether resistance are required to be at least a factor 10 [TBC 39] smaller than the induced EMF over the tether, see also section 2.2.1. Initial tether design will be performed assuming a factor 10 is sufficient resulting in a worst case tether efficiency of 90% in the Delfi-1 orbit range

REQ-53 Tether Voltage Drop

The resistive voltage drop over the tether shall be smaller than the induced EMF by a factor 10

\[
10 \frac{\rho L}{A_{c_{\text{min}}}} I_{max} \ll L_t E
\]

Resulting in a minimum cross sectional area requirement of

\[
A_{c_{\text{min}}} \gg \frac{(10) \cdot I_{max} (T) I_{max}}{E} \quad (5-5)
\]

\[
r_{\text{max}} \quad \text{– specific resistance aluminium at 150°C [Ωm]}
\]

\[
l_{max} \quad \text{– maximum current load of the tether [A]}
\]

With the current distribution shown in figure 2.5 resistance losses will vary with the $I_{OML}$ distribution, equation (5-5) will give an upper limit for the resistance losses.
The tether cross sectional area $A_c$ and current collection area $A_{coll}$ are both a function of the tether width and thickness. For a low tether density $\rho_t$ and efficient current collection area the tape tether is preferable designed as wide as thin as possible. Increasing the thickness of the tether will have a minimal impact on the current collection area but cause a significant increase in the tether conductive cross-sectional area. An effective way of reducing the voltage drop in the tether without significantly increasing the amount of current is by increasing tether thickness. This does however come at a mass and storage penalty; higher current systems require thicker tethers and have more mass.

![Graph showing $\text{t}_{\text{cmin}}$ non-enforced TET w with enforced widths %w](image)

Figure 5.2: $\text{t}_{\text{cmin}}$ non-enforced TET w -30 mm and enforced widths %w -30 mm

Longer tethers require a thicker tether to limit the voltage drop, as can be seen in figure 5.1. and figure 5.2. Designing the tether for a current rating 20 times $I_{\text{OML}}$ max taking peak current level margins of 2 and gas current level margins of 10 into account is impractical and also over-dimensioning the system for a major part of the orbit range leading to required tether thicknesses of up to 250 $\mu$m. To minimise the tether mass and storage dimensions and stiffness $E_A$ (deployability) the maximum design current levels are rated a factor $4 \times I_{\text{OML}}$ max(650 km;110$\degree$) [TBC 40]. This requirement needs to be validated and verified with other EDT designs and will have to be taken into consideration when designing the gas cathode system.

**REQ-54 TET Current Load Rating $I_{\text{max}}$**

The TET will be designed to handle peak and gas current loads of $4I_{\text{OML}}$ max generated in a 650 km-110$\degree$ orbit [TBC 40]

Enforcing the bare tether width on one side over 30% of $w_c$ reduces the current levels $I_{\text{max}}$ however with the cross section also reduced by 1/3 a thicker tether is needed to limit the voltage drop over the tether, this effect is illustrated in the left figure 5.2. Enforcing more width eventually reduces currents and decreases the $A_{\text{cmin}}$, a thinner tether can be used at the cost of a reduced deorbit performance. Limiting the tether temperature will increase the number of tether configurations with an Ohmic voltage drop < 10 EMF by reducing tether resistance, see appendix 6 for specific tether resistance as a function of tether temperature.

**Dielectric Strength & Breakdown**

Kapton$^\circledR$ film has a dielectric strength of 279 V$\mu$m$^{-1}$ for a 2-7.5 $\mu$m substrate the Kapton$^\circledR$ film can handle disruptive discharges produced by 550 V to 2000 V, with the maximum bias of the tether for a 2500 m tether at the cathode end of -150 V for 62 Vkm$^{-1}$ [appendix 5; table a5-2] this is not a critical design issue, thin Kapton$^\circledR$ substrates can be used.

**Mechanical Loads**

With aluminium having both the largest modulus of Elasticity, 70 GPa compared to and Kapton$^\circledR$ and Mylar$^\circledR$ 2.96 GPa -3.79 GPa and the largest cross-sectional area it has been assumed that the conducting part of the tether is also the main load carrier with the Kapton substrate primarily serving as rip stop protection. The conductive bare tether is a mission failure critical component and subsequently needs to be able to handle all the static and dynamic operational and deployment loads including sufficient design margins on these loads. In the following section all loads encountered by the tether combined with the influence of the operating environment are described.
Operating Loads

Using equation (2-18) the maximum tension for an enforced aluminium tether with a ballast mass \( m_b \) of 0.83 kg to 1.83 kg and the long term stable configuration using \( m_b - 4m_t \) [TBC 7](see section 3.3) have been calculated in the Tether Design tool showing that tension at most is 0.35 N for the 650 km orbit altitude. In the figure below results are shown for a constant 1 kg end mass and a 4m, kg end mass, the latter leading to the highest tension loads on the tether.

![Graph showing maximum operating tension loads](image)

**Figure 5.3: Maximum operating tension loads**

Deflecting the tether into the deployment direction introduces shear forces into the tether increasing the risk of tether rupture. A deployment test has shown that pulling the tether from the reel and deflecting the direction by 90° does not show major difficulties if the accelerations are low [Heijning]. A safety factor of 1.5 is added for inhomogeneity and 4 for bending around blunt edges of the tether (deflection roller and reel axel) [Kruijff]. During deployment limiting the maximum end mass (EM) velocity \( v_{EM,max} \) resulting in a tension jerk smaller than the ultimate load of the tether is required, see section 3.3. The work of [Heijning] concludes that tether jerk at the end of deployment is not a critical design issue for deployment due to limited end mass velocities, also see section 6.2. A safety factor of 3 is used in accordance with [Kruijff] on the tether design strength for tether jerks occurring at the end of deployment.

Stress Corrosion [TBD 29]

The tether is subject to a dynamic load environment and the conductive bare tether is a failure critical component combined with its minimum half year storage time on the ground the bare tether needs to have a high resistance to stress corrosion cracking (SCC) even with the low tensile operational forces [ECSS]. A number of aluminium alloys are considered to have a high resistance to SCC with alloys 1000-3000-5000-6000 applicable in all manufacturing conditions.

Thermal Environment

The strength of aluminium alloys is a function of temperature. Most common alloys have a plateau of strength between -100°C and 100°C with higher strengths below this range and lower strengths above it. Ultimate strength increases 30% - 50% below this range, at low temperatures the yield strength increases in the order of 10%. Above 100°C the yield and ultimate strength drop rapidly. Some alloys can operate at temperatures up to 300°C at a lower strength [Harper]. The TET is not near load carrying capacity, thermal heating is not critical for material strength requirements.

Thermo-Mechanical Loads

Under intense heating high temperature gradients may occur across non-metallic tethers with their thermal conductivity \( k_{sub} \) being in the order of 0.12 Wm\(^{-1}\)K\(^{-1}\) for Kapton [appendix 11]. These gradients may cause either overstress or stress relief on the hot side, depending on the sign of the axial thermal expansion coefficient [Cosmo]. With the substrate laminated to the aluminium tether \( [k_{alu} – 250 \text{ Wm}^{-1}\text{K}^{-1}] \) along the entire length and being thin it is assumed that no temperature gradients will occur in the tether. Thermo-mechanical loads peak when the tether moves from solar to eclipse and vice versa when passing the terminator with mean thermo-mechanical loads being a function of \( \alpha \) and \( \Delta T \) between eclipse and solar part of the orbit [Beletsky].
\[
\frac{F_{tm}}{T} = \alpha \Delta T \quad (5-6)
\]

- \(F_{tm}\)  - thermo-mechanical loads [N]
- \(\alpha\)  - CTE thermal expansion coefficient of the material [°C^{-1}]

\(\alpha = 23.4 \times 10^{-6} \text{°C}^{-1}\) is an average value for aluminium alloys at 23°C to 100°C which increases for higher temperatures of the tether. For a maximum \(\Delta T\) of 300°C the mean \(F_{tm}/T\) ratio is 7e-3 for an aluminium tether and 6e-3 for Kapton.

They only occur at the suspension point of the tether where tether is constrained.

**Design Safety Factors Tether Strength**

A safety factor of 18 on the maximum tension occurring during deployment [TBC 41] and a safety factor of 6 during nominal tether operation. The safety factor is comprised of [Kruijff]

- Tension jerk during deployment safety factor: 3 [TBC 41]
- Tether inhomogeneity safety factor: 1.5 [TBC 41]
- Tether bending around edges safety factor: 4 [TBC 41]

**REQ-55 SF Operating Tether Strength**

The design strength of the tether will incorporate a SF of 18

\[T_{des} = 18T_{max} = [0.016 \text{ N to } 5.95 \text{ N}]\]

**Manufacturing, Handling and Winding Loads**

Operating tension levels are not considered to be a driving design parameter for the tether, the tether needs to withstand both manufacturing; handling and winding loads so dimensioning the tether for operating tension will make the tether unmanageable. [Tomlin] recommends an ultimate tensile strength of 100 pounds (445 N) ensuring the tether is not too fragile. This leads to significantly thick tethers for the lower end of the width range being considered. Based on commercial available aluminium foils and EDDE tether being considered sufficiently strong to be manageable and producible the handling load requirement is derived for the EDT. The minimum tether thickness required to allow tape tethers of widths from 5 mm-80 mm to adhere to these handling loads assuming the tether is launched undamaged is calculated using

\[
T_{hand} = \sigma_{ul} w_t t_c, \quad (5-7)
\]

- \(\sigma_{ul}\)  - ultimate strength material [Nm^{-2}]
- \(T_{hand}\)  - handling loads [N]

![Graph](image_url)

**Figure 5.4: Minimum \(t_c\) for handling loads**

The EDDE experiment consisting of a 30 mm wide - 38 mm thick aluminium foil [Pearson] has an ultimate strength of approximately 85 N, manufactured aluminium foils range from 2.3 N-342 N for ordinary household foil; see table a11- 2 in appendix 11. In figure 5.4 the effect on tether thickness \(t_c\) is shown for \(T_{hand} = 25 \text{ N-85 N}\).
With storage dimensions critical for the Delfi-1 mission the minimum handling loads have been selected for the conducting tape tether.

**REQ-13 Minimum Handling Loads Capability**

The conducting foil shall be designed to be able to withstand loads of up to 25 [N] [TBC 42] ensuring the tether is not too fragile.

Winding the tether on the reel under tension can be useful for a stable deployment and ensuring the tether stays on the reel during launch [Heijning]; this is expected to be lower than the required handling loads being 4.5 N for the ATEx tether [Koss].

**Tether Twist (torque)**

All tethers deployed in space have a certain amount of twist. For single winding on a reel with the tape tether it is not possible to counteract this twist when winding the tether on the reel. The amount of twist is mainly a function of length [Tomlin]. All performance calculations of the tether have assumed the tether to be twisted as use is made of the equivalent tether diameter \(d_t\). Tether material should ideally not be damaged during deployment and twist of the tether needs to be taken into account. The amount of torque and twist in orbit is unknown. Generally the torque is expected to be small and may unwind after deployment, thermal effects on twist are expected to be small [Tomlin]. Tests on the foil tether will have to indicate if the tether is capable of handling loads when various amounts of twist are imposed on the tether.

**Tension at rupture (break tension)**

\[
T_{\text{ult}} = \sigma_{\text{ult}} A_c, \quad (5-8)
\]

- \(A_c\) – cross sectional area \([\text{m}^2]\)
- \(T_{\text{ult}}\) – ultimate tension at rupture \([\text{N}]\)

The conductive part is load carrying as it is the stiffer layer of the laminate:

\[
E_c A_c << E_{\text{sub}} A_{\text{sub}}
\]

The margin of safety on operational loads is given as

\[
MS = \frac{T_{\text{yield}}}{T_{\text{ops max}} \times SF} - 1 \quad (5-9)
\]

An aluminium foil having the minimum required \(A_{\text{cmin}}\) from equation (5-5) and a yield strength \(\sigma_{\text{yield}}\) of 28 MPa is capable of meeting the TET design strength requirement by a margin of safety factor \((MS) > 0\) for the \(m_1/m_2\)-0.25 ratio.

The 100% enforced tether requiring smallest \(A_{\text{cmin}}\) to meet the voltage drop requirement due to having the lowest current levels is still capable of achieving a margin of safety of 9-30 on operational loads having ultimate strengths ranging from 0.3 - 155 N. Operational tension loads including a safety factor of 18 are not considered to be design critical.

**5.1.3 Thermal Analysis**

Thermal analysis is performed to determine the extreme temperatures of the tether for the deployment and operational phase of the EDT experiment. The material used for the reinforcing the foil and the protective coating of the tether can help to control the temperature of the conductive aluminium. Tether temperature mainly affects the following properties of the tether:

- Electrical properties; Ohmic resistance [appendix 6]
- Material properties
- Mechanical properties
- Thermal expansion tether and thermal expansion coefficient
  - pay attention to during deployment phase [Gates]
- Temperature gradients causing stress (non-metallic material)
Thermal effects of radiation environment consisting of solar, albedo and infrared radiation and space combined with internal heat generation and heat conduction between SC and EDT determine the thermal balance and heat transfer of the system [TN.4116.01]

\[ \frac{mc}{dt} \frac{dT}{dt} = Q_s + Q_a + Q_w - Q_{out} + Q_{ext,ir} \]  \hfill (5-10)

\[ T \quad – \text{temperature [K]} \]
\[ m \quad – \text{mass [kg]} \]
\[ c \quad – \text{heat capacity [Jkg}^{-1}K^{-1}] \]
\[ Q_\text{– energy [W]} \]

In appendix 13 the thermal inputs for the Delfi-1 orbit range are calculated. A summary of the results obtained are given below.

**Table 5.7: Summary thermal environment EDT**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar constant S_s</td>
<td>1366 Wm^{-2}</td>
</tr>
<tr>
<td>Albedo factor a</td>
<td>0.34 valid for short simulations</td>
</tr>
<tr>
<td>Earth IR radiation Flux</td>
<td>[258\sin^2\rho_E(650 \text{ km}) \text{ Wm}^{-2}]</td>
</tr>
<tr>
<td>Flux IR Day</td>
<td>[216\sin^2\rho_E(1000 \text{ km}) \text{ Wm}^{-2}]</td>
</tr>
<tr>
<td>Temperature Space</td>
<td>0 K</td>
</tr>
</tbody>
</table>

For this initial design phase the steady state temperatures for two extreme scenario’s defining upper and lower bounds of the tether temperature during operation, a cold and a hot case, are examined. In reality due to transient effects temperature will range between these values [Wertz]. The steady state approach provides useful initial design values for determining thermal effects on the design. For steady state temperature analysis the effect of material density and capacity is neglected and the temperature is determined using a simple heat flux balance. The temperature of each node is the required temperature to balance the heat inputs with heat lost due to radiation. Two separate tether geometries have been evaluated for a first approximation tape tether hot – cold case assuming a single tether node

**Case 1:** Consider tether to be a rigid flat plate one side Kapton®/Aluminium, other Aluminium

**Case 2:** Take tether twisting into account using effective diameter tether d_t using equation (2-8) modelling the tether as a cylinder

\[ \beta = 90^\circ \quad \beta = 0^\circ \]

\[ S_s \quad S_s \]

\[ T_{max} \quad \theta_s = 0^\circ \]

\[ T_{min} \quad \beta = 90^\circ \]

Figure 5.5: Hot and cold case schematic

All steady state temperatures derived in this section require a margin of ±15 K during the initial design phase [ECSS]. The steady state temperatures are calculated from (5-10) using equations (A13-7), (A13-9), (A13-12), (A13-13) and (A13-14) from appendix 13.

\[ \frac{dT}{dt} = 0 \quad T_{ss} = \left( \frac{k_s \alpha S_s + k_s \alpha A_s a \cos \theta_s \cos \phi + \alpha_n A_n F S_n + I_{ext,ir} R}{\epsilon_n A_{nir} \sigma} \right)^{1/4} \]  \hfill (5-11)

\[ T_{ss} \quad – \text{steady state temperature [K]} \]
\[ S_\text{– flux [Wm}^{-2}] \]
\[ F \quad – \text{Earth view factor, see appendix 13} \]
\[ \alpha \quad – \text{absorption coefficient} \]
\[ \epsilon \quad – \text{emission coefficient} \]
\[ k_s \quad – \text{solr 1 eclipse 0} \]
\[ A_\text{– surface area normal to specified incoming radiation flux} \]
\[ \sigma \quad \text{– Stephan Boltzmann constant } 5.67 \times 10^{-8} \text{[Wm}^{-2}\text{K}^{-4}] \]
\[ \rho_E \quad \text{– angular radius Earth [rad], see appendix 13} \]
Angular deviation from subsolar point with the subsolar point assumed constant for 1 orbit
\[ \phi_1 \quad \text{– ecliptic angle assumed 0 [°]} \]
\[ \theta_S \quad \text{– orbit angle w.r.t. the subsolar point [°]} \]

The hot case has maximum heat flux exposure, see figure 5.5. When the sun out of plane angle \( \beta \) is 90° the tether is fully exposed to the sun for the orbit angle \( \theta_S \) of 90° - 270°:

\[
T_{\beta=90°} = \left( \frac{k \alpha \epsilon aSF + \epsilon_{ir} \alpha \epsilon_{ir} FS_{solar} + I_{OMI}^2 R_{OMI}}{\epsilon_{ir} \alpha_{ir} \sigma} \right)^{1/4}
\] (5-12)

The cold case simulates minimum heat fluxes absorbed by the tether for eclipse conditions and low heat generation due to tether for the Sun out of plane angle \( \beta \) - 0° for orbit angles \( \theta_S \) ranging from 0° to 360°, see figure 5.5:

\[
T_{\beta=0°} = \left( \frac{\alpha \epsilon aFS + \epsilon_{ir} \alpha \epsilon_{ir} FS_{eclipse} + \alpha \epsilon aFS \cos \phi \cos \theta + I_{OMI}^2 R_{OMI}}{\epsilon_{ir} \alpha_{ir} \sigma} \right)^{1/4}
\] (5-13)

Ohmic losses are negligible for the tether heat balance; solar radiation is the dominant factor for tether heating as can be seen in table 5.8. Optical properties for the enforcing substrate specifically the materials absorptivity change due to environmental effects increasing slightly for the enforcing substrate. Optical properties used for initial temperature analysis are shown below [appendix 11], the final selection of the tether's aluminium alloy and production method and amount of oxidation occurring during production will determine the final optical properties of the tether.

- Aluminium \( \alpha_{alu} \approx 0.35 \), \( \epsilon_{alu} \approx 0.15 \), \( \alpha_{alu}/\epsilon_{alu} \approx 2.3 \) and \( \alpha_{alu} \approx 0.3 \), \( \epsilon_{alu} \approx 0.03 \) [TBD 34]
- Kapton\( ^{(a)} \) \( \alpha_{sub} \approx 0.14 \text{ - 0.25 (EOL)} \), \( \epsilon_{sub} \approx 0.6 \), \( \alpha_{sub}/\epsilon_{sub} \approx 0.2 \) [TBD 35]

Typical results for a tether of 1000 m; 30 mm; 15 \( \mu \)m bare aluminium tether are given for both the flat plate and the cylindrical geometry in the next table.

<table>
<thead>
<tr>
<th>( \alpha ) - 0.35 ( \epsilon ) - 0.15 ( \alpha/\epsilon ) - 2.3</th>
<th>( \alpha ) - 0.35 ( \epsilon ) - 0.15 ( \alpha/\epsilon ) - 2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot case ( \beta=90° ) flat tether</td>
<td>Hot case ( \beta=90° ) equivalent cylinder</td>
</tr>
<tr>
<td>( Q_s )</td>
<td>14343 W</td>
</tr>
<tr>
<td>( Q_a )</td>
<td>0 W</td>
</tr>
<tr>
<td>( Q_{\text{IR}} )</td>
<td>115 W</td>
</tr>
<tr>
<td>( Q_{\text{internal}} )</td>
<td>0.02 W</td>
</tr>
<tr>
<td>( T_{\text{HOT}} )</td>
<td>+136.9 ±15 °C</td>
</tr>
<tr>
<td>Cold case ( \beta=0° ) flat tether</td>
<td>Cold case ( \beta=0° ) equivalent cylinder</td>
</tr>
<tr>
<td>( Q_s )</td>
<td>0 W</td>
</tr>
<tr>
<td>( Q_a )</td>
<td>0 W</td>
</tr>
<tr>
<td>( Q_{\text{IR}} )</td>
<td>86 W</td>
</tr>
<tr>
<td>( Q_{\text{internal}} )</td>
<td>0.0013 W</td>
</tr>
<tr>
<td>( T_{\text{COLD}} ) range</td>
<td>-158.8 ±15 +136.8 ±15 °C</td>
</tr>
<tr>
<td>( \alpha ) - 0.3 ( \epsilon ) - 0.03 ( \alpha/\epsilon ) - 10</td>
<td>( \alpha ) - 0.3 ( \epsilon ) - 0.03 ( \alpha/\epsilon ) - 10</td>
</tr>
<tr>
<td>Hot case ( \beta=90° ) flat tether</td>
<td>Hot case ( \beta=90° ) equivalent cylinder</td>
</tr>
<tr>
<td>( Q_s )</td>
<td>12294 W</td>
</tr>
<tr>
<td>( Q_a )</td>
<td>0 W</td>
</tr>
<tr>
<td>( Q_{\text{IR}} )</td>
<td>23 W</td>
</tr>
<tr>
<td>( Q_{\text{internal}} )</td>
<td>0.2 W</td>
</tr>
<tr>
<td>( T_{\text{HOT}} )</td>
<td>+315.5 ±15 °C</td>
</tr>
<tr>
<td>Cold case ( \beta=0° ) flat tether</td>
<td>Cold case ( \beta=0° ) equivalent cylinder</td>
</tr>
<tr>
<td>( Q_s )</td>
<td>0 W</td>
</tr>
<tr>
<td>( Q_a )</td>
<td>0 W</td>
</tr>
<tr>
<td>( Q_{\text{IR}} )</td>
<td>18 W</td>
</tr>
<tr>
<td>( Q_{\text{internal}} )</td>
<td>0.0013 W</td>
</tr>
<tr>
<td>( T_{\text{COLD}} ) range</td>
<td>-158.7 ±15 +315.4 ±15 °C</td>
</tr>
</tbody>
</table>
The bare tether heats up due to its low optical emittance, for temperatures above 250°C the specific resistance of the tether and subsequent voltage drop will increase by 25%. Choosing the optical properties of the bare tether to limit tether heating will limit the maximum tether temperatures shown in table 5.8. The equivalent cylinder geometry receives less solar radiation due to the smaller projected area compared to the flat tether, in reality the input flux will be in between both cases due to twisting of the tether. Results from the Tether Design tool have shown tether width and length not influencing steady state temperatures significantly; the design variables are the amount of enforcement and the optical properties of the aluminium and enforcing substrate.

REQ-47 Optical Properties TET Aluminium
The $\alpha/\varepsilon$ ratio shall be < 2-2.5 for the aluminium used for the conducting tape [TBC 43]

Steady state temperatures calculated in orbit are shown for both a twisted (cylindrical) and a flat tether geometry. Results obtained for an enforced tether of 1000 m; 30 mm; 15 µm with a substrate thickness of 6 µm having optical properties $\alpha_{alu} - 0.35$  $\varepsilon_{alu} - 0.15$ and $\alpha_{sub} - 0.14$ $\varepsilon_{sub} - 0.6$.

![Figure 5.6: T$_{SS}$ cylinder 0% and 30% substrate $\alpha/\varepsilon_{alu}$2.3 $\alpha/\varepsilon_{sub}$-0.23](image)
The results for the cylindrical geometry above and the flat tether geometry in figure 5.7 show that the substrate is capable of reducing the maximum tether temperature. For the cylindrical geometry the substrate is assumed to be distributed evenly over each area exposed to radiation. In reality twisting of the tether will determine the amount of substrate exposed. Results for the flat tether geometry are shown below, the enforced side oriented towards the sun during the first part of the orbit, bare aluminium for the latter part.

![Figure 5.7: T$_{SS}$ flat tether 0% 30% 50% 100% substrate $\alpha/\varepsilon_{alu}$2.3 $\alpha/\varepsilon_{sub}$-0.23 excl. ±15°C](image)
The rip stop protection having a higher emissivity helps cool the tether down during the solar part of the orbit when the optical properties are $\alpha/\varepsilon < 1$, a thermal coating will also help reduce maximum temperatures however the substrate layer depending on the enforcement area and optical properties is capable of limiting tether maximum temperatures to 100°C reducing the tether resistance losses by 14%.

**REQ-50b**  
**Maximum TET Temperature**  
$T_{\text{tet max}} = 100°C$

**REQ-49-52**  
**Enforcement-Coating (Optical) Properties**  
Enforcing material and coating are required to have $\alpha/\varepsilon < 1$ accounting for an increase in $\alpha_{\text{sub}}$ EOL by a minimum of 0.1 [TBC 44]  
$\alpha/\varepsilon < 0.5$ for 30% enforcement [TBC 44]  
$w_{\text{sub}} \geq 30%w_c$ enabling a tether maximum steady state temperature of 100°C

During eclipse the tether is only subject to Earth infrared radiation and cools down to -158 ±15°C, adhesives and coatings are limited to -115°C resulting in **REQ-50a** $T_{\text{min}} = -100°C$. The minimum temperature depends on the ratio of the area receiving infrared flux and the total area of the tether emitting heat into space.

$$T_{\text{min}} = \left( \frac{\varepsilon_t A_t FS_{\text{infrared}} + I_{\text{OMI}} R_t}{\varepsilon_t A_t \sigma} \right)^{1/4} = \left( \frac{\varepsilon_t A_t FS_{\text{infrared}}}{\varepsilon_t A_t \sigma} \right)^{1/4}$$

(5-14)

The required area ratio for a minimum temperature of -100°C is 0.2, for the flat and cylindrical tether geometry including the Earth View Factors the area ratio is currently 0.06 with the tether hanging vertical along the $z_{\text{OR}}$-axis.

Flying the tether at an angle of 20°C the tether receives more infrared radiation resulting in a minimum temperature of -124±15°C. With a decrease in projected area receiving solar radiation the maximum temperature is also reduced as can be seen below.

![Figure 5.8: TSS flat tether 30% substrate $\alpha/\varepsilon_{\text{alu}} -2.3$ $\alpha/\varepsilon_{\text{sub}} -0.23$ at $\theta_t - 20°$](image)

Modelling the geometry of the tether for various amounts of twist and determining the effect of the substrate on the twist is required as the amount of area with substrate exposed to heat fluxes has a significant impact on tether temperatures.

**Conduction**

Delfi-1 requirements state that each substructure must be thermally conductive with the satellite structure [REQ.4110-4120.20]. This will cause the main satellite to act as a heat source or heat sinks for the tether. A maximum temperature difference $dT$ between the EDT experiment and the satellite structure occurs during passage into and out of the eclipse with tether changing temperature more rapid than the satellite bus.
A maximum $dT$ of 230°C for the satellite entering eclipse and 200°C for the satellite exiting eclipse assuming the satellite bus achieves its maximum and minimum temperatures of -50°C and +80°C. The area over which the conduction to the bus will take place is limited to area of tether attached to the reel and reel connection to the bus. Assuming the EDT experiment conducts heat through the reel axel width with a radius $R_a$ and a length $w_c$ with the reel axel outer diameter at the temperature of the tether and the inner diameter connected to the satellite being at satellite temperature the heat flow to the satellite structure can be calculated. Steady state heat conduction over a cylindrical shape is determined using [Wertz]

$$Q_c = \frac{2\pi k L_a (T_w - T_i)}{\ln(D_{outer}/D_{inner})}$$

(5-15)

$Q_c$ − conduction heat flux [W]

$k$ − thermal conductivity for aluminium $k = 250$ [Wm$^{-1}$K$^{-1}$]

$L_a$ − reel axel length [m]

$D$ − reel axel inner and outer diameter [m]

REQ-56 Thermal Conduction to the Delfi-1 Structure

For a 1 mm thick 30 mm wide aluminium reel axel with tether temperatures ranging from ±150°C the heat flow to the TET entering eclipse is 1360 W and to the bus exiting eclipse is 1570 W

Tether Thermal Deformations

Deformations of the tether due to temperature variations assuming a linear, area and volumetric expansion

$$\Delta L = \alpha L_i \Delta T = \alpha L_i (T_f - T_i)$$

(5-16)

$\alpha$ − linear expansion coefficient of the material [m°C$^{-1}$]

$T_f$ − final temperature [K]

$T_i$ − initial temperature [K]

Amount of thermal expansion causes strain to occur in the material see paragraph 5.1.2

$$\varepsilon_{thermal} = \frac{L_f - L_i}{L_i} = \alpha \Delta T$$

(5-17)

$L_f$ − final length [m]

$L_i$ − initial length [m]

The conducting tether will experience a total thermal expansion of 1.76 m-17.6 m in length between temperature extremes of ±150°C for the tether widths ranging from 5 mm to 80 mm 0.035 mm-0.56 mm and the thickness 0.03 µm-0.6 µm for minimum and maximum $t_c$ values of 5 µm-60 µm. The tether is not required to be retractable so deformations are acceptable for the deployed tether. To reduce the effect of thermal expansion of the tether material during deployment the following requirements where derived in the first part of this study

REQ-57 Deployment Restrictions

Deployment shall not occur during transition from solar to eclipse or vice versa

REQ-19b Deployment Duration

Maximum deployment time is 62.3 min solar and 34.9 min in eclipse excluding a contingency factor [TBD 33]

REQ-58 Deployment Mechanism Verification

The deployment mechanism shall be shown to deploy the tether with tether temperatures ranging from $T_{min}$ to $T_{max}$ during deployment
5.1.4 M/OD Risks

In this section the risk of tether severance due to a collision occurring with micrometeoroids and orbital debris (M/OD) is analysed. Break up of the tether resulting in an uncontrolled hard to track tether in orbit increases the risk of an avoidance manoeuvre required by an operational satellite and is extremely undesirable. In the first part of this study an experiment orbit below the International Space Station (ISS) was already indicated to be preferable for performing the EDT experiment ensuring the ISS is not required to perform a collision avoidance manoeuvre and this altitude ensures a fast deorbit of the system thus reducing the risk of collision with other operational spacecraft considerably [TN.4122.23].

M/OD consists of untrackable particles and larger trackable (operational spacecraft) debris. For meteoroids and untrackable space debris statistical particle flux models are available, trackable objects with known orbital elements can be propagated along their orbit and collision events or near-miss events can be predicted [see appendix 3]. The M/OD risk for untrackable particles is predominantly a function of the tether diameter as shown in figure a3-9 in appendix 3. Space debris is the dominant risk for larger tethers (d_t >3 mm) at altitudes above 400 km-500 km. For thinner tethers and/or lower altitudes the risk is mostly from micrometeoroids [Carroll]. An increasing number of M/OD objects occur at altitudes 700 km-1000 km and inclinations 60°-105° [Kruijff]. At an altitude of 600 km orbital and meteoroid fluxes are similar; at 800 km-1000 km the orbital debris increases [Anselmo]. The distribution of catalogued objects in space that are being tracked shown in [Cooke] indicates that the Delfi-1 orbit of 650 km-1000 km at 70°-110° is situated in a heavy populated area of space (including sun synchronous orbits at 800 km; i>80°) with an increased collision risk for space tethers [Cooke]. For the tether collision risk probability calculations use has been made of available statistical flux models for untrackable particles. The risk analysis for trackable debris has not been performed in this study, this should however be taken into account in further studies. Requirements for the tether maintaining integrity during the experiment duration are applicable to the risk of tether severance due to a fatal impact with M/OD being a critical failure.

REQ-59 Tether Integrity M/OD
95% chance of tether integrity being maintained during EDT experiment duration of a maximum of three months

To determine the risk of a fatal impact during a mission of three months for the Delfi-1 orbit range and various tether dimensions existing relations between tether dimensions and the probability of a fatal impact occurring using the available M/OD flux models have been used. Below the chance of collision occurring, M/OD fluxes encountered by the tether and the size of particles capable of severing a tether are discussed.

Tether Severance Probability

Debris especially meteoroids originate from various directions shown in appendix 3; figure a3-7 requiring the use of the tether effective projected area. With debris particle size and fluxes varying widely between orbits the debris particle sizes versus the tether size has to be taken into account as not every particle impact will sever the tether. In this section the probability of a fatal impact is calculated incorporating the variations in particle fluxes for different orbits and the size of the particle and impact geometry is taken into account. To determine the probability of a collision occurring in a specified time interval the Poisson distribution is used as collisions are uncorrelated events with an assumed known average rate of events. For spacecraft in general the chance of one or more collisions occurring derived in appendix 9 is

\[ p_{m+d}(k \geq 1, F(m)A\Delta t) = [1 - p_{m+d}(0, F(m)A\Delta t)] = 1 - e^{-F_{m+d}(m)A\Delta t} \] (5-18)

\[ F_{m+d}(m) \] – cumulative M and OD flux density for particles of mass > m per unit of time and area
A – area of interest
\Delta t – time of interest

Different from most spacecraft for tethers the size of the particles capable of causing a critical failure are not small compared to the tether diameter and subsequently geometry, dimensions and orientation in orbit need to be taken into account.
Instead of the cumulative flux used in (5-18) differential fluxes need to be used due to the tether diameter being of similar magnitude to the debris [Tomlin]. To this end the Poisson collision risk for spacecraft is adapted to tethers taking into account their deviating geometry, thinness and orientation [Cooke; Tomlin; Anselmo]. The following parameters are required

- Debris flux data [appendix 3]
- Earth shielding and gravitational focussing effects [appendix 3]
- Differential flux $dF_{m+d}(d_{MOD})$ a function of debris particle size $d_{MOD}$
- Effective cross sectional area; projected area (tether angles)

**Differential Flux $dF_{m+d}$**

Use is made of the differential flux $dF_{m+d}(d_{MOD})$ with respect to the particle diameter instead of the cumulative flux $F_{m+d}(m)$ used to determine collision probability for the tether taking into account the size of particles capable of severing the tether. Combining the fluxes for each orbit of the Grün and NASA90 debris flux at epoch 2000, see appendix 3, the cumulative surface and cross-sectional area flux $F_{m+d}(d)$ flux for each orbit is obtained. For the debris size intervals $\Delta d$ the flux is differentiated with respect to the particle diameter giving the average differential particle fluxes $dF_{m+d}$ [Cooke].

**Critical M/OD Impact**

Not every impact will result in a critical tether failure, the impacting particle must be large enough to cause sufficient damage and destroy a minimum amount of the tether diameter causing it to sever. The critical size of a particle depends on both tether material and dimensions-configuration. To determine the critical M/OD particle size impact tests and research of tether material and design are required. Laboratory results of single strand aluminium tethers suggest particles of sizes $\geq 0.25d_t$ for tethers with diameters $> 1$ mm with the particle passing the tether edge within $0.2-0.35d_t$ of centre tether can sever the tether [Cosmo]. Impacts destroying 30% of the tether diameter will sever it. This needs to be re-evaluated for wide foil tether but is assumed to valid at this point.

**Critical Failure Collision**

Tether severance occurring due to impact with a M/OD particle when

1. $d_{MOD} > d_{cr}$ with $d_{cr} = 0.25d_t$ the critical particle size capable of severing a tether
2. Particle hits tether within distance $d_{cr}/2 = 0.35d_t$ from the tether centre with $d_{cr} = 0.7d_t$

**Effective Collision Cross-Sectional Area**

The cross-sectional area $A_{MOD}(d)$ of the tether is a function of the debris size [Cooke]

$$A_{MOD}(d) = (d_{w,MOD} + 0.7d_t)L$$  \hspace{1cm} (5-19)

$d_{w,MOD}$ – particle diameter [m]

$d_t$ – tether effective diameter or projected width [m]

The effective diameter of a tape tether is a round tether with an equal drag to the tape tether and can be used for lifetime and debris impact calculations taking twisting of the tether into account. For a tape tether, no twist occurring, the effective cross-sectional area is a function of the incident angle of the colliding particle and the projected area of the tether normal to the incoming particle, see appendix 9 for calculation of projected tether width. For a tape tether small particles impact on the flat (w) side can take place at very small angles effectively reducing the projected area of the tether. Also particles impacting the w side of the tether have to be larger to cut the tether than particles impacting the t side. The aspect ratio w/t of the tether determines the projected area taking into account the view factor of the vulnerable part of the tether.

The tether severance probability for an equivalent drag cylinder and a tape tether using geometric models from [Pardani; Oishi] see appendix 9, has been calculated with results shown for a 1000 m tether in table 5.9.
Table 5.9: Tape tether projected area vs. equivalent drag tether\(^9\) time period 1 yr

| \(L_t\) | \(1.00E+03\) m |
| \(w\) | \(3.00E+01\) mm |
| \(t\) | \(0.015\) mm |
| \(d_c\) | \(4.78\) mm |
| \(d_{tc}\) | \(13.4\) mm |
| \hline
| \text{tape tether} & \text{equivalent drag cylinder} |
| \# hits per yr & \(7.171E-02\) & \(6.694E-03\) |
| MTBF yr & \(14\) & \(149\) |
| months & \(167\) & \(1793\) |
| 1 yr \(P_{\text{surv}}\) & \(93.33\%\) & \(99.34\%\) |

Debris is assumed capable of severing tether from any incident angle for the equivalent drag cylindrical geometry; this is not realistic for tape tethers. To take into account the directional difference in flux impact directions between meteoroids and debris the used flux data for meteoroids is surface area flux and orbital debris is cross-sectional area flux taking into account the different incident angles of the particles. Below the probability of surviving three months is shown for various tether dimensions.

Table 5.10: Tether dimensions effect on three months survival probability\(^9\)

| \(w\) - 30mm t-15\(\mu\)m | \(L_t\) -1000 m t-15\(\mu\)m | \(L_t\) -1000 m w - 30mm |
| \(L_t\) [m] | \(P_{\text{surv}}\) 3 months | \(w\) [mm] | \(P_{\text{surv}}\) 3 months | \(t\) [mm] | \(P_{\text{surv}}\) 3 months |
| \hline
| 250 | 99.6\% | 5 | 83.0\% | 1.50E-03 | 97.6\% |
| 500 | 99.1\% | 10 | 91.8\% | 5.00E-03 | 98.0\% |
| 750 | 98.7\% | 15 | 94.0\% | 1.00E-02 | 98.2\% |
| 1000 | 98.2\% | 20 | 96.8\% | 1.50E-02 | 98.2\% |
| 1250 | 97.8\% | 30 | 98.2\% | 5.00E-02 | 98.2\% |
| 1500 | 97.4\% | 40 | 98.8\% | 1.00E-01 | 98.5\% |
| 1750 | 96.9\% | 60 | 99.2\% | 5.00E-01 | 99.1\% |
| 2000 | 96.5\% | 80 | 99.6\% | & | |
| 2250 | 96.1\% | & | & | & |
| 2500 | 96.7\% | & | & | & |

As expected longer tethers have an increased collision area and higher risk of fatal impact occurring, all tether lengths are within the 95\% requirement survival chance. Tethers with smaller widths although having a smaller collision area still have an increased particle flux capable of severing the tether, a minimum of 20 mm is required for a 1000 m tether. Longer tethers require more width to meet the 95\% survival probability chance for a three month experiment duration, increasing the tether mass. Using the equivalent drag tether for a quick orbit range determination of the tether survivability, table 5.11, shows a slight variation with inclination and altitude. This process needs to be repeated for the tape tether incorporating incident angles of the debris and meteoroids at a later design stage if optimisation of the tether dimensions is required.

Table 5.11: Chance of survival 1 year for equivalent drag cylinder 1000 m 30 mm 15 \(\mu\)m

| Orbit | \(70^\circ\) | \(80^\circ\) | \(90^\circ\) | \(100^\circ\) | \(110^\circ\) |
| \hline
| 650 km | 99.88\% | 99.83\% | 99.87\% | 99.83\% | 99.86\% |
| 700 km | 99.87\% | 99.82\% | 99.86\% | 99.81\% | 99.25\% |
| 750 km | 99.86\% | 99.81\% | 99.85\% | 99.80\% | 99.84\% |
| 800 km | 99.86\% | 99.81\% | 99.84\% | 99.80\% | 99.83\% |
| 850 km | 99.86\% | 99.80\% | 99.80\% | 99.80\% | 99.83\% |
| 900 km | 99.85\% | 99.80\% | 99.79\% | 99.83\% | & |
| 950 km | 99.85\% | 99.80\% | 99.79\% | 99.83\% | & |
| 1000 km | 99.85\% | 99.80\% | 99.79\% | 99.79\% | 99.83\% |

\(^9\) 650-70° orbit
5.1.5 Tether Constraints

In this section it is shown how tether mass budgets limit the mass density of the materials to be used and how the maximum allowable dimensions for the tether on the reel limits the length and the thickness of the tether.

Tether Mass

The mass of the tether is required to be a maximum of 1.6 kg with a target value of 1.3 kg

\[ m_i = L_i \sum \rho_i A_i = \rho_i L_i \]  

\[ \rho_i \] component of the tether

\[ \rho \] – tether material density \([\text{kgm}^{-3}]\)

\[ \rho_t \] – specific tether density \([\text{kgm}^{-1}]\) \[ \rho_t = \sum \rho_i A_i \]  

In figure 5.9 the specific tether density for a number of possible configurations is shown excluding the mass and thickness of the adhesive and coating.

Figure 5.9: \( \rho_t \) for various configurations 7.5 \( \mu \text{m} \) Kapton\(^{\circledR} \) and \( \rho_t \) required \( m_i \) - 1.3 kg

The maximum specific tether density for a total tether mass of 1.3 kg is also shown above as a function of tether length. For both figures the conducting aluminium material with has a density \( \rho = 2700 \text{ kgm}^{-3} \), the enforcing substrate is assumed to be a Kapton\(^{\circledR} \) having a density \( \rho = 1420 \text{ kgm}^{-3} \).

Storage Restrictions

In the first part of this study the lowest development risk and simplest system for tether storage and deployment was found to be a single wound inertia driven reel not requiring any special winding techniques. This system also has a low risk as to maintaining tether integrity when deploying a thin tape tether minimising the chance of damaging the tether in anyway during winding and deployment. In the design of an electrodynamic tape tether deployment system [Heijning] six methods of tether storage methods were examined listed below

- Spool Level Winding
- Spool Double Winding
- Reel Single Winding
- Reel Level Winding
- 2 reels (tape cassette)
- Z-fold

The only viable options for the tape tether were found to be the single wound reel and the Z-fold method. The reel is the easiest winding technique for the tape tether but limited to low deployment velocities, the Z-fold having small storage volume and unknown unwinding characteristics and behaviour of the folds during and after deployment.
The reel was chosen for the design of the tether deployment system based on experience in industry, past use onboard the ATEx mission and simple winding techniques involved. Using a volumetric approach [Thoen] the allowable length and thickness combinations are calculated. Details of this method are given in appendix 12 equations (A12-1) to (A12-4). To prevent slippage of the tether of the reel during deployment it could be required to extend the diameter of the flanges on the reel by 10 mm [TBD 36] [Thoen], this was not done for the ATEx tether or the EDDE tether they where both wound under tension [Pearson; Koss].

The total tether thickness \( t = t_s + t_c + t_{ad} + t_{out} \) for a single wound tape tether on a reel is critical with respect to the available the storage dimensions for the reel. To facilitate the high ratio of reel diameter vs. height for the DEP system use will be made of a special payload module (SPL) as it will most likely not be possible to fit the reel onto a (double) standard payload module.

The outer envelope of for the tether deployment system has been constrained by [Heijning] to 200 x 200 x 140 m this will enable a reel of 200 mm to fit onboard the payload platform resulting a reasonable range of tether length and thickness combinations.

**REQ-60 Outer Reel Dimensions**

The tether reel outer diameter \( D_R \) shall not exceed 200 [mm]

The required storage dimensions are shown in figure 8.2 for various tether thicknesses and a reel axle diameter of 40 mm and 100 mm. Larger axle diameters reduce the amount of tether length that can be stored within the set dimension constraints and should be kept as small as possible. The effect of inner reel diameter size on the deployment has to be determined. At this point has been assumed the inner reel axle diameter \( D_a \) is 40 mm.

Special payload modules (SPL) currently have no predefined restriction for the dimensions or location onboard the bus at this stage. Mounting the reel onboard the standardised payload platform with the reel axle parallel to the deployment direction resulting in the tether unwinding in the deployment direction has a limitation in the \( z_b \) direction of 140 mm. This limits the tether thickness substantially for the entire tether length range shown in figure 8.2 making this configuration unlikely considering the handling and voltage drop requirements on \( t_{min} \) and combined with commercial 7.5 \( \mu \)m or even a 2 \( \mu \)m substrate thickness and 1 \( \mu \)m -2 \( \mu \)m adhesive.

The SPL module could conceivably be mounted outside the bus on the nadir panel depending on the launch envelope restrictions or be placed at a different location onboard the bus, allowing the reel axle to be perpendicular to the deployment direction, depending on the other payload with the Delfi-1 satellite deviating from the proposed modular design [Rothkrantz]. The systems torque balance would have to be recalculated for deviations of the TES from the centre line of the SC. Another option to reduce the dimensions of the reel is employing multiple stacked platters of tether as done for the EDDE tape tether [Pearson]. It depends on the deployment profile if this method can be used due to the speed variations that will occur during tether deployment when the tether goes from one reel to the next and will increase the complexity of the design; this method of deployment needs to be researched.

The current solution proposed by [Heijning] is the use of a roller to deflect the tether into the desired deployment direction, as shown in figure 4.2. This deployment method was tested] and proven to be a viable method of deploying the tape tether and selected this method for the deployment system of the EDT.

Effects of the tether on the design of the deployment system [TW.4122.02] are summarised below

- The modulus of elasticity and the ultimate tension of the tether determines the necessity of a deployment control system (DCS)
- The susceptibility of the tether to tearing and cracking influences the risk of tether rupture,
- The shape memory effect influences the dynamics of the tether during and after deployment,
- The dimensions of the tether define the volume of the tether storage system (TSS).
The storage effects on the materials need to be determined as the EDT will be deployed after a minimum of 9 months operation of the Delfi-1 satellite [Oedipus]. The tether needs to remain deployable and memory of the material being wound on the reel for a period of at least 15 months including ground storage [REQ-61] needs to be minimal and possibly be actively removed during deployment.

The bending radius of the reel axel, alloy, laminate and coating properties, stiffness $E_A$ and ductility of the tether will all influence deployability. Winding large bending radii and a more viscous alloy of the tether material and coating can improve deployability of the tether [Krujff].

Combining the requirements on tether thickness $t_c$ the combined data for a 50% enforced 30 mm wide tether is shown below. The substrate is assumed 7.5 $\mu$m and 2 $\mu$m thick, coating and adhesive are taken at a total of 2 $\mu$m.

![Figure 5.10: Tether thickness and dimensions, mass for 50% $w_{sub}$ 30 mm $w_c$ tether](image)

The mass constraint is more stringent than the outer diameter of the reel with the tether conductive thickness predominantly being determined by the voltage drop requirement. Reducing the mass to enable a longer tether to remain within mass budget will require limiting the tethers width. The enforcing substrate thickness has a small effect on both mass and on storage dimensions both predominantly determined by the $t_{min}$ determined by the voltage drop requirement. A summary of the requirements and constraints on tether thickness $t_c$ is given below

1. Electrical loads ($L_t, w_{sub}=w_{min}$) $\Delta V_{ohmic loss}(4I_{OMLmax}) < 0.1$ EMF
2. Handling ($w_c$) $T_{hand} = 25$ N
3. Mechanical loads ($L_t,w_{sub}=w_{min}$) $T_{des}=18$ $T_{opsmax}$ for fixed $m_b - 0.83\text{-}1.0$ kg or $m/m_b-0.25$

Constraints:
1. Mass ($L_t,w_c,w_{sub},t_c$) $<1.3$ kg
2. Storage ($L_t,L_i$) $D_R$ outer $< 200$ mm

Tether configurations meeting the electrical and mechanical requirements and mass and storage constraints are shown below. Lower current tether with a larger section of enforcement have more feasible configurations mainly due to their reduced thickness.

<table>
<thead>
<tr>
<th>$L_t$ [m]</th>
<th>$w_{sub}$ -10%$w_c$</th>
<th>$w_{sub}$ -30%$w_c$</th>
<th>$w_{sub}$ -50%$w_c$</th>
<th>$w_{sub}$ -100%$w_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>5 - 80</td>
<td>5 - 80</td>
<td>5 - 80</td>
<td>5 - 80</td>
</tr>
<tr>
<td>500</td>
<td>10 - 20</td>
<td>10 - 60</td>
<td>10 - 80</td>
<td>10 - 60</td>
</tr>
<tr>
<td>750</td>
<td>15 - 20</td>
<td>15 - 40</td>
<td>15 - 60</td>
<td>15 - 60</td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td>20</td>
<td>20 - 30</td>
<td></td>
</tr>
</tbody>
</table>
5.2 Neutral Gas Cathode

A neutral gas cathode is considered as an optional part of the EDT experiment. The objective of the cathode is to demonstrate its potential for enhancing the performance of the EDT by enhancing the current flow (see section 2.2.4). To allow for demonstrating this potential it is required that the cathode produces a distinct effect during operation. This has been discussed in section 4.2.1 and resulted in the following requirement.

Performance Requirement GAS System

The performance requirement for the gas cathode is to deorbit the system 20 m during gas release time $t_{\text{gas}}$ also producing measurable effects in the bias distribution at the suspension of the tether [REQ-25].

Another aspect that should be considered is that a current increase due to gas release must not result in a loss of pointing accuracy of the satellite. Hence adding a gas cathode will limit the number of design solutions, see section 3.2.

The gas cathode is budgeted at 1.0 kg with a current target value of 0.8 kg. To limit the mass it has been proposed to utilise (parts of) the cold gas thruster (CGT) system used for ejecting the end body and tether from the satellite [Heijning²] for the gas cathode. This then implies that the cold (nitrogen) gas used for the CGT’s must also be suitable for charge exchange. This is discussed later in this section in more detail.

Components of the gas cathode system are
- Gas Storage Canister
- Gas Release System
  - Time tagged
  - Mass flow $m_{\text{gas}}$
- Gas
  - Type N₂
  - Amount [TBD 39] [kg]
  - Storage pressure [TBD 40] [Pa]

Design Constraints GAS System
- Volume $\leq 1$ SPL = 3.2e5 [mm$^3$]
- Pressure $\leq$ [TBD 40] [Pa]
- Design target mass $\leq 0.8$ [kg]

Neutral Gas Discharge

The function of the gas is charge exchange; a low density gas having a low specific ionisation energy is preferable. Nitrogen used by the CGT is non toxic, easy to handle and there is a significant amount of experience using it as a propellant for cold gas thrusters. Nitrogen also requires a low storage volume. Charge exchange with the ambient plasma can take place by exchange of positive and negative charged particles over the formed potential sheaths. A neutral gas that is partially ionised at 1% already behaves like plasma reacting to magnetic fields and having a high electrical conductivity [Gilchrist]. The functions that need to be performed by the tether - gas cathode are to
- Eject neutral gas with sufficient mass flow rate to sustain the required $I_{\text{gas}}$
- Ionise neutral gas generating a conductive plasma plume allowing for charge exchange
- Provide sufficient current carriers to maintain $I_{\text{gas}}$
- Ignition (plasma breakdown) into a (self-sustaining) gas current discharge $I_{\text{gas}}$ [TBD 48]
Mechanisms capable of ionising a neutral gas are:

- Secondary electron emission from cathode surface and electrons subsequently colliding with the neutral gas and gaining the required ionisation energy from the electric field due to the voltage drop at tether termination (TSS-1R). The ionisation potential required is determined by gas density \( n_n \) (pressure) and electric field \( E \) (TSS-1R) (determining number of impacts and distance travelled before ionisation energy).

- Self-sustaining discharge mechanism; space plasma electrons are accelerated by the voltage drop at the tether termination and ionise the neutral gas flow from the gas cathode similar to HC in electron emission mode with the electric field having sufficient strength a gas breakdown can be initiated. During the TSS-1R tether break the tether end voltage was -100 V after tether break [Gilchrist] allowing a gas discharge current to be produced.

- Photo ionisation due to UV Radiation. The production rate of ions due to UV photoemission for \( N_2 \) at 1 A.U. is equal to \( 3.52 \times 10^{-7} \) s\(^{-1}\) [SPENVIS] (current levels are expected to be in the order of \( \sim 10^{-10} \) A [TBC 45] being too small to sustain sufficient current).

- Relative velocity of the neutral gas in the plasma surpassing the critical ionisation velocity (CIV); not relevant here as gas exit velocity from the CGT is too low, see appendix 14.

For the EDT gas cathode it is proposed that an expanding neutral gas cloud at velocity \( v_e \) from the CGT nozzle exit is partially ionised by secondary electron emission being a seed source for ionising particles resulting in a cloud of slow moving ions (more secondary emission) in the tether vicinity and a source of rapidly moving electrons ejected into the ionospheric plasma as with the TSS-1R [Gilchrist]. This provides for sufficient current carriers capable of sustaining a current \( I_{gas} \). The source of electrons (high mobility, low mass) being the main current carriers is provided by secondary emission of ions impacting the tether and CGT at the negative cathode bias with respect to the ambient plasma. The voltage drop of the tether potential to the plasma is assumed to drop uniformly across a distance resulting in an electric field \( E \). The electrons are subsequently accelerated by the electric field requiring a fall over a distance \( d \) to obtain the required ionisation energy. Ionising the neutral gas produces more electrons and a (self-sustaining) gas discharge current can occur depending on the electric field profile \( E(R) \) and the gas density \( n_n(R) \) and subsequent pressure profile with a voltage and density (pressure) drop occurring over the distance \( R \) from the exit of the nozzle [Gilchrist, Wagenaars, Walker].

Collisions will occur from secondary electrons emitted and impacting with the neutral gas close to the cathode but they require sufficient ionisation energy to ionise the neutral gas upon impact requiring a minimum distance to be travelled by the secondary emission electrons from the cathode (nozzle-tether). Assuming a -100 V potential is uniformly dropped over a distance of 10 mm [Gilchrist] an electron is required to travel at least 1.56 mm to obtain the required ionisation energy for \( N_2 \) of 15.6 eV, see appendix 14. It has been assumed that complete gas breakdown or ignition is not required to sustain a gas current \( I_{gas} \) in the tether, this is subject to further research [TBD 48].
**Performance CGT**

The cold gas thrusters (CGT) developed for the deployment system can be utilised to eject the gas required to sustain $I_{gas}$. Using this thruster as a gas cathode will enable a higher mass flow rate to be achieved compared to the pinhole gas released at a pressure of 1 atmosphere for the TSS-1R tether. To evaluate the use of the existing CGT design as a neutral gas cathode two cases are assumed; 1) Gas release using a separate CGT similar to the CGT used for deploying a 1000 m tether [Heijning] and case 2) Utilising the remaining gas in the CGT tank after deployment,[TBC 58]. Assuming an ideal gas the mass flow for the isentropic expansion of the gas is calculated for a constant tank temperature $T_T$ of 293 K. The design parameters used for the CGT are listed in appendix 14. Using propellant mass $M_p$ values from [Heijning] of 0.71 kg at an initial tank pressure $p_T$ of 200 bar, the remaining gas after deployment of a 1000 m tether is calculated as

$$m_{gas} = \frac{p_{final} V_T M}{R T_T}$$  \hspace{1cm} (5-21)

$m_{gas}$ – amount of neutral gas in the tank [kg]  
$p_T$ – tank pressure [Nm$^{-2}$]  
$T_T$ – tank temperature [K]  
$R$ – universal gas constant 8.314 [Jmol$^{-1}$K$^{-1}$]  
$M$ – molar mass $N_2$ 0.028 [kgmol$^{-1}$]

The Deployment Profile Tool [Heijning] is used to determine the final pressure in the tank after deployment of the tether shown in table 5.13 also listing performance parameters for each case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank pressure $p_T$</td>
<td>Nm$^{-2}$</td>
<td>2.00E+07</td>
<td>4.09E+06</td>
</tr>
<tr>
<td>Tank volume $V_T$</td>
<td>m$^3$</td>
<td>3.09E-04</td>
<td>3.09E-04</td>
</tr>
<tr>
<td>Propellant mass $M_p$</td>
<td>kg</td>
<td>0.071</td>
<td>0.015</td>
</tr>
<tr>
<td>$p_T$ final [Heijning]</td>
<td>Nm$^{-2}$</td>
<td>4.09E+06</td>
<td>0</td>
</tr>
<tr>
<td>$M_p$ final [Heijning]</td>
<td>kg</td>
<td>0.0162</td>
<td>0</td>
</tr>
<tr>
<td>Chamber pressure $p_c$</td>
<td>Nm$^{-2}$</td>
<td>1.80E+07</td>
<td>3.68E+06</td>
</tr>
<tr>
<td>Exit pressure $p_e$</td>
<td>Nm$^{-2}$</td>
<td>4.61E+03</td>
<td>9.42E+02</td>
</tr>
<tr>
<td>Gas density exit $\rho_e$</td>
<td>kgm$^{-3}$</td>
<td>5.63E-01</td>
<td>1.15E-01</td>
</tr>
<tr>
<td>Gas density chamber $\rho_c$</td>
<td>kgm$^{-3}$</td>
<td>206.9</td>
<td>42.3</td>
</tr>
<tr>
<td>Exit velocity $v_e$</td>
<td>ms$^{-1}$</td>
<td>742.76</td>
<td>742.76</td>
</tr>
<tr>
<td>initial mass flow rate $m_{in}$</td>
<td>kg$s^{-1}$</td>
<td>3.28E-04</td>
<td>6.71E-05</td>
</tr>
<tr>
<td>average mass flow rate $m_{avg}$</td>
<td>kg$s^{-1}$</td>
<td>5.91E-05</td>
<td>1.51E-05</td>
</tr>
<tr>
<td>operating time $t_{CGT}$ [Heijning]</td>
<td>s</td>
<td>319.92</td>
<td></td>
</tr>
<tr>
<td>operating time $t_{gas}$</td>
<td>min</td>
<td>27</td>
<td>16</td>
</tr>
</tbody>
</table>

The mass flow rate of the released gas of the gas cathode when using the CGT system at the exit opening of the nozzle is [Heijning]

$$m_{gas} = \rho_e v_e A_e$$ \hspace{1cm} (5-22)

$\rho_e$ – density gas at nozzle exit [kgm$^{-3}$]  
$A_e$ – exit opening [m$^2$]  
$v_e$ – exit velocity gas [ms$^{-1}$]
The resulting mass flow rates for the gas cathodes are shown in figure 5.12.

![Figure 5.12: Mass flow rate during gas release](image)

Using equation (3-4) a $\Delta$SMA of 20 m during the gas release time of the gas cathode 2b (16 minutes), see requirement, requires an orbital energy dissipation of 3.85 W at an orbit altitude of 650 km. The required drag force on the system is calculated as $F_D = -5.4 - 4$ N. Assuming this increase in drag force is solely due to Lorentz force induced by $I_{gas}$ as the aerodynamic drag component is negligible the required $I_{gas}$ current levels can be calculated. With tether configurations for the Delfi-1 orbit predominantly in between saturated and unsaturated leaning toward saturated the required gas current is calculated assuming a saturated current distribution.

$$I_{gas} = \frac{F_{1,000}}{B \cdot L \cdot \cos \theta}$$  \hspace{1cm} (5-23)

![Figure 5.13: Required $I_{gas}$ for 20 m $\Delta$SMA during $I_{gas}$ 16 min](image)

The number of charge carriers required to sustain the current $I_{gas}$ is calculated as [Gilchrist]

$$\dot{m}_{REQ} = \frac{I_{gas}}{e}$$  \hspace{1cm} (5-24)

$\dot{m}_{REQ}$ – required mass flow rate gas [kgs$^{-1}$] or [molecules per s] see appendix 14 equation (A14-8)

Assuming that 1% of the gas is ionised the mass flow and amount of gas required to sustain the gas current can be calculated, shown as a function of tether length figure 5.13. The resulting performance requirements for the cold gas thruster are given in table 5.14.
Table 5.14: Required performance gas cathode

<table>
<thead>
<tr>
<th>Performance Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta SMA$ 20 m</td>
</tr>
<tr>
<td>$t_{gas}$ 960 s</td>
</tr>
<tr>
<td>$F_{gas}$ 5E-04 N</td>
</tr>
<tr>
<td>$L_t$ [m]</td>
</tr>
<tr>
<td>250</td>
</tr>
<tr>
<td>500</td>
</tr>
<tr>
<td>750</td>
</tr>
<tr>
<td>1000</td>
</tr>
<tr>
<td>1250</td>
</tr>
<tr>
<td>1500</td>
</tr>
<tr>
<td>1750</td>
</tr>
<tr>
<td>2000</td>
</tr>
<tr>
<td>2250</td>
</tr>
<tr>
<td>2500</td>
</tr>
</tbody>
</table>

It shows that the required mass flow rate increases with decreasing tether length as a higher current level needs to be sustained to meet the performance requirements. The maximum required mass flow rate is estimated at 4 milligram per second for the tether length range being considered. Both cathodes have average mass flow rates during operation in excess of 4 milligram per second. A 0.1 kg gas cathode is able to maintain mass flow rates above 4 milligram per second for a period of 16 minutes. Depending on final tether length and time to achieve a $\Delta SMA$ of 20 m the residual gas in the CGT after deployment of the tether can be utilised for the neutral gas cathode providing a time tagged gas release system can be developed to facilitate this.

Gas current levels can potentially conflict with the tether current load rating requirement for $I_{max}$ [REQ-54], see section 5.1.2, depending on final tether dimensions. As a consequence for a short duration the tether resistance will induce a more significant voltage drop. It has to be determined if for the final design this is acceptable for the tether material and performance of the system. With the gas current levels also destabilising the system increasing the gas release time shown below or the decreasing the deorbit requirement will reduce the required gas current levels if required.

Table 5.15: Variation in gas current for $\Delta SMA$ of 20 m

<table>
<thead>
<tr>
<th>$t_{gas}$ [min]</th>
<th>5.5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_t$ [m]</td>
<td>$I_{gas}$ [A]</td>
<td>$I_{gas}$ [A]</td>
<td>$I_{gas}$ [A]</td>
<td>$I_{gas}$ [A]</td>
</tr>
<tr>
<td>250</td>
<td>3.78E-01</td>
<td>2.14E-01</td>
<td>1.43E-01</td>
<td>1.05E-01</td>
</tr>
<tr>
<td>500</td>
<td>1.89E-01</td>
<td>1.07E-01</td>
<td>7.16E-02</td>
<td>5.27E-02</td>
</tr>
<tr>
<td>750</td>
<td>1.26E-01</td>
<td>7.12E-02</td>
<td>4.77E-02</td>
<td>3.51E-02</td>
</tr>
<tr>
<td>850</td>
<td>1.11E-01</td>
<td>6.28E-02</td>
<td>4.21E-02</td>
<td>3.10E-02</td>
</tr>
<tr>
<td>1000</td>
<td>9.46E-02</td>
<td>5.34E-02</td>
<td>3.58E-02</td>
<td>2.64E-02</td>
</tr>
<tr>
<td>1250</td>
<td>7.57E-02</td>
<td>4.27E-02</td>
<td>2.86E-02</td>
<td>2.11E-02</td>
</tr>
<tr>
<td>1500</td>
<td>6.31E-02</td>
<td>3.56E-02</td>
<td>2.39E-02</td>
<td>1.76E-02</td>
</tr>
<tr>
<td>1750</td>
<td>5.41E-02</td>
<td>3.05E-02</td>
<td>2.05E-02</td>
<td>1.51E-02</td>
</tr>
<tr>
<td>2000</td>
<td>4.73E-02</td>
<td>2.67E-02</td>
<td>1.79E-02</td>
<td>1.32E-02</td>
</tr>
<tr>
<td>2250</td>
<td>4.20E-02</td>
<td>2.37E-02</td>
<td>1.59E-02</td>
<td>1.17E-02</td>
</tr>
<tr>
<td>2500</td>
<td>3.78E-02</td>
<td>2.14E-02</td>
<td>1.43E-02</td>
<td>1.05E-02</td>
</tr>
</tbody>
</table>

For tether end potentials below 15.6 V the electrons cannot obtain sufficient ionisation energy over the potential field drop and a gas ionisation does not occur due to secondary electron emission as a seeds source when assuming 0.1 mmV$^{-1}$ drop of the tether potential [Gilchrist].
REQ-62  Ionisation Potential N₂

The tether will induce a potential at the cathode end \( \geq 25 \) [V] to enable gas ionisation of the neutral gas giving a field drop distance of at least 3 mm, this includes a margin of 1.5 on the theoretical required voltage drop of 15.6 [V]

A region with ionised gas will be present at a distance of approximately 2 mm to 10 mm from the nozzle exit area. In orbit the temperature of the gas tank will vary due to solar heating and eclipse conditions. For a constant volume the tank pressure \( p \) changes with tank temperature \( T \) and with it the operational performance of the cold gas thruster. Assuming 0.1 kg of ideal gas at a tank pressure of 180 MPa the initial mass flow rates and the exit velocity of the CGT for tank temperatures ranging from -150 +150°C are determined using equations (5-22) and (A14-1) to (A14-7). In figure 5.14 the variation in initial exit velocity and mass flow rate of the CGT are shown for various temperatures.

Figure 5.14: Mass flow and exit velocity for \( T_{gas} \) range

It would be advantageous to schedule the operation of the gas cathode during part of the orbit with maximum tank temperatures as this will result in a higher exit velocity and mass flow rate of the neutral gas.

REC-2  Gas Discharge Time Schedule

When gas temperature is at \( T_{max} \) for orbital period

Gas cathode performance variables to be taken into consideration are summarised below
- Voltage [electric field]
- Gas number density
- Gas Pressure [collision frequency; mean free path]
- Electric field geometry
- Gas flow rate
- Cathode characteristics (material and temperature) [secondary electron emission]

An initial mass estimate for the gas cathode as a separate system is made using data from the CGT design from [Heijning\(^2\)] results shown below. Comparing this estimate with the initial mass budget for the experiment of 1.0 kg it seems likely that the budget has been overestimated substantially and can be reduced. In the EDT System Requirements Specification listed in the annex of this report the GAS system requirements are listed.

Table 5.16: Gas cathode mass estimate

<table>
<thead>
<tr>
<th>Component</th>
<th>Actual Mass [kg]</th>
<th>Design Maturity [%]</th>
<th>Current Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Cathode GAS</td>
<td>0.4</td>
<td>20%</td>
<td>0.48</td>
</tr>
<tr>
<td>Gas</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tank</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time tagged release mechanism</td>
<td>TBD 41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nozzle and valves</td>
<td>TBD 41</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3 Developed Tools Overview

The theory and models derived in the previous chapters outlining tether performance, system stability, material and configuration requirements, thermal extremes in orbit and impact probability with micrometeoroids and orbital debris have been applied in a number of tools in aid of designing and sizing the EDT experiment for Delfi-1. In the table below an overview of these tools is given.

Table 5.17: Overview Design Tools

<table>
<thead>
<tr>
<th>Tool</th>
<th>Input Data</th>
<th>Output Data</th>
<th>Models</th>
<th>Sections/Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT Environment</td>
<td>Orbit Parameters</td>
<td>Data sheets orbit averaged environment</td>
<td>Tilted Dipole Magnetic Field</td>
<td>Section 2.1 Appendix 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Kepler Orbit Propagation</td>
<td>Appendix 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reference Frame Transformations</td>
<td>Appendix 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ionosphere data</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Atmosphere data</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>M/OD data</td>
<td></td>
</tr>
<tr>
<td>EDT Bias and Current Profiles</td>
<td>Orbit Environment Tether</td>
<td>current and bias profile along tether for orbit averaged environment</td>
<td>Bias Distribution ( I_{\text{OML}}; I_{\text{gas}} )</td>
<td>(2-10) (2-11)</td>
</tr>
<tr>
<td></td>
<td>Dimensions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tether Risk Analysis</td>
<td>Tether Dimensions Operational</td>
<td>Survival chance untrackable M/OD during orbital time</td>
<td>MTBF values Equivalent Drag Tether Flat Tether Geometry</td>
<td>EDT Prelim Appendix 9</td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td></td>
<td></td>
<td>Section 5.1.4 Appendix 9</td>
</tr>
<tr>
<td>Tether Design</td>
<td>TET SC Mass and Dimensions</td>
<td>YES or NO for requirements performance of configuration over orbit range</td>
<td>OML – GAS Current Levels orbit range and in orbit for orbit extremes</td>
<td>Section 2.2 Section 2.2</td>
</tr>
<tr>
<td></td>
<td>Performance requirements</td>
<td></td>
<td>Forces on Tether – System</td>
<td>Section 2.3</td>
</tr>
<tr>
<td></td>
<td>Table 8.3</td>
<td></td>
<td>Change in SMA</td>
<td>Section 3.1</td>
</tr>
<tr>
<td></td>
<td>Environment Data Sheets EDT</td>
<td></td>
<td>Static Torque Equilibrium System</td>
<td>Section 3.2</td>
</tr>
<tr>
<td></td>
<td>Environment tool</td>
<td></td>
<td>Static Torque Equilibrium Tether – Critical Current levels</td>
<td>Section 3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Electric and Mechanical Loads</td>
<td>Section 5.1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature Extremes Tether</td>
<td>Section 5.1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tether Mass and Storage Dimensions</td>
<td>Section 5.1.5</td>
</tr>
</tbody>
</table>

The Tether Design tool is the main design tool using input data from the EDT Environment tool. Tether performance has been calculated using orbit averaged environmental values. Static system attitude and tether and steady state temperature analysis have been performed for the orbit range extremes. This allows direct insight into the performance of a configuration over the entire orbit range also enabling most of the system requirements to be evaluated using a single design tool. The tool is currently configured to evaluate tape tether designs operating in 650-1000 km orbits for 70°–110° inclinations. The tool will allow for additional orbit data to be added increasing the orbit ranges. A wire tether design can also be applied, also adding a section of mechanical tether for stability purposes can be implemented. Results obtained using the Tilted Dipole model in EDT Environment tool have been verified using [Spervis] and [ETBSim]. Average values for the induced EMF calculated using the Tether Design tool have been verified using [ETBSim]. Validation of the used geometrical thermal model and research into tether transient thermal behaviour is required to determine if it is possible to achieve a minimum temperature of the tether of -100°C [REQ-50] or if the \( T_{\text{SSmin}} \) of -158°C is a valid minimum temperature for the tether oriented along the nadir. ETBSim results for temperatures in orbit indicate a minimum temperature range of -100°C to -60°C and a maximum temperature of +40°C. These results have been obtained for tethers with larger IP and OOP angles than the \( \pm 5° \) predicted for the EDT in part explaining the deviation, further research and validation of the thermal model is required. The current static torque equilibrium approach has been verified with results obtained for the Delfi-1 attitude control and dynamics system. As of yet tether obtained current levels for the floating (short) configuration have not been verified. The Tether Design and Risk Analysis tools are applied in the next chapter to evaluate tether and end mass configurations suitable for use onboard the Delfi-1 constraints.
6 EDT EXPERIMENT ONBOARD DELFI-1

In this chapter configurations for the TET and EM that meet the set requirements and constraints are derived and an overview of the design and performance for the experiment is given. In the first section the bare floating tape tether and the required end mass are evaluated. Next the addition of the gas cathode is examined and a sensitivity analysis is performed of the requirements and design. In the final section a description of the baseline design for the experiment is given, performance and operation of the experiment are summarised with weak and critical points of both the mission and design listed.

6.1 TET-EM Configuration

The tether dimensions and the amount of end mass required for both passive and gas cathode operation are determined in this section. The theory outlined in the previous chapters has been incorporated in the Tether Design tool [TN.4122.19]. In this section this tool is used to determine if possible configurations of the tether and end mass meeting the EDT performance requirements and constraints and the resulting effect on the tether and end mass design parameters \[L_t, w, t, m_b\]. An overview of these requirements and constraints derived in the previous chapters is given in table 8.3 and in table 8.4 the impact on the tether and end mass configurations is summarised. These form the basis in determining which configurations are feasible for the Delfi-1 mission. For each design parameter of the TET and EM systems shortly described below an initial design range is chosen based on the conclusions drawn from previous sections in this study.

Tether Length \(L_t\)

For performance calculations the effective tether length is assumed to be reduced due to unknown system resistance losses associated with the ionospheric current closure loop estimated to be a maximum of 50 \(\Omega\), see section 2.2.1 and appendix 6. Resulting in a tether length loss of 0.2%-4.4% for the tether dimensions of 250 m-2500 m; 5 mm-40 mm being considered. The effects of this loss on EDT performance are a slight reduction in \(F_L\) and the total drag \(F_D\) and a decrease in the ratio \(F_L/F_D\). Initially the feasible configurations are determined assuming no tether length is lost as longer tethers are more stable and the effect on electric loads is assumed minimal. The feasible configurations storage and mass performance are recalculated adding a margin to the physical length of the tether for both mass and storage performance compensating for the voltage loss. All requirements influencing the tether length are listed table 8.4.

Tether Width \(w_c\)

OML current collection is assumed to occur at a conducting tether width of 2-4\(\lambda_{De}\). A maximum \(w_c\) of 40 mm is chosen for the entire orbit altitude range with the enforcing substrate \(w_{sub} = 50\% w_c\) limiting the required tether thickness due to the voltage drop requirement \textbf{REQ-54} and limiting the maximum \(T_{ss}\) temperatures to 100\(^\circ\)C reducing Ohmic voltage losses of the tether. All requirements influencing the tether width are listed in table 8.4.

Tether Thickness \(t = t_c + t_{sub} + t_{adh} + t_{coat}\)

For performance calculations initially \(t_c = 15\ \mu m\) is taken as it does not have a significant influence on deorbit performance and is mainly determined by the voltage drop, handling loads requirement and storage constraints. The substrate, required coating and adhesive are budgeted at a total thickness of 9.5 \(\mu m\) based on commercially available Kapton and an estimate of 2 \(\mu m\) for adhesive and coating. All requirements and constraints influencing the tether thickness are listed in table 8.4.

End Mass \(m_b\)

A maximum of 0.83 kg is available for the end mass (EM) which consists of 75\% of the DEP system \[\text{Heijning}^2\]. For the experiment including a gas cathode a maximum of 1.0 kg may be added. The current budget for the EDT experiment does not include any additional ballast mass for stabilisation which ideally will be provided entirely by the DEP and GAS systems. Requirements affecting the amount of end mass required are listed in table 8.4.
The initial values for the tether dimensions and the end mass are summarised below in table 6.1.

**Table 6.1: Range of values for tether configuration and end mass**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_t$</td>
<td>250-2500 m</td>
<td></td>
</tr>
<tr>
<td>$\theta_t$</td>
<td>5°</td>
<td></td>
</tr>
<tr>
<td>$w_c$</td>
<td>5 - 40 mm</td>
<td></td>
</tr>
<tr>
<td>$w_{sub}$</td>
<td>50%$w_c$</td>
<td>mm</td>
</tr>
<tr>
<td>$t_c$</td>
<td>15 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>$t_{tub} + t_{adh}$</td>
<td>2 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>$m_b$</td>
<td>0 - 0.83 kg</td>
<td></td>
</tr>
</tbody>
</table>

Combinations of $L_t$, $w_{sub}$, $w_c$, $m_b$ and $t_c$ are evaluated for the requirements and constraints listed in table 8.3 and incorporated in the Tether Design tool leading to feasible configurations for the experiment onboard the Delfi-1 satellite. The requirements and constraints are evaluated in order of their impact on the final design as shown below:

1. Tether Performance Requirements (section 4.2.1)
2. Stability (Static) Requirements (section 3.2 and 3.3)
3. Electrical and Mechanical Loads (section 5.1.2)
4. Mass and Storage Restrictions (section 5.1.5)
5. Micrometeoroid and Orbital Debris Survivability (section 5.1.4)
6. Thermal Control (section 5.1.3)

### 6.1.1 Design for Deorbit Performance

The driving performance requirement for the EDT is to ensure a measurable deorbit using the GPS receiver for the entire orbit range and a conclusive determination of the Lorentz drag force.

- **REQ-20** Deorbit $\Delta$SMA of 80 m-200 m (SA) in two weeks
- **REQ-24** Filtering Signal $F_L/F_D > 50\%$ Filtering of measurements

Using equations (3-4) and (3-5) the minimum drag force (Lorentz and aerodynamic drag) induced by the tether on the system required can be calculated for the orbit range of Delfi-1. For a total system mass of 45 kg based on the configuration listed in appendix 7 having a tether mass of 1.3 kg results are shown below.

**Table 6.2: Operational phase I (total) drag force requirement**

<table>
<thead>
<tr>
<th>Deorbit 2 weeks [m]</th>
<th>$F_{D_{min}}$ (650 km) [N]</th>
<th>$F_{D_{min}}$ (1000 km) [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>1.63e-6</td>
<td>1.51e-6</td>
</tr>
<tr>
<td>200</td>
<td>1.36e-5</td>
<td>1.26e-5</td>
</tr>
</tbody>
</table>

Assuming selective availability of the GPS system is not switched on (section 4.2.1) the following drag force requirement (Lorentz and aerodynamic) for the tether can be derived based on the largest drag force necessary to achieve the set deorbit requirement over the entire orbit range for the EDT experiment as stated in chapter 1

**REQ-64** Drag Force $F_D$

The TET shall induce a minimum $F_D$ of 1.63e-6 [N] consisting of Lorentz and aerodynamic drag over the entire orbit range resulting in a deorbit of 80 [m] over a period of two weeks enabling the GPS system to determine the deorbit performance of the EDT within two weeks of operation.

If as a backup the Delfi-1 ground based tracking system is used to determine whether the tether operates as intended a minimum $F_D$ of 1.36e-5 N is required to deorbit the system by 4 km within the maximum operating time of three months, see section 4.2.1.

Tether in plane angles for the static torque balance achieve a maximum value of 5.73° for the 250 m - 40 mm wide tether at 650 km altitudes affecting the deorbit performance of the tether slightly for the longer part of the $L_t$ range being considered as shown in figure 2.15.
For performance calculations it is assumed the tether operational angle is at a maximum of 5° from the $z_{OR}$ axis. The effect of this angle was discussed earlier in section 2.3. The initial range of the design parameters used for tether performance calculations are listed in table 6.1. Using the $I_{OML}$ levels from section 2.2 and the drag forces as defined in section 2.3 the total drag force has been calculated for the worst case orbit. In section 2.3 it was demonstrated that both Lorentz and aerodynamic drag forces decrease with increasing altitude. In addition it was shown that the Lorentz force is at a minimum for 85° inclinations, the deorbit performance is evaluated for 1000 km - 85° orbits with the results shown below.

### Table 6.3: Minimum ΔSMA in m for two week operation for 1000 km-85° orbit

<table>
<thead>
<tr>
<th>$L_t$ [m]</th>
<th>$w_c$ - 5 [mm]</th>
<th>$w_c$ - 10 [mm]</th>
<th>$w_c$ - 15 [mm]</th>
<th>$w_c$ - 20 [mm]</th>
<th>$w_c$ - 30 [mm]</th>
<th>$w_c$ - 40 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>14</td>
<td>22</td>
<td>31</td>
<td>39</td>
<td>56</td>
<td>73</td>
</tr>
<tr>
<td>500</td>
<td>31</td>
<td>57</td>
<td>83</td>
<td>109</td>
<td>160</td>
<td>212</td>
</tr>
<tr>
<td>750</td>
<td>62</td>
<td>118</td>
<td>174</td>
<td>230</td>
<td>342</td>
<td>454</td>
</tr>
<tr>
<td>1000</td>
<td>108</td>
<td>210</td>
<td>314</td>
<td>414</td>
<td>618</td>
<td>823</td>
</tr>
<tr>
<td>1250</td>
<td>172</td>
<td>339</td>
<td>508</td>
<td>672</td>
<td>1005</td>
<td>1338</td>
</tr>
<tr>
<td>1500</td>
<td>258</td>
<td>509</td>
<td>765</td>
<td>1012</td>
<td>1515</td>
<td>2017</td>
</tr>
<tr>
<td>1750</td>
<td>365</td>
<td>724</td>
<td>1089</td>
<td>1442</td>
<td>2159</td>
<td>2876</td>
</tr>
<tr>
<td>2000</td>
<td>498</td>
<td>988</td>
<td>1486</td>
<td>1968</td>
<td>2949</td>
<td>3929</td>
</tr>
<tr>
<td>2250</td>
<td>656</td>
<td>1303</td>
<td>1962</td>
<td>2599</td>
<td>3894</td>
<td>5188</td>
</tr>
<tr>
<td>2500</td>
<td>841</td>
<td>1674</td>
<td>2521</td>
<td>3339</td>
<td>5003</td>
<td>6667</td>
</tr>
</tbody>
</table>

Blue values indicate those that provide the required change in SMA meeting the deorbit performance requirement for this mission. All tether lengths of 1000 m and longer are considered a feasible design considering the deorbit performance.

Next to enable filtering of the deorbit measurement so that the separate drag components can be determined the drag force ratio $\frac{F_L}{F_D}$ was required to be a minimum of 50% [TBC 17] over the entire orbit range in section 4.2. This requirement has been analysed using the Tether Design tool with the extreme values of the drag force ratio shown in figure 6.1. Results show a minimum required tether length of 1500 m for the 50% enforced tether [REQ-2] for the 650 km and 85° orbit. The more favourable orbit altitude of 1000 km predominantly inducing Lorentz drag forces on the system meets the 50% ratio for tethers of 500 m in length shown in figure 6.1. Enforcing the tether over a smaller width will reduce the required length for meeting this requirement as the induced $F_L$ drag force increases with the increased current collection area available while the aerodynamic drag force is not effected. This can be seen when comparing figure 6.1 with figure 3.2 derived for the 30% enforced tether requiring 1250 m of tether length. Tether libration angle has a minimal influence on the ratio, both affecting the $F_L$ and $F_{ad}$ drag components.

![Figure 6.1: Orbit extremes of the $F_L/F_D$ ratio for the 50% enforced tether](image-url)
6.1.2 Design for Stability

The main driver for system and tether stability is the absolute pointing error requirement set by the Delfi-1 satellite. In section 3.2 and 3.3 the requirements for system stability and the maximum tether angle were derived, these are summarised below.

Stability Requirements

System Stability

- **REQ-4** \( \text{3APE} \leq \pm(5^\circ - \omega_n)/3; \ T_{\text{GG}}(5^\circ)/T_{\text{DIST}} \geq 1 - 3 \)
- **REQ-7** MoI for passive gravity gradient stabilisation
- **REQ-8** 20% resonance separation system libration frequencies

Tether Librations

- Stable equilibrium requirements [Beletsky]
  - **REQ-15** \( I_t(\text{max}) < I_{\text{crit}} \)
  - **REQ-16/17-REQ-18** electric equilibrium
  - **REQ-16/17-REQ-18** aerodynamic equilibrium
- **REQ-14** \( T_{\text{GG}}(20^\circ)/T_{\text{DIST}} \geq 3 \)
- **REC-1** \( m_b = 4m_t \) [Kruijff] long term passive EDT stability

Restricting the tether length range in accordance with the deorbit performance derived in the previous section the requirements for system stability and tether librations are evaluated using the Tether Design tool for the configurations listed table 6.4. The effect of the filtering ratio requiring tether lengths of at least 850 m is not taken into account at this point as it is still to be confirmed pending further study and limits the configurations considerably.

Table 6.4: Input stability calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_t )</td>
<td>500-2500 m</td>
<td>m</td>
</tr>
<tr>
<td>( \omega )</td>
<td>TBD</td>
<td>°</td>
</tr>
<tr>
<td>( w_c )</td>
<td>5-40 mm</td>
<td>mm</td>
</tr>
<tr>
<td>( m_b )</td>
<td>0-0.83 kg</td>
<td>kg</td>
</tr>
<tr>
<td>( w_{sub} )</td>
<td>50%( w_c )</td>
<td>mm</td>
</tr>
<tr>
<td>( l_c )</td>
<td>15 ( \mu ) m</td>
<td>( \mu ) m</td>
</tr>
<tr>
<td>( t_{\text{coat}} + t_{\text{adh}} )</td>
<td>2 ( \mu ) m</td>
<td>( \mu ) m</td>
</tr>
</tbody>
</table>

Tether Librations

Stable equilibrium according to [Beletsky] based on tension control of the tether is shown in table 6.5 for the configuration length and width extremes. Stable equilibrium is met for all the tether dimensions for the end mass \( m_b \) of 0.83 kg. The maximum current levels meet the first critical current criteria \( I_{\text{crit}} \leq I_{\text{oml}} \) being met for passive tether operation at OML current levels without requiring any ballast mass for the entire orbit range.

Table 6.5: Stable equilibrium electric and aerodynamic [Beletsky]

<table>
<thead>
<tr>
<th>Tether 500 m - 5 mm ( m_b ), 0.83 kg</th>
<th>Tether 500 m - 40 mm ( m_b ), 0.83 kg</th>
<th>Tether 2500 m - 5 mm ( m_b ), 0.83 kg</th>
<th>Tether 2500 m - 40 mm ( m_b ), 0.83 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{\text{oml}} ) = 0.006 A</td>
<td>( I_{\text{oml}} ) = 0.0049 A</td>
<td>( I_{\text{oml}} ) = 0.0069 A</td>
<td>( I_{\text{oml}} ) = 0.0051 A</td>
</tr>
<tr>
<td>( I_{\text{crit}} ) = 0.115 A</td>
<td>( I_{\text{crit}} ) = 0.335 A</td>
<td>( I_{\text{crit}} ) = 0.115 A</td>
<td>( I_{\text{crit}} ) = 0.335 A</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( E ) = 5250 N</td>
<td>( E ) = 42000 N</td>
<td>( E ) = 5250 N</td>
<td>( E ) = 42000 N</td>
</tr>
<tr>
<td>( T ) = 0.0015 N</td>
<td>( T ) = 0.0023 N</td>
<td>( T ) = 0.0015 N</td>
<td>( T ) = 0.0023 N</td>
</tr>
<tr>
<td>( F_{\text{admax}} ) = 2.76e-5 N</td>
<td>( F_{\text{admax}} ) = 2.20e-4 N</td>
<td>( F_{\text{admax}} ) = 1.38e-4 N</td>
<td>( F_{\text{admax}} ) = 1.1e-03 N</td>
</tr>
<tr>
<td>( r^* ) = 500 m</td>
<td>( r^* ) = 500 m</td>
<td>( r^* ) = 2500,0034 m</td>
<td>( r^* ) = 2500,0004 m</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>( \text{N} )</td>
<td>( \text{N} )</td>
<td>( \text{N} )</td>
<td>( \text{N} )</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

96/206 DELFI.1.TW.4122.11
All of the tether configurations meet the stability ratio requirement [REQ-14] with an end mass $m_b$ of 0.83 kg as shown in table 6.6. In table 6.8 the required amount of end mass is shown for the tether width range. The configuration with the lowest stability ratio 500 m-40 mm tether requires a minimum ballast mass $m_b$ of 0.7 kg to meet the stability ratio with a margin of 3 [REQ-18b].

Table 6.6: Stability Ratio’s $T_{GG}(20°)/T_{DIST}$ TET configurations $m_b = 0.83$ kg OML

<table>
<thead>
<tr>
<th>$L_t$ [m]</th>
<th>$w_c = 5$ [mm]</th>
<th>$w_c = 10$ [mm]</th>
<th>$w_c = 20$ [mm]</th>
<th>$w_c = 30$ [mm]</th>
<th>$w_c = 40$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>22.4</td>
<td>11.6</td>
<td>6.2</td>
<td>4.4</td>
<td>3.5</td>
</tr>
<tr>
<td>750</td>
<td>21.9</td>
<td>11.6</td>
<td>6.4</td>
<td>4.7</td>
<td>3.8</td>
</tr>
<tr>
<td>1000</td>
<td>31.4</td>
<td>11.5</td>
<td>6.5</td>
<td>4.9</td>
<td>4.0</td>
</tr>
<tr>
<td>1250</td>
<td>20.7</td>
<td>11.3</td>
<td>6.6</td>
<td>5.0</td>
<td>4.2</td>
</tr>
<tr>
<td>1500</td>
<td>20.0</td>
<td>11.1</td>
<td>6.6</td>
<td>5.1</td>
<td>4.3</td>
</tr>
<tr>
<td>1750</td>
<td>19.3</td>
<td>10.9</td>
<td>6.6</td>
<td>5.2</td>
<td>4.4</td>
</tr>
<tr>
<td>2000</td>
<td>18.6</td>
<td>10.6</td>
<td>6.5</td>
<td>5.2</td>
<td>4.5</td>
</tr>
<tr>
<td>2250</td>
<td>19.9</td>
<td>10.3</td>
<td>6.5</td>
<td>5.2</td>
<td>4.6</td>
</tr>
<tr>
<td>2500</td>
<td>17.3</td>
<td>10.6</td>
<td>6.4</td>
<td>5.2</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Long term stability $m_t/m_b - 0.25$ ratio [REC-1] [TBC 7] for the combined mass target for the tether and ballast mass $m_b$ of 2.1 kg would lead to a maximum tether mass of 0.42 kg with an end mass of 1.68 kg [REQ-18c]. For a 50% enforced 10 mm-40 mm tether densities and lengths are calculated using equation (5-20). The tether-ballast mass ratio limits the maximum tether length as shown in table 6.7 [REQ-2h].

Table 6.7: Maximum tether length for $m_t/m_b - 0.25$ for $t_c 15$ [µm]

<table>
<thead>
<tr>
<th>$w_c$ [mm]</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_t$ [kgm$^{-1}$]</td>
<td>2.29E-04</td>
<td>4.58E-04</td>
<td>9.17E-04</td>
<td>1.37E-03</td>
<td>1.83E-03</td>
</tr>
<tr>
<td>$L_t$ max [m]</td>
<td>1834</td>
<td>917</td>
<td>458</td>
<td>306</td>
<td>230</td>
</tr>
</tbody>
</table>

System Stability

As in the previous section the 500 m-40 mm is the most critical configuration for the system achieving the absolute pointing error of ±5° at an orbit of 650 km - 110° having the lowest stability ratio of 1.33. The 5 mm and 10 mm tether are able to meet the 3APE requirement using an end mass $m_b$ of 0.83 kg. All configurations meet the stability ratio requirement [REQ-4] without a design margin (APE) for the 0.83 kg end mass. The 40 mm wide tether requires a minimum ballast mass $m_b$ of 0.8 kg, when including a design margin of three on the absolute pointing error to compensate for simplified linear model a $m_b$ of 2.9 kg is required [REQ-18a] shown in table 6.8. Limiting the width to reduce the required $m_b$ to the maximum budget for EM of 0.83 kg requires $w_c \leq 10$ mm [REQ-3b] to achieve 3APE for the system static torque equilibrium.

Table 6.8: Required $m_b$ for tether and system stability $L_t - 500$ m tether

<table>
<thead>
<tr>
<th>$w_c$ [mm]</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>APE</td>
<td>0.15</td>
<td>0.22</td>
<td>0.3</td>
<td>0.45</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>3APE</td>
<td>0.4</td>
<td>0.8</td>
<td>1.2</td>
<td>1.5</td>
<td>2.2</td>
<td>2.9</td>
</tr>
<tr>
<td>$T_{GG20°}/T_{DIST} \geq 3$</td>
<td>0.1</td>
<td>0.2</td>
<td>0.25</td>
<td>0.35</td>
<td>0.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>

The configurations 500 m-2500 m and 5 mm-40 mm all show the Mol distribution stated in table 6.9 for a total end mass of 0.83 kg with the tether at a ±5° angle from the nadir, the mass distribution of the satellite will have to be adjusted or a method of damping added to the system, see section 3.2.

Table 6.9: Mol requirement passive GG stabilisation

| $I_x > I_z$ | STABLE |
| $I_y < I_x + I_z$ | STABLE |
| $I_y > I_x + I_z$ | UNSTABLE |
| $I_y > I_z$ | STABLE |
| $I_x < I_y + I_z$ | STABLE |
The system libration frequency separation from the orbital frequency by > 20% is not met for the roll motion librations of the system as shown in Table 6.10, this is an inherent characteristic of the current design of the Delfi-1 satellite, see also section 3.2. The tether does not influence the systems libration frequencies significantly for the static torque equilibrium case when using the rigid fixed tether approximation for determining the systems static torque stability.

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td>1%</td>
<td>27%</td>
<td>200%</td>
</tr>
<tr>
<td>850</td>
<td>9%</td>
<td>35%</td>
<td>200%</td>
</tr>
<tr>
<td>1000</td>
<td>15%</td>
<td>40%</td>
<td>200%</td>
</tr>
</tbody>
</table>

For the system in passive drag operation with a width of wc of 5 mm-40 mm tether lengths of 500 m -2500 m are able to meet both APE and TGG(20°)/TDIST ≥ 3 requirements within the set design target for m_b of 0.83 kg. The passive OML tether is capable of meeting the 3APE requirement with wc constrained ≤10 mm for 0.83 kg, see also table 6.8 showing the minimum required ballast mass for meeting the stability requirements as a function of tether width.

### 6.1.3 Design for Electrical & Mechanical Loads

Based on the model described in section 5.1.2 the electrical and mechanical loads have been estimated for the tether and end mass parameter range of table 6.11 using the design tool developed in this study. This tool is used to determine the required thickness of the conducting tape tether meeting both the electrical and mechanical loads as stated in table 8.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_t</td>
<td>500-2500</td>
<td>m</td>
</tr>
<tr>
<td>L_t storage</td>
<td>110%L_t</td>
<td>m</td>
</tr>
<tr>
<td>wc</td>
<td>5-40 mm</td>
<td>mm</td>
</tr>
<tr>
<td>wc_sub</td>
<td>50%wc</td>
<td>mm</td>
</tr>
<tr>
<td>tc</td>
<td>TBD</td>
<td>µm</td>
</tr>
<tr>
<td>tc_sub</td>
<td>7.5 µm</td>
<td>µm</td>
</tr>
<tr>
<td>tc_coat + tc_adh</td>
<td>2 µm</td>
<td>µm</td>
</tr>
</tbody>
</table>

The thickness of the tether required for handling loads is determined using the entire conducting cross-section and the voltage drop requirement over the enforced cross-section of the tether. The results are shown below. The conducting thickness for the 5-10 mm wide tethers is predominantly determined by the handling load requirement (66 and 33 µm); with increasing width the voltage drop requirement drives the dimensions of tc.

<table>
<thead>
<tr>
<th>L_t [m]</th>
<th>wc - 5 [mm]</th>
<th>wc - 10 [mm]</th>
<th>wc - 15 [mm]</th>
<th>wc - 20 [mm]</th>
<th>wc - 30 [mm]</th>
<th>wc - 40 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>66</td>
<td>33</td>
<td>22</td>
<td>16</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>750</td>
<td>66</td>
<td>33</td>
<td>22</td>
<td>16</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>1000</td>
<td>66</td>
<td>33</td>
<td>22</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>1250</td>
<td>66</td>
<td>33</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>1500</td>
<td>66</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>1750</td>
<td>66</td>
<td>45</td>
<td>45</td>
<td>45</td>
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<td>45</td>
</tr>
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<td>55</td>
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<td>55</td>
<td>55</td>
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<td>66</td>
<td>66</td>
<td>66</td>
<td>65</td>
<td>65</td>
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<td>2500</td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>77</td>
<td>77</td>
</tr>
</tbody>
</table>

As shown in table 6.12 tether thickness decreases with increasing width of the conducting tape tether whereas longer tether require an increase in thickness. In the next section it is shown that tether thickness is limited due to onboard storage restrictions.
6.1.4 Design based on Storage, Mass Constraints & M/OD Survivability

In this section the storage and mass constraints are evaluated for the tether design range shown in table 6.13. The 5 mm wide tether has been dropped due to the required thickness derived in the previous section. In this section the micrometeoroid and orbital debris survivability requirement is also evaluated for the remaining tether configurations.

Table 6.13: Input storage & mass calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_t$</td>
<td>500-2500</td>
<td>m</td>
</tr>
<tr>
<td>$L_{st}$</td>
<td>$L_t$</td>
<td>m</td>
</tr>
<tr>
<td>$w_c$</td>
<td>10 - 40</td>
<td>mm</td>
</tr>
<tr>
<td>$w_{sub}$</td>
<td>50%$w_c$</td>
<td>mm</td>
</tr>
<tr>
<td>$t_c$</td>
<td>see Table 6.12</td>
<td>µm</td>
</tr>
<tr>
<td>$w_{sub}$</td>
<td>7.5</td>
<td>µm</td>
</tr>
<tr>
<td>$t_{coat} + t_{adh}$</td>
<td>2</td>
<td>µm</td>
</tr>
<tr>
<td>$D_a$</td>
<td>40</td>
<td>mm</td>
</tr>
</tbody>
</table>

The outer diameter of the tether on the reel $D_R$, is calculated assuming a 40 mm tether reel axle diameter $D_a$ using the relations given in appendix 12 which have been incorporated in the Tether Design tool.

Table 6.14: Outer diameter of tether on reel $D_R$ [mm] and tether mass $m_t$ [kg] for tethers meeting E&M loads

<table>
<thead>
<tr>
<th>$D_R$ [mm]</th>
<th>$L_t$ [m]</th>
<th>$w_c$ - 10 [mm]</th>
<th>$w_c$ - 15 [mm]</th>
<th>$w_c$ - 20 [mm]</th>
<th>$w_c$ - 30 [mm]</th>
<th>$w_c$ - 40 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>169</td>
<td>147</td>
<td>135</td>
<td>121</td>
<td>114</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>205</td>
<td>178</td>
<td>162</td>
<td>151</td>
<td>151</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>236</td>
<td>204</td>
<td>196</td>
<td>196</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>1250</td>
<td>263</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td>245</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>297</td>
<td>296</td>
<td>296</td>
<td>296</td>
<td>296</td>
<td></td>
</tr>
<tr>
<td>1750</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td></td>
</tr>
<tr>
<td>2250</td>
<td>466</td>
<td>465</td>
<td>465</td>
<td>465</td>
<td>465</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>526</td>
<td>526</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_t$ [kg]</th>
<th>$L_t$ [m]</th>
<th>$w_c$ - 10 [mm]</th>
<th>$w_c$ - 15 [mm]</th>
<th>$w_c$ - 20 [mm]</th>
<th>$w_c$ - 30 [mm]</th>
<th>$w_c$ - 40 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.24</td>
<td>0.25</td>
<td>0.26</td>
<td>0.27</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>0.48</td>
<td>0.49</td>
<td>0.51</td>
<td>0.55</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.96</td>
<td>0.99</td>
<td>1.18</td>
<td>1.77</td>
<td>2.37</td>
<td></td>
</tr>
<tr>
<td>1250</td>
<td>1.19</td>
<td>1.50</td>
<td>2.00</td>
<td>3.00</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>1.55</td>
<td>2.32</td>
<td>3.09</td>
<td>4.64</td>
<td>6.18</td>
<td></td>
</tr>
<tr>
<td>1750</td>
<td>2.24</td>
<td>3.36</td>
<td>4.48</td>
<td>6.72</td>
<td>8.96</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>3.10</td>
<td>4.65</td>
<td>6.20</td>
<td>9.30</td>
<td>12.40</td>
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</tr>
<tr>
<td>2250</td>
<td>4.14</td>
<td>6.20</td>
<td>8.26</td>
<td>12.39</td>
<td>16.52</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>5.35</td>
<td>8.02</td>
<td>10.69</td>
<td>16.04</td>
<td>21.39</td>
<td></td>
</tr>
</tbody>
</table>

Values in blue indicate dimensions that are in agreement with the requirement on maximum reel outer dimensions ($D_R \leq 200$ mm) and the maximum tether mass target of 1.3 kg and are considered feasible design with respect to mass and storage constraints. Results show only short tape tethers can be accommodated onboard.

Micrometeoroid and Orbital Debris Collision Risk

Using the Tether Risk Analysis tool [TN.4122.10] the M/OD survivability chance for the tape tether during an operational period of three months has been investigated. The theory used has been explained in section 5.1.4. The goal is to determine the tether length and width combinations with a M/OD survivability probability $P_{surv} \geq 95\%$ for an experiment duration of three months. In table 6.15 the results are shown for the configurations listed in table 6.13 using the flat tether geometry.
Table 6.15: $P_{\text{surv}}$ 3 month mission for various $L_t$, $w_c$ combinations [REQ-2g -3d]

<table>
<thead>
<tr>
<th>$L_t$ [m]</th>
<th>$w_c$ -10 mm</th>
<th>$w_c$ -15 mm</th>
<th>$w_c$ -20 mm</th>
<th>$w_c$ -30 mm</th>
<th>$w_c$ -40 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>95.71%</td>
<td>97.59%</td>
<td>98.36%</td>
<td>99.10%</td>
<td>99.42%</td>
</tr>
<tr>
<td>750</td>
<td>93.71%</td>
<td>96.44%</td>
<td>97.56%</td>
<td>98.66%</td>
<td>93.13%</td>
</tr>
<tr>
<td>1000</td>
<td>91.80%</td>
<td>95.31%</td>
<td>96.78%</td>
<td>98.23%</td>
<td>98.84%</td>
</tr>
<tr>
<td>1250</td>
<td>89.97%</td>
<td>94.00%</td>
<td>96.00%</td>
<td>97.79%</td>
<td>98.56%</td>
</tr>
<tr>
<td>1500</td>
<td>88.23%</td>
<td>93.13%</td>
<td>95.25%</td>
<td>97.36%</td>
<td>98.28%</td>
</tr>
<tr>
<td>1750</td>
<td>86.58%</td>
<td>92.08%</td>
<td>94.50%</td>
<td>96.94%</td>
<td>98.00%</td>
</tr>
<tr>
<td>2000</td>
<td>85.00%</td>
<td>91.06%</td>
<td>93.76%</td>
<td>96.51%</td>
<td>97.72%</td>
</tr>
<tr>
<td>2250</td>
<td>83.50%</td>
<td>90.07%</td>
<td>93.04%</td>
<td>96.10%</td>
<td>97.44%</td>
</tr>
<tr>
<td>2500</td>
<td>82.07%</td>
<td>89.10%</td>
<td>92.34%</td>
<td>95.68%</td>
<td>97.16%</td>
</tr>
</tbody>
</table>

For increasing tether length and decreasing width the probability of mission failure increases. For a tether widths in excess of 30 mm the survivability requirement is always met showing the advantage of thin wide tape tethers already mentioned in the part I of this study. When cut the tether must be designed to spend a minimal time in the operational satellite environment, the area time product needs to be minimised [REQ-65]. This requirement requires analysis quantifying a ballistic drag coefficient requirement for the tether design. The tether design is required to maximise the drag area and minimise the tether mass, thin and wide tethers having a favourable deorbit performance.

### 6.1.5 Final TET-EM Configurations

The Tether Design tool [TN.4122.19] allows various TET-EM configurations to be analysed showing their performance for each of the requirements mentioned in this section. Taking into account the effective tether length loss due to unknown system resistance losses [REQ-2a] the tether configurations and their performance that meet most of the requirements also having a sufficient deorbit rate at $\frac{1}{2}$OML current levels, see section 6.1.6, are listed in table 8.5 with the mass and dimension range summarised below.

Table 6.16: Feasible TET-EM configurations

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Parameter</th>
<th>Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-2</td>
<td>Effective $L_t$</td>
<td>500-900 m</td>
</tr>
<tr>
<td>REQ-3</td>
<td>$w_c$</td>
<td>15-20 mm</td>
</tr>
<tr>
<td>REQ-69</td>
<td>$t_c$</td>
<td>16-22 µm</td>
</tr>
<tr>
<td>REQ-18</td>
<td>$m_b$</td>
<td>1.1-1.5 kg</td>
</tr>
<tr>
<td>REQ-60</td>
<td>$D_R$</td>
<td>134-195 mm</td>
</tr>
<tr>
<td>REQ-70+REQ-18</td>
<td>$m_b + m_e$</td>
<td>1.9-2.4 kg</td>
</tr>
</tbody>
</table>

As can be seen in table 8.5 the 650 m and 750 m-15 mm tether configurations have the lowest mass, requiring a relatively low stabilising end mass due to reduced disturbance torques acting on the tether combined with a low mass for the tether. The 500 m-20 mm tether has the smallest storage dimensions when on the reel; the 900 m-15 mm is just within the 200 mm storage constraint. The 20 mm wide tethers out perform their 15 mm counterparts for storage dimensions due the drop in tether thickness for increasing widths. If the final tether design choice is driven by mass the 15 mm tethers are favourable, for storage the wider 20 mm tethers are preferred. For deorbit performance, $F_L/F_D$ ratio and a higher bias tether for OML validity the choice will be to fly the longest-widest tether possible, the 900 m-20 mm being the configuration requiring the entire mass budget available.

### Thermal Performance

As already discussed in section 5.1.3 tether temperature affects various tether properties. For the configurations considered here the following steady state temperatures are derived using the flat plate geometry for the tether.

Table 6.17: $T_{\text{SS}}$ max and min 50% enforced tether

<table>
<thead>
<tr>
<th>$T_{\text{HOT}}$</th>
<th>$T_{\text{COLD}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>84±15 °C</td>
<td>-159±15 °C</td>
</tr>
</tbody>
</table>
The optical properties for the conducting aluminium and the enforcing substrate used in determining the steady state temperatures are identical to those used for figure 5.6 and figure 5.7. The maximum steady state temperature for the tether is within the required $T_{\text{max}}$ of 100°C mainly due to the percentage of the Kapton® substrate with this effect already shown in figure 5.7. The minimum temperature requirement of -100°C is not met due to the ratio of the infrared flux area and the total area of the tether emitting thermal radiation. As the tether angle from the nadir is limited to approximately 5° the tether will not receive sufficient infrared radiation to achieve a higher temperature. At these low temperatures the critical elements of the tether design consist of the adhesive laminating the substrate and the coating. The load carrying aluminium alloy will be able to perform its load carrying and conductive functions at these temperatures.

Another requirement not met by the feasible configurations is the end mass budget of 0.83 kg, an additional ballast mass of 0.2 kg-0.7 kg is required for the floating tether configuration. In table 8.6 an overview of requirements not met by the remaining configurations is provided, these are addressed further in section 6.1.8. Weak points of surviving concept designs are the amount of Lorentz drag compared to total drag for the 650 km-85° orbit at 17%-34% for the configurations and the low levels of induced bias for the 100 km-85° orbit possibly leading to part of the tether not being within the OML current collection regime, see section 2.2 and 6.1.6.

### 6.1.6 Design Risks TET-EM Systems

Failure modes and their impact on the mission, experiment and performance have in part been analysed for the experiment and are discussed in this section. A risk map has been generated using the functional breakdown and the subsystem allocation matrix of the EDT Functional Specification (3.0) [SPC.4122.03] and is partly shown below. In total 11 risk elements have been identified. They are shown on the left of table 6.18 with the first column giving the ID. The criticality of the various risks is shown in the right four columns. To reduce the risk and the impact of a risk element occurring the goal is to move highly critical items to the lower left corner of the risk matrix. This is done by reducing the criticality of a failure and or minimise the chance of a failure occurring by increasing the design maturity of the system. The mission criticality has been defined according to [Hamann] as follows:

- **High** – Delfi-1 Mission (impact 0.9)
- **Medium** – EDT Experiment (impact 0.7)
- **Low** – Performance Degradation of EDT Experiment (impact 0.5)
- **Minimal** – Non Operational impact, Reduction in Performance (impact 0.1)

#### Table 6.18:TET-EM design part of risk map and mitigation plan TET-EM subsystems

<table>
<thead>
<tr>
<th>Function ID</th>
<th>Risk Element</th>
<th>Feasible in Theory</th>
<th>Criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4</td>
<td>keep EDT in operational condition during onboard storage</td>
<td>Working Laboratory Model (verified simulation)</td>
<td>Low</td>
</tr>
<tr>
<td>8.1</td>
<td>remain operational during deployment integrity tether deployment loads (Tension jerk) deployability system dynamics</td>
<td>Based on Existing Design</td>
<td>Medium</td>
</tr>
<tr>
<td>8.4</td>
<td>generate Lorentz force generate bias collect sufficient current orbit determination</td>
<td>Extrapolated from Existing Flight Design</td>
<td>High</td>
</tr>
<tr>
<td>9.0.1</td>
<td>orbit determination</td>
<td>Proven (flight) Design</td>
<td>Low</td>
</tr>
<tr>
<td>9.0.2</td>
<td>system dynamics</td>
<td></td>
<td>Medium</td>
</tr>
<tr>
<td>9.3.1</td>
<td>Criticality</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>9.4.3</td>
<td>system within APE ±5°tether ±20°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.6.1</td>
<td>remain operational during experiment system dynamics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.6.2</td>
<td>survive M/OD survive operational loads</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

101/206 DELFI.1.TW.4122.11
Risk mitigation strategies impacting the design and configuration of the TET and EM subsystems are shown in the table below.

Table 6.19: Risk mitigation plan TET-EM subsystems

<table>
<thead>
<tr>
<th>Function ID</th>
<th>Risk Element</th>
<th>Approach for Risk Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4</td>
<td>storage impact tether</td>
<td>analysis, test</td>
</tr>
<tr>
<td>8.1</td>
<td>loads &amp; deployability</td>
<td>analysis, deployment tests and verification</td>
</tr>
<tr>
<td>8.4</td>
<td>control deployment</td>
<td>test brake coating and deployability tether</td>
</tr>
<tr>
<td>9.0.1</td>
<td>generate sufficient bias</td>
<td>analysis adapt orbital inclinations alternative design</td>
</tr>
<tr>
<td>9.0.2</td>
<td>collect sufficient current</td>
<td>conservative w, max 40 mm analysis design margins</td>
</tr>
<tr>
<td></td>
<td></td>
<td>½ IOM or 10-20 V loss [TBD 42] margin 2 on required deorbit performance</td>
</tr>
<tr>
<td>9.3.1</td>
<td>orbit determination</td>
<td>DDTS backup system</td>
</tr>
<tr>
<td>9.4.3</td>
<td>increase deorbit 20 m during gas release</td>
<td>analysis</td>
</tr>
<tr>
<td>9.6.1</td>
<td>remain within APE ±5°</td>
<td>analysis (dynamical), margin 3</td>
</tr>
<tr>
<td>9.6.2</td>
<td>loads</td>
<td>analysis and test</td>
</tr>
<tr>
<td>M/OD</td>
<td>Collision operational satellites</td>
<td>analysis final flight orbit, EOL strategies</td>
</tr>
</tbody>
</table>

Highly critical elements are the deployment system, the systems dynamical behaviour and tether integrity. The latter taken into account when designing the tether to withstand the load environment by design with adequate design margins and proof of design by testing the chosen tether design. The meteoroid and orbital debris risk for the tether in orbit was taken into account in the configurations width and length combinations in section 6.1.4. Uncertainties as to the dynamics of the system and tether also require design approaches with sufficient design margins, analysis and further simulation to reduce the risk of a failure occurring. Two additional risks have been identified both having a major impact on the performance requirements of the tether and subsequent dimensions, a GPS malfunction requiring GS tracking to determine the deorbit performance of the system and the tether design not achieving OML current values.

**GPS Malfunction**

Using the DDTS as a back up system for determining the deorbit rate of the system reducing the impact of a GPS receiver malfunction affects the required deorbit capability of the tether and its subsequent dimensions. The required tether length for achieving a 3 month deorbit of 4 km is 1250 m. A minimum increase of $D_R$ to 246 mm, $m_c$ to 2.0 kg and a ballast mass of 1.5 kg is required increasing their combined mass budget by 1.1 kg. The DDTS deorbit measurement method is not achievable within the current mass budget and storage $D_R$ constraints for the EDT Using GPS velocity measurements will require a minimum 1250 m-20 mm-27 µm tether also not within budget constraints.

**Current Collection**

Largest uncertainty in performance of the tether is the OML current collection capability of the low bias (section of) tether. In this thesis work the current distribution along the tether has been assumed to be consistent with equation (2-11) and maximum current levels have been determined using (2-12) for a maximum of 20 mm-40 mm wide conducting tape. The impact part of the tether not being in the OML regime for the relatively low induced bias inherent to the short tape tether design and high altitude and inclination range noting that OML theory is valid for biases $e\Delta V > K_B T_{el} & \frac{1}{2}m_e V^2$ is evaluated by assuming the tether collects current levels $\frac{1}{2} I_{OML}$ or that 10 V-20 V of the induced EMF is lost reducing the effective length of the tether available for current collection as proposed by [Topholm]. The main effect is a reduction in the deorbit performance of the system and the $F_L/F_D$ ratio with the system being more stable due to lower current levels.

The deorbit rate is simplified by using equation (3-3), the maximum effect of current reduction and decrease in Lorentz drag occurs for the tether having 90% of the total drag force consisting of $F_L$ for 1000 km -110° orbits. Reducing the OML current by a factor 2 approximately reduces the total drag and the deorbit rate of the tether by a factor 0.45 for the drag ratio of 90%. Tethers achieving a deorbit rate of 160 m in two weeks will be able to meet **REQ-20** at the decreased current collection performance for the following minimum dimensions shown below.
The configurations shown in table 6.16 and highlighted in table 6.21 have sufficient deorbit performance capabilities to perform a measurable deorbit by the GPS receiver when the assumed $I_{OML}$ current levels are reduced by a factor 2. Taking the actual $F_L/F_D$ ratio into account the deorbit performance has been recalculated using the Tether Design tool [TN.4122.19] for $\frac{1}{2}I_{OML}$ current values with the results shown below. As can be seen in table 6.20 this leads to more configurations having sufficient deorbit performance.

Table 6.21: Minimum deorbit performance two weeks $\frac{1}{2}I_{OML}$ current levels

<table>
<thead>
<tr>
<th>$1000-85^\circ$</th>
<th>$w_c - 5$ [mm]</th>
<th>$w_c - 10$ [mm]</th>
<th>$w_c - 15$ [mm]</th>
<th>$w_c - 20$ [mm]</th>
<th>$w_c - 30$ [mm]</th>
<th>$w_c - 40$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>13</td>
<td>20</td>
<td>27</td>
<td>34</td>
<td>48</td>
<td>63</td>
</tr>
<tr>
<td>500</td>
<td>24</td>
<td>43</td>
<td>62</td>
<td>81</td>
<td>119</td>
<td>156</td>
</tr>
<tr>
<td>750</td>
<td>42</td>
<td>79</td>
<td>116</td>
<td>153</td>
<td>227</td>
<td>301</td>
</tr>
<tr>
<td>850</td>
<td>52</td>
<td>98</td>
<td>145</td>
<td>191</td>
<td>284</td>
<td>377</td>
</tr>
<tr>
<td>1000</td>
<td>69</td>
<td>132</td>
<td>195</td>
<td>258</td>
<td>384</td>
<td>510</td>
</tr>
<tr>
<td>1250</td>
<td>104</td>
<td>202</td>
<td>301</td>
<td>399</td>
<td>596</td>
<td>792</td>
</tr>
<tr>
<td>1500</td>
<td>150</td>
<td>294</td>
<td>437</td>
<td>581</td>
<td>869</td>
<td>1156</td>
</tr>
<tr>
<td>1750</td>
<td>207</td>
<td>407</td>
<td>608</td>
<td>808</td>
<td>1209</td>
<td>1610</td>
</tr>
<tr>
<td>2000</td>
<td>276</td>
<td>545</td>
<td>815</td>
<td>1084</td>
<td>1623</td>
<td>2161</td>
</tr>
<tr>
<td>2250</td>
<td>358</td>
<td>709</td>
<td>1061</td>
<td>1412</td>
<td>2114</td>
<td>2816</td>
</tr>
<tr>
<td>2500</td>
<td>454</td>
<td>901</td>
<td>1348</td>
<td>1795</td>
<td>2688</td>
<td>3581</td>
</tr>
</tbody>
</table>

Assuming a voltage loss of 10 V-20 V reduces the effective length of the tether and subsequent current levels depending on the orbit and induced E the amount of tether length lost to non OML regime can be calculated, results shown below.

Table 6.22: Effective tether length loss non OML regime

<table>
<thead>
<tr>
<th>Loss $L_t$ [m]</th>
<th>650 km $E_{min}$</th>
<th>650 km $E_{avg}$</th>
<th>650 km $E_{max}$</th>
<th>1000 km $E_{min}$</th>
<th>1000 km $E_{avg}$</th>
<th>1000 km $E_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 V</td>
<td>971</td>
<td>279</td>
<td>162</td>
<td>1205</td>
<td>330</td>
<td>190</td>
</tr>
<tr>
<td>20 V</td>
<td>1942</td>
<td>557</td>
<td>323</td>
<td>2410</td>
<td>661</td>
<td>380</td>
</tr>
</tbody>
</table>

Designing the system with a margin for the 10 V-20 V loss would limit the experiment orbital inclinations to reduce the amount of tether length required so it can fit within Delfi-1 constraints. With the 200 mm storage constraint having a maximum capacity of 1000 m of tether the 10 V-20 V voltage loss limits the minimum orbital induced E values to 0.02 V m$^{-1}$ and 0.04 V m$^{-1}$ giving a minimum deorbit performance of 80 m for the 1000 m tethers for the following orbits:
- 10 V loss 650 km-1000 km 70°-80° and 100°-110°
- 20 V loss 650 km-1000 km 70° and 105°-110°

Longer tethers are more likely to be within OML regime for a sufficient section of tether length, see appendix 5, table a5- 1 and table a5- 2. They are required to be wider to meet M/OD survivability requirements $P_{surv} \geq 95\%$ and thinner to meet the storage and mass constraints. In the next design phase of the experiment more research into the current collected by the short passive EDT tether operating at high inclinations and thus inducing a significantly lower bias than most EDT systems previously considered will have to be performed. Research how the current collection deviates from the proposed OML theory and the influence of other current sources on induced current levels is required. A minimum tether length of 1250 m-1750 m will work for most part of the Delfi-1 orbit range, requiring more storage and an increased mass budget or a thinner tether design, this minimum length is advisable depending on more conclusive results as to the current and bias distribution in the Delfi-1 orbit range including the auroral and polar regions of the ionosphere.
6.1.7 Gas Cathode Operation

In this section the affect operating the neutral gas cathode on the tether and end mass system configuration is evaluated. The passive tether and end mass configurations derived in the previous sections combined with data from section 5.2 is used as input values and using the Tether Design tool the deorbit performance, stability of the system and induced current levels are determined.

Table 6.23: Input gas cathode calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_t)</td>
<td>500-900 m</td>
<td></td>
</tr>
<tr>
<td>(w_c)</td>
<td>15-20 mm</td>
<td></td>
</tr>
<tr>
<td>(w_{sub})</td>
<td>50% (w_c) mm</td>
<td></td>
</tr>
<tr>
<td>(t_c)</td>
<td>16-22 (\mu m)</td>
<td></td>
</tr>
<tr>
<td>(m_b)</td>
<td>1.1-1.5 kg</td>
<td></td>
</tr>
<tr>
<td>(m_t)</td>
<td>7.5 kg</td>
<td></td>
</tr>
<tr>
<td>(t_{gas})</td>
<td>16-27 min</td>
<td></td>
</tr>
<tr>
<td>available (m_{gas})</td>
<td>15-71 g</td>
<td></td>
</tr>
</tbody>
</table>

Performance & Stability

Performance requirements for the gas cathode consist of achieving a measurable deorbit (section 4.2.1) and inducing sufficient bias to allow the neutral gas to ionise (section 5.2) summarised below.

- **REQ-25** Deorbit during gas release of 20 m
- **REQ-62** Induced EMF [during gas release] \(-V_{end} > 25 \text{[V]}\) to achieve ionisation potential \(N_2\)

Neutral gas ionisation of the \(N_2\) gas necessary for sustaining a constant \(I_{gas}\) current requires a tether end bias potential to the ambient plasma of -25 V to accelerate the secondary emitted electrons to their ionisation potential over the electric field [**REQ-62**]. For the 1000 km 85° orbit the lowest induced \(E\) of 0.008 \(\text{Vm}^{-1}\) results in a minimum required tether length of 3200 m [**REQ-2f**], at average \(E\) values of 0.033 \(\text{Vm}^{-1}\) and maximum of 0.062 \(\text{Vm}^{-1}\) the required length is reduced to 775 m and 425 m. Gas ionisation potential requirement [**REQ-62**] is not achievable using the induced EMF for a tape tether onboard the Delfi-1 satellite for the entire orbit range requiring an increase in length to 3200 m storage, mass and M/OD requirements make this requirement unachievable. For the \(850\) m tether an orbital inclination restriction 70°-75° and 100°-110° is required to generate sufficient bias at the tether cathode end for gas ionisation.

**REQ-2f** Tether Length Gas Cathode Operation

\(L_t \geq 850\) m

The required performance of the gas cathode is a function of tether length, orbit and the time \(t_{gas}\) in which the 20 m \(\Delta SMA\) is to be achieved. With the \(850\) m tether having the highest \(I_{gas}\) requirement for the tether range of \(850-2500\) m the required gas cathode mass flow rates are calculated as a function of gas release time. Results shown in table 6.24, longer gas release operation reduces the required current levels and subsequent mass flow rate of the cathode.

Table 6.24: Gas cathode performance requirement 850 m tether

<table>
<thead>
<tr>
<th>time (t_{gas}) [min]</th>
<th>(&lt;F_{gas}&gt;) [N]</th>
<th>(&lt;I_{gas}&gt;) [A]</th>
<th>(&lt;\dot{m}_{REQ}&gt;) [molecules s(^{-1})]</th>
<th>(&lt;\dot{m}_{REQ}&gt;CGT) [molecules s(^{-1})]</th>
<th>(&lt;\dot{m}_{REQ}&gt;CGT) [kg s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.63E-03</td>
<td>1.30E-01</td>
<td>8.09E+17</td>
<td>8.09E+19</td>
<td>3.76E-06</td>
</tr>
<tr>
<td>10</td>
<td>8.17E-04</td>
<td>6.49E-02</td>
<td>4.05E+17</td>
<td>4.05E+19</td>
<td>1.88E-06</td>
</tr>
<tr>
<td>15</td>
<td>5.45E-04</td>
<td>4.33E-02</td>
<td>2.70E+17</td>
<td>2.70E+19</td>
<td>1.26E-06</td>
</tr>
<tr>
<td>20</td>
<td>4.09E-04</td>
<td>3.25E-02</td>
<td>2.03E+17</td>
<td>2.03E+19</td>
<td>9.44E-07</td>
</tr>
<tr>
<td>25</td>
<td>3.27E-04</td>
<td>2.60E-02</td>
<td>1.62E+17</td>
<td>1.62E+19</td>
<td>7.54E-07</td>
</tr>
<tr>
<td>30</td>
<td>2.72E-04</td>
<td>2.16E-02</td>
<td>1.35E+17</td>
<td>1.35E+19</td>
<td>6.27E-07</td>
</tr>
<tr>
<td>35</td>
<td>2.33E-04</td>
<td>1.85E-02</td>
<td>1.16E+17</td>
<td>1.16E+19</td>
<td>5.37E-07</td>
</tr>
</tbody>
</table>
The remaining gas for case 2 will produce mass flow rates (table 5.13) in excess of the required values resulting in maximum current levels shown below.

<table>
<thead>
<tr>
<th>initial mass flow rate $m_{in}$</th>
<th>kgs$^{-1}$</th>
<th>3.28E-04</th>
<th>6.71E-05</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{gas\ max}$</td>
<td>A</td>
<td>11.3</td>
<td>2.31</td>
</tr>
<tr>
<td>average mass flow rate $&lt;m_{in}&gt;$</td>
<td>kgs$^{-1}$</td>
<td>5.91E-5</td>
<td>1.51E-5</td>
</tr>
<tr>
<td>$&lt;I_{gas}&gt;$</td>
<td>A</td>
<td>2.04</td>
<td>0.52</td>
</tr>
</tbody>
</table>

The maximum current $I_{gas} = I_t$ is constrained stability requirements and by the maximum current load rating for the tether [REQ-54] for the 850 m-15 mm tether this is 1.86e-2 A. A gas release time of 35 minutes is required for average gas current levels to be sufficiently low. Deorbiting the system 20 meters during gas cathode operation of 35 minutes requires a Lorentz force $F_L$ of 2.3e-4 N due for an 850 m tether. This would still result in peak current levels in excess of the 1.86e-2 A. Designing the cathode for peak mass flow in concurrence with the maximum current requirement would limit initial mass flows to be in the order of 5e-7 kgs$^{-1}$. Further research is required to determine if a short duration increase of the current levels beyond $4I_{OML}$ is acceptable in terms of voltage drop losses for gas release to shorten the operational time of the gas cathode.

**System Stability**

- **REQ-4** $APE \leq \pm (5^\circ - \omega_n) ; \frac{T_{GG}(5^\circ)}{T_{DIST}} \geq 1.3$

**Tether Librations**

- **REQ-14** $\frac{T_{GG}(20^\circ)}{T_{DIST}} \geq 3$
- **REQ-15** $I_t(max) < I_{crit}$
- **REQ-11** $T_{gas} < [TBD 43] [Nm]$

Assuming average current levels of 0.52 A during gas release, current levels are below $I_{crit}$ of 0.166 A [REQ-15] for the 850 m tether with a ballast mass of 1.1 kg. The stability ratio of the tether and required end mass will alter during gas release due to the change in current distribution and Lorentz torque; see section 2.2.4, 3.2 and 3.3. For the $I_{gas}$ of 0.52 A the tether has a current distribution that is between saturated and unsaturated current distribution for 650 km orbit altitudes. Assuming saturated current distribution the required end mass $m_b$ is calculated with results shown below.

<table>
<thead>
<tr>
<th>$m_b - 1.1$ kg</th>
<th>$I_{gas} - 0.52$ A</th>
<th>EM.04a – b</th>
<th>$I_{gas}$ [mA]</th>
<th>$m_b$ [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>APE</td>
<td>40</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3APE</td>
<td>2</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{T_{GG20^\circ}}{T_{DIST}} \geq 3$</td>
<td>45</td>
<td>2.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dynamic simulations taking into account the duration of the increased Lorentz torque due to gas release and the change in mass flow rate and current levels in the tether as the gas is released are necessary for a more definitive determination of the tether dynamics for the $I_{gas}$ current distribution. Reducing gas current levels to 40 mA will allow for an APE of 5° and tether stability ratio $> 3$ and also allows for **REQ-54** to be met. An increase in end mass or a gas current limitation, summarised in table 6.25, is required for the system and tether to meet the system and tether stability requirements. A reduction of gas current levels also reduces the deorbit performance requiring a gas cathode operation of 15 minutes (table 5.15) assuming average current levels of 40mA with the tether generating a Lorentz drag force of 5.5e-4 N resulting in a measurable deorbit. The amount of neutral gas remaining after tether deployment is sufficient to perform the neutral gas experiment. The mass flow rate of the CGT will have to be adapted to ensure induced gas currents do not destabilise the system. Redesign is also required to minimise the disturbance torques on the system gas release in opposing directions.

**REQ-66** **Gas Release Current $I_{gas}$**

Average $I_{gas} = 40$ [mA] to increase the deorbit rate by a factor 20 [m] at orbit altitude of 650 [km] and 85° inclination during $t_{gas}$ of 15 minutes [DROPPING **REQ-54**]
REQ-67  Required Mass Flow Rate Gas Cathode

Assuming 1% ionisation of the neutral gas the required average mass flow rate from the gas cathode is \( m_{\text{req}} = 1.16 \times 10^{-6} \text{ [kgs}^{-1}] \) to sustain a 40 [mA] gas discharge current.

6.1.8 Requirement Sensitivity Analysis

In section 6.1.5 it was already indicated that the feasible configurations of the experiment do not meet all the requirements stated in table 8.3. In this section the requirements that cannot be met by the configurations, their impact and the required action and subsequent conflicts occurring have been listed in table 8.6 with the following criticality criteria similar to the risk map [Hamann].

- **High** – Delfi-1 Mission Failure (impact 0.9)
- **Medium** – EDT Experiment Failure (impact 0.7)
- **Low** – Performance Degradation of EDT Experiment (impact 0.5)
- **Minimal** – Non Operational Impact, Reduction in Performance (impact 0.1)

Conflicting Requirements

**REQ-24 \( F_L/F_D \) ratio impact 0.5**

Requires an increase of the tether length to \( L_t = 1500 \text{ m} \) for this requirement to be met for the 650 km - 85° orbit and this is not within mass and storage constraints due to the voltage drop requirement impact on \( t_c \) and M/OD requirement on \( w_c \). Increasing the storage and mass for the longer tethers, ignoring the M/OD, \( D_R \) requirements and requiring 0.4 kg extra ballast mass the following system will achieve a \( F_L/F_D \) ratio > 50%.

- \( L_t = 1500 \text{ m} \)
- \( w_c = 10 \text{ mm} \)
- \( t_c = 36 \mu\text{m} \)
- \( m_t = 1.57 \text{ kg} \)
- \( m_b = 1.2 \text{ kg} \)
- \( D_R = 299 \text{ mm} \)

With a stability ratio \( m_t/m_b \) of 1.31 this system could have long term stability issues [TBD 44].

**REQ-18 required for meeting APE Delfi-1**

**REQ-4 impact 0.9-0.5**

Decreasing the tether width to 5 mm wide tethers reducing the amount of ballast mass required conflicts with deorbit and storage constraints due to the required thickness \( t_c \) (handling loads and voltage drop). An increase of \( m_b \) above the set budget of 0.83 kg is required to achieve 3APE for widths beyond 15 mm. For long term stability the longer tethers require more ballast mass than the 3APE requirement, an increase of the ballast mass is required being 2 kg to 3.8 kg for the configurations listed in table 6.16, this is not achievable for the Delfi-1 mission as it is over half the total mass budget for the experiment.

Effects of Altering Requirements

**Decreasing \( F_L/F_D \) ratio**

Initial estimates for the \( F_L/F_D \) ratio were set at 50%-90% in chapter 4, at this point it is uncertain what the minimum value for this requirement should be to derive a conclusive proof of concept of Lorentz drag induced by the bare floating tether when measuring the deorbit performance. Flying the experiment at low inclinations and especially high altitudes will give a good indication of Lorentz drag force acting on the system as the aerodynamic drag in these orbits is less compared to the Lorentz drag force. Adapting the requirement to 30% pending on further research into methods of estimating the amount of aerodynamic drag and density in orbit the longer tether configurations > 800 m) will be able to meet this requirement.

**Dropping 3APE**

Dropping the 3APE systems state error will enable the ballast mass to remain within the set design target of 0.83 kg, see table 6.8. Meeting the 3APE requirement during gas cathode operation requiring 10 kg based on steady state torque balance of the system is not achievable within Delfi-1 mission constraints. Further study will have to determine the effect of dropping the margin of 3 on the APE requiring dynamical stability analysis to be performed.
Decrease Voltage Drop Requirement

By dropping the maximum current rating of the tether from $I_{\text{OML}}(\text{max})$ to $2I_{\text{OML}}(\text{max})$ the required conducting thickness $t_c$ of the tether is effectively halved as can be seen in equation (5-5). The effect on both mass and required storage dimensions is considerable increasing the amount of configurations within the current design constraints as shown below.

### Table 6.26: Increase in tethers meeting mass and storage constraints

<table>
<thead>
<tr>
<th>$4I_{\text{OML}}$</th>
<th>$L_t$ [m]</th>
<th>$w_c$-5 [mm]</th>
<th>$w_c$-10 [mm]</th>
<th>$w_c$-15 [mm]</th>
<th>$w_c$-20 [mm]</th>
<th>$w_c$-30 [mm]</th>
<th>$w_c$-40 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>500</td>
<td>NOT OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>750</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>850</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>NOT OK</td>
</tr>
<tr>
<td>1000</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>OK</td>
<td>OK</td>
<td>NOT OK</td>
</tr>
<tr>
<td>1250</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$2I_{\text{OML}}$</th>
<th>$L_t$ [m]</th>
<th>$w_c$-5 [mm]</th>
<th>$w_c$-10 [mm]</th>
<th>$w_c$-15 [mm]</th>
<th>$w_c$-20 [mm]</th>
<th>$w_c$-30 [mm]</th>
<th>$w_c$-40 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>500</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>750</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>850</td>
<td>NOT OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>1000</td>
<td>NOT OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
</tr>
<tr>
<td>1250</td>
<td>NOT OK</td>
<td>OK</td>
<td>OK</td>
<td>OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
</tr>
<tr>
<td>1500</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
<td>NOT OK</td>
</tr>
</tbody>
</table>

This would allow a 1250 m tether to fit onboard at a slight increase in mass and storage budgets having a sufficient margin for 20 V voltage losses for $E_{\text{avg}}$ orbits and almost meeting the filtering ratio requirement. A 1750 m tether having sufficient margin for 10 V losses at $E_{\text{min}}$ is still considerably out of budget for the Delfi-1 constraints for the thinner configuration.

### Table 6.27: Configurations with DDTS capability and voltage loss margin

| REQ-2 | $L_t = 1250$ m | $w_c = 20$ mm | $w_c = 50\% w_c$ | $t_c = 17$ µm | $m_b = 1.5$ kg | $m = 1.34$ kg | $m/m_b = 0.9$ | $D_b = 211$ mm | $m + m_b = 3.2$ kg | 46% |
| REQ-3 | $L_t = 1750$ m | $w_c = 20$ mm | $w_c = 50\% w_c$ | $t_c = 22.5$ µm | $m_b = 1.5$ kg | $m = 2.4$ kg | $m/m_b = 1.6$ | $D_b = 272$ mm | $m + m_b = 5.9$ kg | 59% |

**Increase $D_R$**

Increasing the storage dimensions allows longer tethers, the $F_l/F_D > 50\%$ requirement can be met for $D_R$ of 300 mm as was shown on the previous page. The ballast mass requirement can also be reduced as the tether can be made thicker allowing a decrease in $w_c$. For $D_R$ 237 mm a 1000 m-10 mm tether with 0.83 kg $m_b$, $t_c$, 33 µm, 210 m deorbit in two weeks can be flown. Both these configurations do not achieve $P_{\text{surv}}>95\%$ [REQ-59].

**Decrease $T_{\text{HAND}}$ 10 N**

Dropping the $T_{\text{HAND}}$ requirement to 10 N allows more stable $w_c$ 5 mm-10 mm and $L_t$ up to 1000 m 10 mm-20 mm tethers to fit within the required dimensions having a slight effect on possible configurations.

**Decrease M/OD $P_{\text{surv}}$**

Decreasing the $P_{\text{surv}}$ below 95% reduces tether width required for the longer tethers being considered and increases the amount of tether lengths fitting within 1.6 kg the mass budget of the tether and smaller width tethers also require less ballast mass to stabilise. Decreasing the tether width will have an impact on storage dimensions for some configurations.
To remove conflicting requirements a requirement review is advised for the following requirements:

- **REQ-24** \( \frac{F_i}{F_0} \) filtering requirement is unfeasible for the short tether lengths able to fit within Delfi-1 constraints, research filtering approaches to determining Lorentz drag effect on deorbit rate of the system or decrease tether thickness and increase mass and storage budgets.

- **REQ-4** Verify the necessity of the 3APE requirement and research the long term libration behaviour of the tether. Also review the 3APE and stability ratio \( T_{GG}(20^\circ)/T_{DIST} \geq 3 \) requirements for the short duration gas release.

- **REQ-53** Determine if voltage drop requirement can be made less stringent allowing for a thinner tether to be flown.

- **REQ-18** A review of the EM mass budget of 0.83 kg (1.83 kg including GAS) determine if it is sufficient for (long term) stability.

- **REQ-59** M/OD requirement relaxation will allow a reduction in tether width for longer tethers having a positive effect on the mass budget.

- **REQ-21** and **REQ-22** a wire tether can be made significantly longer with current collection in the OML regime and reaching ionisation potentials for the \( N_2 \) gas cathode operation.

### 6.2 EDT Baseline Design & Performance

In this section an overview of the design characteristics for the experiment determined in the previous sections and part I of this study is provided. The performance and operation of the design are highlighted and the each of the systems is briefly described. To give an overview of the design derived in the previous chapters a systems breakdown for the EDT experiment is shown below.

![EDT Systems breakdown](image)

Characteristics of the experiment systems are summarised in a table 6.28. For a description of the deployment mechanism systems shown in figure 6.2 the reader is referred to the thesis work of [Heijning]¹. The experiments power and structure systems have not been developed in this thesis work, they are integral components with the Delfi-1 payload platform with the payload bay and will be designed as the payload platform and the special payload module used for the experiment are developed.
Table 6.28: EDT experiment systems description

<table>
<thead>
<tr>
<th>System</th>
<th>Description</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tether</strong></td>
<td>a bare floating tape tether deployed nadir direction</td>
<td>Lt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>wt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>t</td>
</tr>
<tr>
<td><strong>Conducting Tether</strong></td>
<td>1000-series conductive tape</td>
<td>tc</td>
</tr>
<tr>
<td><strong>Substrate</strong></td>
<td>50% wt, rip stop protection layer consisting of for example commercially available 7.5 µm Kapton®</td>
<td>wsub</td>
</tr>
<tr>
<td><strong>Adhesive</strong></td>
<td>acryl or silicon type</td>
<td>tadh</td>
</tr>
<tr>
<td><strong>Coating</strong></td>
<td>AO protective coating for example TOR-BP®</td>
<td>tcoat</td>
</tr>
<tr>
<td><strong>tether mass</strong></td>
<td></td>
<td>mt</td>
</tr>
<tr>
<td><strong>End Mass</strong></td>
<td>stabilising system to APE ≤ ±5° &amp; θ ≤ ±20°</td>
<td>mB</td>
</tr>
<tr>
<td></td>
<td>consisting of 0.83 kg DEP system and additional ballast mass and/or a gas cathode</td>
<td></td>
</tr>
<tr>
<td><strong>Telemetry</strong></td>
<td>GPS, bias measurement, turn counter data</td>
<td></td>
</tr>
<tr>
<td><strong>additional</strong></td>
<td>Temperature, Tension, Langmuir Probe data</td>
<td></td>
</tr>
<tr>
<td><strong>Deployment</strong></td>
<td>passive mechanism using a reel storage system and cold gas thrusters to eject the tether</td>
<td></td>
</tr>
</tbody>
</table>

**Performance**

The feasible tether configurations are designed to deorbit the system by a minimum of 100 m [REQ-20] during a two week operational period for the worst case 1000 km-85° orbit in the orbit range of the Delfi-1 satellite excluding the inclination range between 85°-95° due to the low induced bias in this region. In table 8.5 the performance characteristics of the feasible configurations for the experiment are shown for each configuration. In table 6.29 the expected performance range for the current baseline design configuration is shown.

Table 6.29: Performance range of feasible configurations for orbit range Delfi-1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Minimum Range</th>
<th>Maximum Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔSMA 2 weeks</td>
<td>m</td>
<td>107 - 328</td>
<td>1393 - 3721</td>
</tr>
<tr>
<td>F_L/F_D ratio</td>
<td>%</td>
<td>17% - 34%</td>
<td>72% - 82%</td>
</tr>
<tr>
<td>EMF V</td>
<td></td>
<td>4.2 - 7.5</td>
<td>31 - 56</td>
</tr>
<tr>
<td>I_{OML} max</td>
<td>mA</td>
<td>0.3 - 0.7</td>
<td>2.5 - 6.0</td>
</tr>
<tr>
<td>m_t/m_B</td>
<td></td>
<td>0.34</td>
<td>0.77</td>
</tr>
<tr>
<td>T_{SS} °C</td>
<td></td>
<td>-158</td>
<td>+83.8</td>
</tr>
<tr>
<td>B_{all} m^2 kg</td>
<td></td>
<td>20</td>
<td>26</td>
</tr>
</tbody>
</table>

The final tether and end mass design will be driven by the user preference either focussing on low cost by limiting the experiment mass and storage volume or by deorbit performance of the experiment. This will also depend on the method of filtering of the Lorentz drag force from the deorbit rate and the frequency of orbital position updates required when applying this method. Weak points of the current design and mission for the experiment are the limited Length L_t inherent to storage and mass constraints and the tape tether design.

The length of the tape tether is limited by the storage restrictions onboard the Delfi-1 satellite restricting the potential deorbit performance and $F_L/F_D$ ratio of the tether discussed in section 6.1. In the first part of this study the advantage of tape tethers per meter of length was discussed, results showing their increased collection area, increased drag area and lower mass properties per unit of tether length when compared to wire tethers having equivalent drag or mass properties.

The main advantages of wire tethers over tape tethers is their limited storage volume and low specific tether mass density $\rho_t$. Depending on wire diameter longer tethers can fit within the storage constraints as they can be level wound on a spool generally leading to higher $F_L/F_D$ drag ratios tethers when compared with the tape tether. Thin wires (d-0.25 mm) can achieve a similar deorbit performance as the feasible configuration at lengths of 5-10 km. This results in significantly larger $F_L/F_D$ ratios for the low altitudes and high inclination range.
The drawback of using a thin wire is that for an increased length and decreased cross wise dimensions the collision risk with micrometeoroids and orbital debris increases significantly. Wires that show equivalent survivability performances as the feasible configurations have diameters in the order of 0.85-1 mm; they require a substantial increase in mass or a decrease in deorbit performance. Both thin and thick wire tethers have a lower ballistic drag coefficient compared to the tape tether designs. The tape tether provides a significant advantage in reducing the risk of M/OD impact and the chance of collision with an operational satellite when severed from the main satellite in combination with high current levels, having the highest ballistic coefficients and survivability rates per unit of current compared wire tethers.

For each EDT system the requirements derived in this thesis work have been listed in EDT System Requirements provided in the annex of this thesis report, all aspects of the design and requirements that have to either be determined or confirmed are listed in table 8.8 continuing the list derived in the first part of this report. The current mass, power distribution for the experiment are shown in table 6.30. The mass budget given in the EDT Preliminary Design study is met with the tether being within budget and the initial overestimation of the gas cathode compensating for increased end mass \( m_b \) and the telemetry system mass. The end mass requires an additional 0.53 kg -1.0 kg including a design contingency margin of 20% to stabilise the system. An end mass allocation of 28% (1.7 kg for a 6 kg experiment) was also seen in the mass budget distribution of the experiment including an end mass in the first part of this study, the budget for the end mass needs to be revised accordingly.

### Table 6.30: EDT systems current mass, power and volume

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>EDT Payload</td>
<td>EDT</td>
<td>6.0</td>
<td>3.8-5.7</td>
<td>6</td>
</tr>
<tr>
<td>Deployer</td>
<td>DEP</td>
<td>1.0</td>
<td>1.10</td>
<td>2</td>
</tr>
<tr>
<td>Telemetry</td>
<td>TLM</td>
<td>1.0</td>
<td>0.42-1.33</td>
<td>5</td>
</tr>
<tr>
<td>Power</td>
<td>EPS</td>
<td>0.6</td>
<td>0.48</td>
<td>2</td>
</tr>
<tr>
<td>Structure and Harnessing</td>
<td>STS</td>
<td>0.7</td>
<td>0.70</td>
<td>0</td>
</tr>
<tr>
<td>Tether</td>
<td>TET</td>
<td>1.6</td>
<td>0.60-1.14</td>
<td>DEP</td>
</tr>
<tr>
<td>End Mass (( m_b ))</td>
<td>EM</td>
<td>0.83</td>
<td>1.32-1.72</td>
<td>0</td>
</tr>
<tr>
<td>75% DEP located at end mass</td>
<td>DEP</td>
<td>0.83</td>
<td>0.83</td>
<td>0</td>
</tr>
<tr>
<td>additional ballast mass required</td>
<td></td>
<td>0</td>
<td>0.53-1.01</td>
<td>1</td>
</tr>
<tr>
<td>Neutral gas cathode</td>
<td>GAS</td>
<td>1.0</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

The electrical power and structure & harnessing systems have to be developed taking this into consideration the remaining subsystems should not increase in mass by any significant amount during subsequent design stages. The total volume of the experiment is within budget. This is however an estimate based on hardware component volumes. Breadboarding the entire experiment will result in a better indication as to the total volume of the payload.

### Telemetry for the Experiment

The telemetry system strains the mass budget considerably if the full complement of proposed instruments is flown requiring the bare minimum complement of instrumentation to be flown, see section 4.3. The main instruments for the experiment are a GPS receiver, a tether bias sensor and an optical turn counter. Data from the Delfi-1 ADCS and EPS are used to provide information on the local magnetic field strength and direction, solar angle and power and bus attitude angles. The telemetry can be expanded to allow for more information on tether performance aiding in the determination of tether performance from the GPS orbit signal. These consist of a tether tension measurement during both the deployment and operational phase. A temperature sensor (calibration) and if sufficient budget is available a Langmuir Probe used for determining plasma density, temperatures and plasma potential. By combining GPS orbit data with local magnetic field strength, tether bias and possibly Langmuir probe the effect of the Lorentz forces can be determined [TBC 57].
Using the cyclic nature of both the aerodynamic and solar radiation forces will require multiple GPS data arcs to show diurnal variations. Combining tether bias variations with magnetic field strength and components and tension measurements will give an indication of tether current levels. Meeting the power budget requires a scheduling of measurements to take place during the operational phases of the experiment for the full instrumentation, see table 6.31.

Table 6.31: Peak power usage during each experiment phase

<table>
<thead>
<tr>
<th>Experiment Phase</th>
<th>Description</th>
<th>Peak Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>GPS</td>
<td>1 W</td>
</tr>
<tr>
<td>Deployment</td>
<td>HDRM; TC; TEN</td>
<td>2.4 W</td>
</tr>
<tr>
<td>Operation phase I</td>
<td>see Table 4.11</td>
<td>1.7-2.2 W</td>
</tr>
<tr>
<td>Operation phase II</td>
<td>see Table 4.11</td>
<td>1.5 W</td>
</tr>
<tr>
<td>Termination phase</td>
<td>GPS; ADCS; TBM; TEN</td>
<td>2.2 W</td>
</tr>
</tbody>
</table>

The deployment is required to take place during the eclipse part of the orbit by [Heijning²] [REQ.4122.TDS.75]. A total power of 2.4 W is required during deployment assuming the hold down and release mechanics (HDRM) and the telemetry are activated simultaneously. This conflicts with the 1 W of power available during eclipse [REQ-45] and it is advised to schedule the deployment in the solar part of the orbit. Requirements derived for the telemetry system are listed in the system requirements listing located in the annex of this report.

Operational Timeline
The experiment will operate in the last phase of the Delfi-1 mission; the tether will be deployed after which the payload will begin gathering scientific data. Adhering to the payload mission modes of the Delfi-1 project stated in the EDT Systems Requirements stated in part I of this study, the experiment will have the mission modes and experiment timeline stated in table 8.7.

Deployment Mechanism
The deployment of the tether using cold gas thrusters (CGT) ejection has been shown capable of providing sufficient ejection force to deploy a 1000 m, 30 mm and 17.5 μm thick tether with an end mass of 0.83 kg from a reel by [Heijning²]. The tether and end mass are deployed using a cold gas thruster; a section of tether has an adhesive coating applied to increase friction and controlling the deployment if required. Using equation (3-27) the maximum allowable end mass velocity at the end of deployment [REQ-68] \( l(t) = L \) can be determined for the feasible tether and end mass configurations. Assuming the enforced cross-sectional area \( A_{\text{min}} \) carrying the load of the tether jerk at the end of the deployment the allowable end mass becomes a function of the percentage of tether width enforced and the conducting thickness \( t_c \) determined by either the 25 N handling load requirement or the voltage drop requirement with the area \( A_{\text{min}} \) determined by \( t_c \) and \( w_{\text{sub}} \). Results for the current configurations range from 2-2.8 ms\(^{-1}\) shown in the \( v_{\text{EM}} \) max column of table 6.32. No deployment control system (DCS) is required as the final deployment velocity of the end mass is below the critical velocities to cause a tension jerk in the tether large enough to sever it. The effect of increasing the friction of the final 10% of tether length to 0.1 N is shown to decrease end mass velocities.

The constraints and requirements for the deployment system design and the deployment profile addressed in section 3.3 are summarised in the EDT System Requirements overview provided in the annex. Analysis of the dynamic motions of the tether during deployment, final libration angles and the allowable initial deployment velocity assuring the tether does not pitch back causing the system to tumble or entangle with the bus need to be performed. Also the allowable deployment torque and momentum acting on the bus keeping the systems absolute pointing error within the set ±5° and the tether libration angle within ±20° need to be verified as they where determined for tether libration angles within ±30°. Current configurations are well within the set 50 Ns disturbance impulse [REQ.4122.TDS.73] shown in table 6.32.
Table 6.32: $V_{EM}$ allowable for TET-EM configurations and results deployment profile [Heijning$^3$]

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$L_{eff}$ [m]</th>
<th>$t_c$ [µm]</th>
<th>$m_b$ [APE] [kg]</th>
<th>$v_{EM} max$ [ms$^{-1}$]</th>
<th>$v_{EM}$ [ms$^{-1}$]</th>
<th>$t_{dep}$ [s]</th>
<th>DCS 0.1 N 10%$L_t$ $v_{EM max}$ [ms$^{-1}$]</th>
<th>$t_{dep}$ [s]</th>
<th>Total impulse [Ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{eff}$ - 500 [m]</td>
<td>20</td>
<td>16</td>
<td>1.5</td>
<td>1.95</td>
<td>1.80</td>
<td>196</td>
<td>1.55</td>
<td>203</td>
<td>29.4</td>
</tr>
<tr>
<td>$L_{eff}$ - 650 [m]</td>
<td>15</td>
<td>22</td>
<td>1.2</td>
<td>2.42</td>
<td>1.97</td>
<td>213</td>
<td>1.67</td>
<td>218</td>
<td>30.8</td>
</tr>
<tr>
<td>$L_{eff}$ - 750 [m]</td>
<td>20</td>
<td>16</td>
<td>1.5</td>
<td>2.18</td>
<td>1.82</td>
<td>234</td>
<td>1.50</td>
<td>240</td>
<td>32.9</td>
</tr>
<tr>
<td>$L_{eff}$ - 850 [m]</td>
<td>15</td>
<td>22</td>
<td>1.1</td>
<td>2.64</td>
<td>2.02</td>
<td>224</td>
<td>1.70</td>
<td>228</td>
<td>31.8</td>
</tr>
<tr>
<td>$L_{eff}$ - 900 [m]</td>
<td>20</td>
<td>16</td>
<td>1.5</td>
<td>2.31</td>
<td>1.80</td>
<td>256</td>
<td>1.42</td>
<td>262</td>
<td>34.8</td>
</tr>
</tbody>
</table>

Neutral Gas Release

Increasing tether current levels by use of a gas cathode releasing a neutral gas at the tether termination [REQ-22] is to be considered a secondary mission objective, depending on the final orbit and uncertainties in orbit insertion as it will only work for low inclination orbits for the tape tether experiment onboard Delfi-1. The floating tether configurations capable of inducing sufficient $L_t \geq 850$ m can handle a gas release current up to 40 mA without requiring more ballast mass. A redesign of the CGT adapted for longer gas release duration and lower mass flow rates is required. The initial mass budget for the gas cathode of 1 kg is expected to be an overestimation with 0.5 kg being a more realistic mass.
7 CONCLUSIONS & RECOMMENDATIONS

In this section the conclusions for the electrodynamic tether experiment onboard Delfi-1 satellite, recommendations and items for further development of this experiment are listed.

7.1 Conclusions

A design tool set to aid in sizing an EDT tape experiment onboard a spacecraft operating in a low Earth orbit has been developed with an overview shown in section 5.3. Known weak points in current performance models used for the Tether Design tool that require verification are

- OML validity assumed for short tethers, low induced bias
- Effects solar radiation drag not taken into account for orbit perturbations
- Ionospheric auroral and polar regions not modelled accurately for off nominal conditions
- Static torque balance used for determination of tether angles, needs to be described dynamically

Using these tools a study has been performed to determine a feasible design for an EDT experiment onboard Delfi-1. From the results obtained in this study the following conclusions can be drawn as to the proposed baseline design for the EDT experiment onboard Delfi-1.

A bare floating tape tether configuration is feasible for operation onboard Delfi-1 based on deorbit performance for restricted inclinations of 70°-85° and 95°-110° excluding the (near) polar orbits. The proposed EDT experiment, described in section 6.2, with tether lengths ranging from 500-900 m is capable of producing measurable effects in the deorbit rate of the Delfi-1 satellite for the orbit altitude range and restricted inclination range.

Depending on the preference of the user the final design can be optimised for either low mass and volume (cost) or deorbit performance. The tether dimensions derived in this study are driven by performance in the high inclination and altitude orbits of the Delfi-1 mission being able to operate over the entire altitude range and the restricted inclination range of Delfi-1. The tether dimensions can be optimised for the final operational orbit of the satellite ensuring the system is not over dimensioned for low inclination and orbit altitudes and tether width is optimised for collecting maximum current levels within the Orbit Motion Limited regime. The technical specifications of the experiment allow it to operate on a multi-payload mission of the Delfi-1 satellite reducing the costs of the experiment.

The experiment has been designed for passive operation of both the deployment system and the operation of the tether reducing the complexity and both power and data rates required for the experiment. Inherent to the selected tape design the tether has a high probability of surviving three months of operation in the micrometeoroid and orbital debris environment, high ballistic drag coefficient allowing for rapid deorbit when cut and is efficient at collecting current within survivability and collision risk constraints. To ensure the tether experiment does not increase the risk of collision with any operational satellite the International Space Station the experiment has to be performed at altitudes below the International Space Station (350 km). The current configuration of the Delfi-1 satellite cannot operate below 650 km with this altitude already on the threshold of the satellites capability to meet its absolute pointing requirement of ±5°.

Using a tape tether onboard Delfi-1 limits the amount of tether length due to both storage and mass constraints. This also limits the inclination range suitable for the experiment to below 85° and above 95° not being able to operate over the entire Delfi-1 orbit range. Determining the amount of induced Lorentz drag force and the subsequent performance of the tether has to be performed by combining deorbit data with magnetic field strength, tether bias measurements and possible Langmuir probe data providing data on the local plasma environment. The use of a relatively short tether reduces the $F_L/F_D$ ratio making it more challenging to filter the various drag forces deorbiting the satellite.
The theoretical minimum ratio of Lorentz drag over total drag for feasible configurations is between 17% and 34% for the low altitude and high inclination orbits being considered not meeting the initial $F_L/F_D > 50\%$ requirement set to enable filtering of the drag signal. This would require tether lengths exceeding the storage capability of the Delfi-1 payload platform. Estimating the amount of aerodynamic drag force will be difficult as there are major uncertainties in modelling the atmospheric density and the ballistic drag coefficient of the system. The solar pressure force can be estimated using Delfi-1 solar panel performance and sun sensor angle data from the ADCS. Aerodynamic and solar radiation forces have a cyclic nature, this will aid in distinguishing them from the Lorentz forces; this will require multiple GPS data arcs for each orbit. Combining tether bias variations with magnetic field strength and components and tension measurements will give an indication of tether current levels.

With the minimum of telemetry available (no direct current measurements) the experiment depends heavily on the GPS receiver functioning. Using the ground based Delfi Doppler Tracking System as a back up for deorbit measurements will require the tether to remain operational for the entire period of three months and require a tether length of at least 1250 m and 20 mm wide not feasible for the current payload storage and mass constraints.

A secondary objective of the experiment was to determine if the release of a neutral gas is capable of enhancing the tether current allowing for a short duration increase in tether performance. Due to the limited length of the tether is not capable of inducing sufficient bias to allow the neutral gas cathode to operate over the entire inclination range of the Delfi-1 orbit. A minimum tether length of approximately 850 m combined with an even further limitation of the inclination range of the Delfi-1 orbit range is required to achieve this objective. The cold gas thrusters used for tether deployment are capable of providing the gas required for the experiment, an adaptation of the thrusters design is required to achieve the necessary mass flow rates for the gas release experiment.

### 7.2 Recommendations

**Experiment Design**

Optimisation of the current floating tether experiment configuration using the following variables is recommended focussing on a longer tether design being within OML regime and having a higher $F_L/F_D$ ratio

- $t_c$ [Voltage drop requirement based on $I_{max}$ and $w_{sub}$]
- $D_R$, $L_i$, $m_t$
- $m_t + m_b$

It is not efficient for the current configuration of the experiment to be flown across the entire Delfi-1 orbit range due to variation in air drag and the effect on deorbit of the system. Recommendation is to design a passive system for 750 km-1000 km range where aerodynamic drag affects are minimal and an active cathode system for 650 km-750 km. A configuration with an cathode deploying the tether upwards with electron emission at the satellite end inducing higher both current levels and having a measurable current at the tether suspension point using one of the following cathodes to distinguish $F_L$ from $F_{as}$. Cathode options are

- FEAC
- Hollow Cathode
- Heated Filament

An option is to use FEAC cathode configuration designed for the DTUSat mission by R. Fleron having a lower power usage compared to a hollow cathode and not requiring any additional gas.

For the telemetry the minimum instrument complement if compatible with filtering of the drag signal is advisable to stay within the set mass, power and data rate budgets. A standby redundancy of critical sensors, like the tether bias measurement, is preferable pending on CDHS capabilities as the power and data rate budgets are critical for the experiment.
Further development of longer tape tether configurations capable of producing a DDTS deorbit measurement and having a higher $F_L/F_D$ min ratio is advisable. Either increase mass and storage budgets at a higher experiment cost or revaluate the current voltage drop requirement and determine if a thinner tether can be designed meeting both electrical and handling loads. Thin wire tethers can also be considered as an alternative for the tape tether for achieving a higher $F_L/F_D$ min. Also determine a method of filtering the satellites orbital position data into separate drag components acting on the tether using the cyclic nature of the aerodynamic and solar forces enabling a filtering approach to be conceived for shorter tape tethers having a relatively low Lorentz drag force in comparison with the total drag force.

For low inclination orbits the proposed neutral gas cathode is a feasible experiment, gas release mass flow rate of the cathode needs to be optimised for system stability (current levels) and performance. Flying a wire tether will enable more length to fit onboard Delfi-1 satellite allowing for higher tether end potentials to be achieved enabling the gas cathode to operate at higher orbital inclinations. The stability of the tether and system during gas release and increase on tether current will have to be evaluated in further detail.

Grounding of the experiment is important to reduce the noise in system. REC-03 EMC Grounding Requirements EDT all [TBC 46]

- Instrumentation and TLM components containing ADC are required to be grounded using a noise free ground
- Delfi-1 Chassis ground (SPG)
  - GPS antenna signal line is grounded using multipoint grounding to the chassis ground interface
  - Tether bias
  - LP - Hot probe configuration
  - Roller integrated with tension transducer
  - Tether temperature sensor isolated from electrical environment
  - Magnetometer
- Tether positive termination ground
  - Tether temperature sensor
  - Roller integrated with tension transducer

Experiment Mission

The killer altitude requirement mentioned in the EDT Preliminary Design section of this thesis requires an alternative experiment platform below a flight altitude of 350 km either using a satellite possibly a second generation Delfi type satellite designed to operate below the ISS allowing for the satellite to meet it’s own mission objective for disposal at EOL by using the EDT or a sounding rocket mission. The EDT Environment tool and the Tether Design tool used for sizing the EDT experiment can be expanded to incorporate various orbits and can also be adapted for a wire tether design if required.

Options being considered for flying the tether experiment payload on a LEO satellite are [DES.4122.01]

- As part of a multi payload mission like the Delfi-1 satellite
- Dedicated bus: - 10 kg-100 kg micro satellite
  - CubeSat (nanosatellite) 10x10x10 cm, a few kg’s
  - TubeSat [TN.4122.26]
  - Foton

Another option for a demonstration mission of EDT technology is to use a sounding rocket as a platform. European sounding rockets to be considered are the MAXUS or TEXUS. A dedicated sounding rocket mission is probably required to be able to separate the tether payload in its main and sub-satellite parts. For each mission option there are various similar technologies required, for example the development of the tape tether and a deployment device capable of deploying the tether needs to be done regardless of which mission is finally implemented. This implies that any development and research done for one of the mission options is applicable to the other missions.
7.3 Further Research

Requirements Review
A review is required for a number of requirements, the combination of a tape tether and gas cathode are hard to achieve on the Delfi-1 bus due to required length and limited storage dimensions available. Also, the required filtering ratio needs to be re-evaluated as it conflicts with the storage dimensions of the Delfi-1 payload bay. The current requirement on maximum current levels of the tether being \( I_{\text{OML max}} \) needs to be re-evaluated as it has major implications for the thickness of the tether and is also in conflict with the required performance during gas release. Stability of both the tether and the system needs to be extended to dynamic simulations as the equilibrium of a tether cannot be described statically.

Focus for the deployment phase is determining the tether libration angles along the deployment profile ensuring the tether is deployed to nadir without excessive librations possibly causing the system to tumble. Determine the time frame of instabilities occurring for the tether and analyse the current recommendation of having a ballast mass of four times the tether mass which would limit the feasible configurations to the shorter length tethers. Determination dynamics during a short duration deployment and gas release torque disturbance on the system absolute pointing error and tether dynamics. Also, a mission re-evaluation if the current flight altitude is required concerning collision risks with operational satellites and the space station with a current killer altitude requirement of \( h < 350 \text{ km} \). A review concerning the minimum handling loads and voltage drop requirement is advisable as both have major impact on the mass and storage dimensions of the tether.

Environment and Performance modelling
- More research ionospheric environment for auroral and polar cap region and subsequent charging effects
- Validity-deviation from OML current collection for short EDT tether at low induced biases, research how the current collection deviates from the proposed OML current distribution and the influence of other current sources on induced current levels.
- Discrete modelling current and bias distribution, in orbit simulation [ETBSim]
- Model the effect of solar radiation pressure, aerodynamic and Lorentz drag on the orbit of the tethered system with in orbit simulations showing the cyclic nature of these forces enabling a filtering approach to be determined
- Modelling the geometry of the tether for various amounts of twist and determining the effect of the substrate on the amount of twist
  - effect of twist geometry on tether temperatures
  - effect of twist geometry on current collection area
- Self-induction needs to be verified for complete conducting tape
  - Check magnetic guiding effects would reduce effectiveness of fully conductive tape approach. Alternatives thin conductive film design, see section 2.2 requires further research

Stability and Dynamics modelling
- Deployment Profile and Dynamics \( v_{\text{dep}}(\text{max}) \) and tether librations during and after deployment
- Re-evaluation of deployment torques, impulse, momentum and tip off rates for the \( \pm 5^\circ \) APE error requirement with a margin of 3 using OPSim and by performing tether deployment dynamic analysis
- Re-evaluate the \( \pm 5^\circ \) absolute pointing error requirement including a margin of 3 for short duration disturbances \( T_{\text{dep}} \) and \( T_{\text{gas}} \)
- Further research into attitude dynamics of the system and tether librations using a flexible tether and dynamic stability analysis with in orbit variations of magnetic field, ionospheric plasma, atmospheric density and solar radiation pressure
- Long term tether dynamics simulation \( m_t/m_b \) ratio requirement determination and determination the time frame of instabilities occurring for the EDT for current configurations
- Gas discharge from the cathode effect on stability and dynamical analysis gas release
Measurement techniques
Filtering techniques for determining the Lorentz drag part of the deorbit rate need to be researched possibly allowing for the use of $F_L/F_D$ ratio’s below 50%.

- Filtering techniques research distinguishing between effects of solar and aerodynamic and small Lorentz drag forces with both solar and aerodynamic having a cyclic nature
- Simulation and propagation models, GPS data and determining the required frequency of measurements to enable filtering of the signal into separate drag components, see previous point
- Research the feasibility of measuring the operational tension loads using a tension transducer or accelerometer and determine required measurement frequency
- Feasibility study of in house development of a Langmuir probe design suitable for the low mass, power and data rates inherent to the Delfi-1 mission

Hardware
- Confirm manufacturability of current tether configuration of the tether
- Determine deployability of the current tether design and long term storage effects including cold welding by method of test and analysis
- Effects temperature ($T_{min}$) and twisting on mechanical properties
- Optical properties of the complete tether need to be verified
- Research design of rip-stop protection for the bare aluminium foil; possibly in combination with the adhesive coating
- Properties and application of the protective (film) coating
- Evaluate stacked tether reel design as done for the EDDE experiment
- Bread boarding the entire experiment
- Gas cathode design (redesign CGT)
- Impact tests determining the critical M/OD particle size for foil tethers

Operational Risks
- Tether Area-Life Time Analysis to determine EOL strategy tether cut or no cut for orbits below 800 km altitude
- Area Time Product, risk analysis for collision with trackable orbital debris and operational satellites in the Delfi-1 orbit range
- Examine alternative missions meeting killer requirement $h \leq 350$ km
## 8 LARGE TABLES AND FIGURES

In this section of the report large tables and figures are placed.

### 8.1.1 Large Tables

Table 8.1: EDT experiment measurements listing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Resolution$^{10}$</th>
<th>Frequency$^{11}$</th>
<th>Data Set #</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>2 wks – 3 months</td>
<td>1 s</td>
<td>1 Hz</td>
<td>1,2,3,4</td>
<td>Time stamping of measurements</td>
</tr>
<tr>
<td>Local magnetic field strength</td>
<td>$\pm 3.5e-5$ T</td>
<td>±nT</td>
<td>10 Hz</td>
<td>3,4</td>
<td>Magnetic field vector strength and direction EDT Environment</td>
</tr>
<tr>
<td>Ionospheric density$^{12}$</td>
<td>$3e10 - 2.5e11[5e11]$ m$^{-3}$</td>
<td>±e5 – ±e9 m$^{-3}$</td>
<td>1 Hz</td>
<td>3,4</td>
<td>IRI; ETBSim; EDT Environment</td>
</tr>
<tr>
<td>Electron/ion temperature</td>
<td>2800 – 3200 K 1850 – 2650 K</td>
<td>50 K</td>
<td>1 Hz</td>
<td>3,4</td>
<td>IRI; EDT Environment</td>
</tr>
<tr>
<td>Solar activity &amp; performance</td>
<td>Solar panel performance</td>
<td>[TBD 20]</td>
<td>1 Hz</td>
<td>3,4</td>
<td>EPS Delfi-1</td>
</tr>
<tr>
<td>Orbit altitude</td>
<td>650-1000 km</td>
<td>&lt; 14-18 m 0 - 1 km</td>
<td>6-10 x per orbit</td>
<td>1,3,4</td>
<td>function of EDT performance 2 weeks ops</td>
</tr>
<tr>
<td>Orbital velocity</td>
<td>7350 – 7531 ms$^{-1}$</td>
<td>0.1-1 ms$^{-1}$</td>
<td>6-10 x per orbit</td>
<td>1,3,4</td>
<td>function of EDT performance 2 weeks ops [TBC 11]</td>
</tr>
<tr>
<td>Orbital period</td>
<td>5864 – 6307 s</td>
<td>1 s</td>
<td>For each GS contact</td>
<td>1,3,4</td>
<td></td>
</tr>
<tr>
<td>Accelerations $a_{sc}$</td>
<td>±0.04 ng to ±11 kg</td>
<td>±0.7 ng to ±12 kg</td>
<td>1 ng</td>
<td>1 Hz</td>
<td>1,2,3,4 To determine effect of drag forces</td>
</tr>
<tr>
<td></td>
<td>±0.009 µg to ±11 µg</td>
<td>±0.15 µg to ±85µg</td>
<td>1 µg [TBC 12]</td>
<td>1 Hz</td>
<td></td>
</tr>
<tr>
<td>Attitude Dynamics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating tension</td>
<td>0 – 7.4e-4 N 0 – 4.4e-2 N</td>
<td>5 µN 0.5mN [Cosmo]</td>
<td>1 Hz 8 Hz [Cosmo]</td>
<td>3,4</td>
<td>Dynamics current and force level Resolution source ETBSim</td>
</tr>
<tr>
<td>Accel. $a_{sc}$</td>
<td>±10 mg</td>
<td>±1.5 µg to ±85µg</td>
<td>80µg 10 ng 0.7µg [Cosmo]</td>
<td>1 Hz 8 Hz &gt;&gt; Nyquist frequency of system [Cosmo]</td>
<td>2,3,4 tension tether during and after deployment</td>
</tr>
<tr>
<td>Pitch and roll angles Delfi-1 bus</td>
<td>± 5°</td>
<td>0.1°[TBD 19]</td>
<td>1 Hz</td>
<td>2,3,4</td>
<td>[TBD 19] ADCS Delfi-1</td>
</tr>
<tr>
<td>Tether Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tether bias at suspension</td>
<td>±0.085 – ± 5.4 V</td>
<td>10 µV – 10 mV</td>
<td>1 Hz 8 Hz [Cosmo]</td>
<td>2,3,4</td>
<td>Floating tether potential anode end Tether Design tool</td>
</tr>
<tr>
<td>Deployed tether length L(t)</td>
<td>0 – 2500 m</td>
<td>0.1 – 1 m</td>
<td>1 Hz</td>
<td>2</td>
<td>[TBC 13]</td>
</tr>
<tr>
<td>Deployment velocity $v_{dep}$</td>
<td>0 – 5 ms$^{-1}$</td>
<td>0.1 ms$^{-1}$</td>
<td>1 Hz</td>
<td>2</td>
<td>[Heijning] Deployment Profile Determination v1.0</td>
</tr>
<tr>
<td>Tether Temperature $T_t$</td>
<td>-150°C +150°C</td>
<td>1-10 °C</td>
<td>0.1 Hz</td>
<td>3,4</td>
<td>[TBC 15]</td>
</tr>
</tbody>
</table>

$^{10}$ Resolution is smallest detectable change in stimulus causing a change in output, accuracy is the ratio of maximum error of output signal to full-scale output signal [%] [Jongkind]

$^{11}$ All frequencies mentioned are still to be confirmed

$^{12}$ ETBSim n0 650 km-70° eclipse data

$^{13}$ Values for $L_t$ - 1000 m and $t_t$ - 17.5 µm thick tether deployed of a 20 mm inner diameter reel
Table 8.2: Document requirements REQ-# to PUID requirements

<table>
<thead>
<tr>
<th>REQ #</th>
<th>PUID</th>
<th>REQ #</th>
<th>PUID</th>
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<tr>
<td>REQ-1</td>
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<td>REQ.4122.TLM.24</td>
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<td>REQ-2</td>
<td>REQ.4122.TET.17</td>
<td>REQ-37</td>
<td>REQ.4122.TLM.25</td>
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<td>REQ-3</td>
<td>REQ.4122.TET.18</td>
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<td>REQ.4122.TLM.26</td>
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<tr>
<td>REQ-4</td>
<td>REQ.4122.EDT.16</td>
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<tr>
<td>REQ-6</td>
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<tr>
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<td>REQ.4122.TET.61</td>
<td>REQ-42</td>
<td>REQ.4122.TLM.29</td>
</tr>
<tr>
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<td>REQ.4122.TLM.03</td>
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<tr>
<td>REQ-9</td>
<td>REQ.4122.EDT.15</td>
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<td>REQ.4122.EDT.18</td>
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<tr>
<td>REQ-10</td>
<td>REQ.4122.DE.P.11</td>
<td>REQ-45</td>
<td>REQ.4122.EPS.06</td>
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<td>REQ-11</td>
<td>REQ.4122.GAS.03</td>
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<td>REQ.4122.TET.21</td>
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<td>REQ.4122.TET.33</td>
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<td>REQ.4122.TET.31</td>
<td>REQ-52</td>
<td>REQ.4122.TET.22</td>
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<td>REQ.4122.EM.04</td>
<td>REQ-53</td>
<td>REQ.4122.TET.24</td>
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<tr>
<td>REQ-19</td>
<td>REQ.4122.DE.P.09a</td>
<td>REQ-54</td>
<td>REQ.4122.TET.23</td>
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<tr>
<td>REQ-20</td>
<td>REQ.4122.SC.01</td>
<td>REQ-55</td>
<td>REQ.4122.TET.28</td>
</tr>
<tr>
<td>REQ-21</td>
<td>REQ.4122.SC.02</td>
<td>REQ-56</td>
<td>REQ.4122.STS.04</td>
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<td>REQ-57</td>
<td>REQ.4122.DE.P.08</td>
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<td>REQ.4122.TET.09</td>
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<td>REQ-60</td>
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<td>REQ.4122.TET.01-05</td>
<td>REQ-61</td>
<td>REQ.4122.EDT.01-05</td>
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<td>REQ-27</td>
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<td>REQ-62</td>
<td>REQ.4122.GAS.05b</td>
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<td>REQ.4122.TET.19</td>
<td>REQ-63</td>
<td>REQ.4122.TET.09</td>
</tr>
<tr>
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<td>REQ-64</td>
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<td>REQ-30</td>
<td>REQ.4122.TET.09</td>
<td>REQ-65</td>
<td>REQ.4122.TET.09</td>
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<td>REQ-31</td>
<td>REQ.4122.TET.19</td>
<td>REQ-66</td>
<td>REQ.4122.GAS.06</td>
</tr>
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<td>REQ-32</td>
<td>REQ.4122.TET.20</td>
<td>REQ-67</td>
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</tr>
<tr>
<td>REQ-33</td>
<td>REQ.4122.TET.21</td>
<td>REQ-68</td>
<td>REQ.4122.DE.P.16</td>
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<td>REQ-34</td>
<td>REQ.4122.TET.19</td>
<td>REQ-69</td>
<td>REQ.4122.TET.19</td>
</tr>
<tr>
<td>REQ-35</td>
<td>REQ.4122.TET.23</td>
<td>REQ-70</td>
<td>REQ.4122.TET.05</td>
</tr>
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<table>
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<tr>
<th>REC #</th>
<th>PUID</th>
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<tbody>
<tr>
<td>REC-1</td>
<td>REQ.4122.EDT.60</td>
</tr>
<tr>
<td>REC-2</td>
<td>REQ.4122.GAS.07</td>
</tr>
<tr>
<td>REC-3</td>
<td>REQ.Delfi1.4122.TLM.28</td>
</tr>
</tbody>
</table>
### Table 8.3: EDT experiment performance requirements & constraints

<table>
<thead>
<tr>
<th>Title</th>
<th>REQ-#</th>
<th>PUID</th>
<th>Value</th>
<th>Margin</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DEORBIT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collect OML current</td>
<td>REQ-3</td>
<td>REQ.4122.TET.18a</td>
<td>(w_c \leq 20-40 \text{ mm})</td>
<td></td>
<td>OML</td>
</tr>
<tr>
<td>Deorbit rate</td>
<td>REQ-20</td>
<td>REQ.4122.SC.01</td>
<td>(\Delta \text{SMA} \geq 80 - 200 \text{ [m]}) 2 weeks</td>
<td>2</td>
<td>GPS</td>
</tr>
<tr>
<td>(F_d) total</td>
<td>REQ-64</td>
<td>REQ.4122.TET.01</td>
<td>(F_d \text{ min} \geq 1.6\times10^6 \text{ N}) 2 weeks</td>
<td>2</td>
<td>GPS</td>
</tr>
<tr>
<td>Deorbit GAS Release</td>
<td>REQ-25</td>
<td>REQ.4122.GAS.09</td>
<td>(I_{\text{gas}}) shall decrease the SMA by a 20 m during gas release</td>
<td></td>
<td>GPS</td>
</tr>
<tr>
<td>Ionisation potential</td>
<td>REQ-62</td>
<td>REQ.4122.GAS.05b</td>
<td>(V_{\text{ion}} \geq -25 \text{ V}) 1.5</td>
<td></td>
<td>Ionisation (N_{\text{e}})</td>
</tr>
<tr>
<td><strong>FILTERING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_i/F_d)</td>
<td>REQ-24</td>
<td>REQ.4122.TET.29</td>
<td>(\geq 50%)</td>
<td></td>
<td>Filtering (F_i) from (F_d)</td>
</tr>
<tr>
<td><strong>STABILITY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Stability</td>
<td>REQ-4</td>
<td>REQ.4122.EDT.16</td>
<td>(\text{APE} \pm 5^\circ) 1</td>
<td></td>
<td>De lI-1</td>
</tr>
<tr>
<td>Passive GG stab Mol</td>
<td>REQ-7</td>
<td>REQ.4122.EDT.61</td>
<td>(I_x&gt;l_z; I_y&gt;I_z; I_y&lt;I_x+l_z)</td>
<td></td>
<td>passive ACS</td>
</tr>
<tr>
<td>20% separation freq</td>
<td>REQ-8</td>
<td>REQ.4122.EDT.62</td>
<td>20%</td>
<td></td>
<td>Resonance</td>
</tr>
<tr>
<td>Stability ratio TET-EM</td>
<td>REQ-43</td>
<td>REQ.4122.EDT.59</td>
<td>(T_{\text{GG20}}/T_{\text{DIST.max}} \geq 3)</td>
<td>3</td>
<td>linear model</td>
</tr>
<tr>
<td>Stable Equilibrium</td>
<td>REQ-16-17-18</td>
<td>REQ.4122.EDT.03-TET.30-31-EM.04</td>
<td>(I_{\text{l}}(\text{max}) &lt; I_{\text{lux}})</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Long term Stability</td>
<td>REC-1</td>
<td>REQ.4122.EDT.60</td>
<td>(m/m_b - 0.25)</td>
<td></td>
<td>-</td>
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<tr>
<td><strong>ELECTRICAL LOADS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective (L_t)</td>
<td>REQ-2</td>
<td>REQ.4122.TET.17a</td>
<td>(L/90*100) 10%</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Current Load TET (I_{\text{max}})</td>
<td>REQ-54</td>
<td>REQ.4122.TET.23</td>
<td>(4I_{\text{opt, max}}) 4</td>
<td></td>
<td>Peak and Gas</td>
</tr>
<tr>
<td>Voltage Drop TET</td>
<td>REQ-53</td>
<td>REQ.4122.TET.24</td>
<td>(\leq0.1x\text{EMF ignore Ohmic}) 4</td>
<td></td>
<td>Bias Distribution</td>
</tr>
<tr>
<td><strong>MECHANICAL LOADS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_{\text{des}})</td>
<td>REQ-55a-55b</td>
<td>REQ.4122.TET.28a-28b</td>
<td>18 (\text{ max})</td>
<td></td>
<td>[Kruijff]</td>
</tr>
<tr>
<td>(T_{\text{MAX}}) Handling</td>
<td>REQ-13</td>
<td>REQ.4122.TET.27</td>
<td>25 N</td>
<td></td>
<td>Estimate</td>
</tr>
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<td><strong>THERMAL</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TET temperature range</td>
<td>REQ-50</td>
<td>REQ.4122.TET.10</td>
<td>(-100^\circ \text{C} +100^\circ \text{C})</td>
<td></td>
<td>material</td>
</tr>
<tr>
<td><strong>CONSTRAINTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage</td>
<td>REQ-60</td>
<td>REQ.4122.DEP.14</td>
<td>(D_b &lt; 200 \text{ mm})</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Mass TET</td>
<td>REQ-70</td>
<td>REQ.4122.TET.05</td>
<td>1.3 kg</td>
<td>23%</td>
<td>17.5 SPL</td>
</tr>
<tr>
<td>Mass GAS+EM</td>
<td>REQ.4122.GAS.02-EM.03</td>
<td></td>
<td>(0.83-1.83 \text{ kg}) 23%</td>
<td></td>
<td></td>
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<tr>
<td><strong>MOD</strong></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>MOD survival TET</td>
<td>REQ-59</td>
<td>REQ.4122.TET.08</td>
<td>(P_{\text{survive}} 3 \text{ months} &gt; 95%)</td>
<td></td>
<td>NASA</td>
</tr>
<tr>
<td>MOD collision avoidance</td>
<td>REQ.4122.UR.01</td>
<td></td>
<td>(h &lt; 350 \text{ km})</td>
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<td>MOD</td>
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### Table 8.4: Overview of TET-EM design parameter requirements

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Value</th>
<th>Margin</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length $L_t$</td>
<td>REQ.4122.TET.17a</td>
<td>$L_t$ effective loss of max 10% due to 50Ω loss</td>
<td>-</td>
<td>Unknown $R_{int}$ 50Ω</td>
</tr>
<tr>
<td></td>
<td>REQ-2</td>
<td>$L_t$ 250 - 2500 m</td>
<td>3</td>
<td>$3\theta_{SSE} &lt; 20°$</td>
</tr>
<tr>
<td></td>
<td>REQ.4122.TET.17b</td>
<td>$L_t$ 250 - 2500 m</td>
<td>0.83 kg OML</td>
<td></td>
</tr>
<tr>
<td></td>
<td>REQ.4122.TET.17c</td>
<td>$L_t$ 250 - 2500 m</td>
<td>1</td>
<td>APE $m_b$ 0.83 kg OML</td>
</tr>
<tr>
<td></td>
<td>REQ.4122.TET.17d</td>
<td>$L_t \geq 500$ m $w_c \geq 15$ mm</td>
<td>3</td>
<td>$3\theta_{SSE} &lt; 20°$</td>
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<tr>
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<td>REQ.4122.TET.17e</td>
<td>$L_t \geq 750$ m $w_c \geq 10$ mm</td>
<td>-</td>
<td>$m_b$ 0.83 kg OML</td>
</tr>
<tr>
<td></td>
<td>REQ.4122.TET.17f</td>
<td>$L_t \geq 1000$ m $w_c \geq 5$ mm</td>
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Table 8.5: Feasible configurations

| Performance Parameter | \( m_t \) [kg] | \( m_b \) [kg] | \( L_t \) [m] | \( D_{ri} \) [mm] | \( m_t + m_b \) [kg] | \( m_t / m_b \) [-] | \( F_{i/F_c} \) min [-] | \( F_{i/F_c} \) max [-] | min \( \Delta S \)MA (2 weeks) [m] | DDTS [m] | EMF min [V] | \( V_A \) [V] | \( V_C \) [V] | \( B_{ald} \) [m^2*kg^-1] |
|------------------------|----------------|----------------|--------------|----------------|------------------|----------------|----------------|----------------|------------------|-------------|------------|-------------|-------------|-------------|----------------|
| Required               | 1.3            | 0.83           | -            | 200            | 2.1-2.4          | 0.25           | 50%            | 90%            | 80               | 4000        | -          | 0.25        | -25         | TBD          | 52           |
| \( L_{eff} = 500 \) [m] | 20             | 16             | 0.50         | 1.5            | 505              | 134            | 2.0            | 0.34           | 17%              | 72%          | 107        | 644         | 4.2-31      | 0.17-1.0    | 4.0-30        | 26           |
| \( L_{eff} = 650 \) [m] | 15             | 22             | 0.65         | 1.2            | 655              | 167            | 1.85           | 0.54           | 23%              | 80%          | 131        | 778         | 5.4-40.2    | 0.22-1.3    | 5.2-38.9      | 20           |
| \( L_{eff} = 750 \) [m] | 20             | 16             | 0.66         | 1.5            | 657              | 151            | 2.16           | 0.44           | 24%              | 80%          | 173        | 1033        | 6.2-46.4    | 0.26-1.5    | 6.0-45        | 26           |
| \( L_{eff} = 850 \) [m] | 15             | 22             | 0.75         | 1.1            | 757              | 179            | 1.85           | 0.68           | 27%              | 83%          | 172        | 1030        | 7.1-52.6    | 0.29-1.7    | 6.8-50.9      | 20           |
| \( L_{eff} = 900 \) [m] | 20             | 16             | 0.86         | 1.5            | 861              | 172            | 2.36           | 0.57           | 32%              | 86%          | 292        | 1752        | 7.5-55.7    | 0.31-1.8    | 7.2-53.9      | 26           |
| \( L_{eff} = 950 \) [m] | 15             | 22             | 0.90         | 1.3            | 909              | 195            | 2.20           | 0.69           | 34%              | 87%          | 248        | 1487        | 7.8-55.9    | 0.32-1.8    | 7.4-53.9      | 20           |
| \( L_{eff} = 1000 \) [m] | 20             | 17             | 0.96         | 1.5            | 912              | 180            | 2.41           | 0.64           | 34%              | 87%          | 328        | 1970        | 7.9-56.1    | 0.33-1.8    | 7.5-53.9      | 25           |
### Table 8.6: Requirements not met by feasible design configuration

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### Table 8.7: Operational modes EDT experiment

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<th>Description</th>
<th>Experiment Data Sets</th>
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<td>EDT will remain in Off Mode during 9 months with intervals of Safety Mode for CHECKOUT. During Off Mode the EDT experiment will receive no power or data input</td>
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<td>When switched on go to Safety Mode</td>
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<td>2</td>
<td>Perform systems checkout</td>
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<td>Go to Off Mode</td>
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<td>3b</td>
<td>Activate Safety Mode</td>
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<td>Safety Mode</td>
<td>During Safety Mode the EDT will perform a systems check and experiment data set 1 will be acquired by operating the GPS. Diagnostics of each system can be performed in this mode.</td>
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<td>1</td>
<td>CHECKOUT</td>
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<td>2a</td>
<td>Experiment data set 1 will be acquired if checkout OK</td>
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</tr>
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<td></td>
<td>Experiment data set 1 will be processed to</td>
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</tr>
<tr>
<td></td>
<td>• GPS orbit determination</td>
<td></td>
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<td></td>
<td>• Satellite attitude determination (ADCS)</td>
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model air drag, solar radiation parameters
and define baseline of Delfi-1 dynamics in
orbit
2b Perform systems check if checkout NOT
OK
3 CHECKOUT
4a Activate Standby Mode if checkout OK
4b Remain in Safety Mode perform systems
check if checkout NOT OK

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<tr>
<th>Standby Mode</th>
<th>During Standby Mode the EDT will listen for HDRM release commands and perform health checks</th>
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<tr>
<td>1 CHECKOUT</td>
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<tr>
<td>2a</td>
<td>List for HDRM commands if checkout OK</td>
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<tr>
<td>2b</td>
<td>Go to Safety Mode and perform systems check if checkout NOT OK</td>
</tr>
<tr>
<td>3 CHECKOUT</td>
<td></td>
</tr>
<tr>
<td>4a</td>
<td>Activate HDRM if check out OK</td>
</tr>
<tr>
<td>5a</td>
<td>Activate Deployment Mode if checkout OK</td>
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<td>5b</td>
<td>Go to Safety Mode perform systems check if checkout NOT OK</td>
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<th>Deployment Mode</th>
<th>During the Deployment Mode the EDT will be deployed from the satellite to desired end conditions</th>
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<tr>
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<td>2a</td>
<td>Eject tether from satellite at required velocity and deploy tether to desired end conditions if checkout OK by activating TES</td>
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<td>2b</td>
<td>Experiment data set 2 will be acquired</td>
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<td>Experiment data set 2 will be processed to determine performance deployment mechanism</td>
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<td>Release system preventing premature gas release if checkout OK</td>
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<tr>
<td>2b</td>
<td>Go to Safety Mode perform systems check if checkout NOT OK</td>
</tr>
<tr>
<td>3 CHECKOUT</td>
<td></td>
</tr>
<tr>
<td>4 Release gas if checkout OK</td>
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<tr>
<td>5a Experiment data set 4 will be acquired consisting of the following measurements if checkout OK</td>
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<td>Receive Termination signal</td>
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<td>3</td>
<td>Go to Off Mode</td>
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<td>Description</td>
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<td>contingency factor dep. time</td>
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<td>absolute rate error deg/s Delfi-1</td>
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<td>% generated PL data to PI’s Delfi-1 CDHS</td>
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<td>maximum area time product or allowable sweep volume of the tether + SC and tether when cut</td>
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<td>expel remaining $N_2$ CGT after deployment time tagged</td>
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<td>mobility of ions is negligible compared to the process for floating tether OML current collection for Delfi-1 orbit</td>
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<td>Ion ram current effects on tether current Unsure if this is the case for un-insulated tether as ram current just alters bias distribution as it takes place over the entire tether</td>
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<td>TBW 2</td>
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8.1.2 Large Figures

Figure 8.1: Extremes for drag forces occurring in orbit 1000 m 30 mm tether
Figure 8.2: Reel outer diameter for various tethers; inner reel diameter $D_a = 40$ mm above and 100 mm below
REFERENCES

[Aase] Aase, J., Development of a Prototype Langmuir Probe for the ICI-1 Sounding Rocket, University of Oslo, Department of Physics, October, 2005.


[Unwin] Unwin, M., Oldfield, M., The Design and Operation of a COTS Space GPS Receiver, AAS 00-046.


[Zedd] Zedd M., Experiments in Tether Dynamics Planned for ATEx's Flight, Naval Research Laboratory, Washington DC.

**Links**


[SSTL] http://www.SSTL.co.uk


**User Manuals and Product Datasheets**

**GPS Receivers**

[SSTL-27433] Data Sheet SGR05-U and P GPS Receiver http://www.SSTL.co.uk


Dataseeth AN9 Series magnetic position sensor, [www.cherrycorp.com](http://www.cherrycorp.com)
Small Optical Encoders, HEDS 9700 Series, Agilent technologies, [www.agilent.com](http://www.agilent.com)
TWK-Elektronik GmbH, [www.twk.de](http://www.twk.de)
Honeywell Thermal Sensors Product Range Guide
Honeywell HEL-700 Series, [www.honeywell.com/sensing](http://www.honeywell.com/sensing)
Honeywell Thermal Sensors Product Range Guide
HTS-570-series, [www.honeywell.com/sensing](http://www.honeywell.com/sensing)
ZARM FGM Analogue magnetometer, ZARM Technik AG, [www.zarm-technik.de](http://www.zarm-technik.de), accessed 2011
Billingsly TFM100G2 [Steindl]

### Internal Documents

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<td>[Wijnans⁵]</td>
<td>DELFI.1.TN.4122.15</td>
<td>Instrumentation for an Electrodynamic Tether Experiment onboard Delfi-1, Spacecraft Mechatronics, AE4-S02 essay, June 2007.</td>
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<td>[Wijnans⁵]</td>
<td>DELFI.1.TN.4122.15b</td>
<td>Instruments Past Experiments, technical note AE4-S02 essay, June 2007.</td>
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<td>Deployment Profile Determination v1.0</td>
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<td>[Rothkrantz]</td>
<td>personal communication May 2004</td>
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<td>[Vink]</td>
<td>Vink, R. Design Drawings Delfi-1 Satellite</td>
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**Tools**

EDT Technical Budgets  DELFI.1.TN.4122.08 EDT Technical Budgets (2.1) Excel sheet based tool the mass, power and data rate and dimensions budgets are managed

EDT Environment Tool DELFI.1.TN.4122.12 Excel based tool orbit environment Delfi-1

Tether Design Tool DELFI.1.TN.4122.19 Excel based design tool

Tether Risk Analysis(2.0) DELFI.1.TN.4122.10 Excel based tool for M/OD risk calculations

EDT Current and Bias Profiles DELFI.1.TN.4122.27 Matlab based tool


TN is Technical Note, DES is Design document, SPC is specification document.
This appendix provides an overview of reference frames used to describe the position and orientation of a spacecraft in space relative to a known reference point. It also provides for the necessary transformations between the various reference frames in use partly shown below. These have been implemented in the EDT Environment tool to determine direction, strength and angles with the tether of the magnetic field in orbit.

Earth Centred Inertial Reference Frame (ECI)
A pseudo-inertial reference frame, $Z_{ECI}$ aligned with rotation axis Earth, $X_{ECI}$ is in the Earths equatorial plane pointing to the first point of Aries $\gamma$ [Vernal Equinox], $Y_{ECI}$-axis completes the reference frame to a right handed orthogonal axis system $[X,Y,Z]_{ECI}$.

Earth Centred Earth Fixed Reference Frame (ECEF)
Earth fixed reference frame, $Z_{ECEF}$ coincides with the rotation axis of Earth, $X_{ECEF}$ coincides with the Greenwich meridian and $Y_{ECEF}$ completes the orthogonal right-handed reference frame.

Spacecraft Body (Fixed) Reference Frame (B)
The spacecraft attitude is measured in this reference frame. Its origin is always situated at the instantaneous centre of mass; both for boom extended and retracted modes. The rotations from the orbit reference frame (OR) are:
- x Roll $\phi$
- y Pitch $\theta$
- z Yaw $\psi$

Magnetic Field Reference Frame (MAG)
The $Z_{MAG}$ is aligned with the dipole axis of the magnetic field. The dipole M is oriented to the magnetic north pole in $-Z_{MAG}$ direction, $X_{MAG}$ is assumed to coincide with the $X_{ECEF}$-axis for initial performance calculations. $Y_{MAG}$ completes the orthogonal right-handed reference frame.
Figure A1-1: MAG reference Frame

**Tether Reference Frame (T)**

Tether body reference frame \([x_t, y_t, z_t]\) is attached to the satellite at point O, the z-axis is orientated along the tether length and is the orbital horizontal reference frame transformed under a pitch (tether IP angle with respect to \(Z_{OR}\)) and roll transformation (tether OOP angle with respect to \(Z_{OR}\)) and a translation from c.m. of system to tether suspension point O.

### A-1.2 Transformations

**Keplerian orbital elements** \([a, e, i, \Omega, \omega, \tau]\) used for integration of the SC orbit

- **a** – semi major axis of orbit
- **e** – eccentricity of orbit
- **i** – inclination of orbit
- **\(\Omega\)** – right ascension of ascending node RAAN
- **\(\omega\)** – argument of perigee
- **\(\tau\)** – time of perigee passage

**Cartesian coordinates** \([x, y, z, \xi, \eta, \zeta]\)

**Spherical coordinates** \([r, \theta, \phi]\)

- **r** – radius
- **\(\theta\)** – declination or latitude
- **\(\phi\)** – right-ascension or longitude

\(\theta_c\) – co-latitude = 90º-\(\theta\)

Spherical coordinates transformed to Cartesian coordinates

\[
x = r \cos \theta \cos \phi \\
y = r \sin \theta \cos \phi \\
z = r \sin \theta
\]

**Conversion from Keplerian to Cartesian Coordinates ECI Frame**

Transformation from Kepler orbital elements to the Cartesian ECI reference frame is performed according to [Wakker] by method of rotation matrices. The transformations used in the EDT Environment tool consist of

\[
x = l_x \xi + l_y \eta \\
y = m_x \xi + m_y \eta \\
z = n_x \xi + n_y \eta
\]
\[
\begin{align*}
\dot{x} &= l_1 \dot{\xi} + l_2 \dot{\eta} \\
\dot{y} &= m_1 \dot{\xi} + m_2 \dot{\eta} \\
\dot{z} &= n_1 \dot{\xi} + n_2 \dot{\eta}
\end{align*}
\]  
(A1-2)

\[l_1 = \cos \omega \cos \Omega - \sin \omega \sin \Omega \cos i\]
\[m_1 = \cos \omega \sin \Omega + \sin \omega \cos \Omega \cos i\]
\[n_1 = \sin \omega \sin i\]

\[l_2 = -\sin \omega \cos \Omega - \cos \omega \sin \Omega \cos i\]
\[m_2 = -\sin \omega \cos \Omega + \cos \omega \cos \Omega \cos i\]
\[n_2 = \cos \omega \sin i\]

\([\xi, \eta, \zeta]\) is a geocentric non rotating reference frame located at origin of \([X,Y,Z]_{\text{ECI}}\) with the \(\xi\)-axis oriented towards the peri-centre of the satellite’s orbit, \(\eta\)-axis along the velocity vector at the peri-centre and the \(\zeta\)-axis completes the frame. The axis can be expressed in Keplerian elements as

\[
\begin{align*}
\dot{\xi} &= r \cos \theta \\
\eta &= r \sin \theta \\
\dot{\xi} &= r \cos \theta - r \dot{\theta} \sin \theta \\
\dot{\eta} &= r \sin \theta + r \dot{\theta} \cos \theta
\end{align*}
\]  
(A1-4)

\[r = \frac{a(1 - e^2)}{1 + e \cos \theta}\]
\[\dot{r} = \frac{\mu \sin \theta}{H}\]

\[r \dot{\theta} = \frac{\mu}{H}(1 + e \cos \theta)\]
\[H = r^2 \dot{\theta} = \sqrt{\mu a(1 - e^2)}\]

**ECI to ECEF Frame**

Earth rotates in the \(X,Y\) plane about the \(Z\) axis. To determine \(X\) and \(Y\) coordinates in the ECEF frame uses is made of \(\theta_0(t)\) the local sidereal time giving the angle between the vernal equinox vector \(X_{\text{ECI}}\) and the Greenwich meridian vector. Sidereal time being defined as time measured relative to the stars, mean solar time relative to the Sun. For the EDT performance and modelling tools the position of the vernal equinox is irrelevant and sidereal and mean solar time are assumed to coincide.

**Earth Rotation Angle**

\[\epsilon = \omega_x(t - t_e)\]  
(A1-6)

\[\epsilon\]– Earth rotation angle [°]

\[E = \begin{bmatrix}
\cos \epsilon & \sin \epsilon & 0 \\
-\sin \epsilon & \cos \epsilon & 0 \\
0 & 0 & 1
\end{bmatrix} \text{ and } E^T = \begin{bmatrix}
\cos \epsilon & -\sin \epsilon & 0 \\
\sin \epsilon & \cos \epsilon & 0 \\
0 & 0 & 1
\end{bmatrix}\]  
(A1-7)

\[\begin{bmatrix}
X \\
Y \\
Z_{\text{ECEF}}
\end{bmatrix} = E \begin{bmatrix}
X \\
Y \\
Z_{\text{ECI}}
\end{bmatrix} \text{ and } \begin{bmatrix}
X \\
Y \\
Z_{\text{ECEF}}
\end{bmatrix} = E^T \begin{bmatrix}
X \\
Y \\
Z_{\text{ECEF}}
\end{bmatrix}\]  
(A1-8)

**ECI and ECEF to MAG Frame**

Magnetic Field Reference frame is the ECEF reference frame tilted with respect to the rotation axis of the Earth by an angle \(t_m = -10.5^\circ\). The angle \(t_m\) is the tilt of the magnetic dipole axis with respect to Earth rotation axis, taking into account N-S orientation of magnetic field dipole is reversed with respect to N-S orientation of ECEF frame, see figure a1-2.
The transformation matrix from ECEF to MAG is given by $T$, and the reverse transformation by its transpose $T^T$:

$$
T = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos t_n & \sin t_n \\
0 & -\sin t_n & \cos t_n
\end{bmatrix}
$$

and

$$
T^T = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos t_n & -\sin t_n \\
0 & \sin t_n & \cos t_n
\end{bmatrix}
$$

\[ (A1-9) \]

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_MAG = T
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_ECEF \quad \text{and} \quad
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_ECEF = T^T
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_MAG
$$

Transformation from ECI to MAG reference frame:

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_MAG =
\begin{bmatrix}
\cos \varepsilon & \sin \varepsilon & 0 \\
-\cos t_n \sin \varepsilon & \cos t_n \cos \varepsilon & \sin t_n \\
\sin t_n \sin \varepsilon & -\sin t_n \cos \varepsilon & \cos t_n
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_ECI
$$

\[ (A1-10) \]

Reverse transformation:

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_ECI =
\begin{bmatrix}
\cos \varepsilon & -\cos t_n \sin \varepsilon & \sin t_n \sin \varepsilon \\
\sin \varepsilon & \cos t_n \cos \varepsilon & -\sin t_n \cos \varepsilon \\
0 & \sin t_n \cos \varepsilon & \cos t_n
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}_MAG
$$

\[ (A1-11) \]

The MAG reference frame rotates about Earth’s spin axis $Z_{ECI}$, the local magnetic field rotational velocity in the ECI frame is:

$$
\overline{v}_{mef}_{ECI} = \overline{\omega}_{C} \times \overline{r}_{m} = \omega_{m} - Y
$$

\[ (A1-12) \]

\begin{align*}
X &= r \cos \omega_{t} \\
Y &= r \sin \omega_{t} \\
\dot{X} &= \dot{r} \cos \omega_{t} - r \omega_{z} \sin \omega_{t} = -\omega_{y} Y \\
\dot{Y} &= \dot{r} \sin \omega_{t} + r \omega_{z} \cos \omega_{t} = \omega_{x} X
\end{align*}

Transformations between T and OR frame

The angles $\theta$ and $\phi$ give the position of the tether in the orbital plane and out of the orbital plane. Transformation from OR frame to tether reference frame $T$ is a translation from the c.m. of the system to the suspension point of the tether at point O and subsequent rotation using Euler angles with rotation sequence pitch – roll $\theta \rightarrow \phi$ or 2-1 [Sidi]

$$
\begin{bmatrix}
X_{OR} \\
Y_{OR} \\
Z_{OR}
\end{bmatrix}_{OR} = [A_{B}]_{OR} \begin{bmatrix}
X_{O} \\
Y_{O} \\
Z_{O}
\end{bmatrix}_{O} =
\begin{bmatrix}
\cos \theta & 0 & -\sin \theta \\
\sin \theta \sin \phi & \cos \theta & \cos \theta \sin \phi \\
\sin \theta \cos \phi & -\sin \phi & \cos \theta \cos \phi
\end{bmatrix}
\begin{bmatrix}
X_{OR} \\
Y_{OR} \\
Z_{OR}
\end{bmatrix} +
\begin{bmatrix}
x_{0} \\
y_{0} \\
z_{0}
\end{bmatrix}_{OR}
$$

\[ (A1-13) \]

And reverse transformation back to the orbital reference frame:

$$
\begin{bmatrix}
X_{OR} \\
Y_{OR} \\
Z_{OR}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta \sin \phi & \sin \theta \cos \phi \\
0 & \cos \phi & -\sin \phi \\
-\sin \theta & \cos \theta \sin \phi & \cos \theta \cos \phi
\end{bmatrix}
\begin{bmatrix}
x_{t} \\
y_{t} \\
z_{t}
\end{bmatrix}_{T} =
\begin{bmatrix}
x_{0} \\
y_{0} \\
z_{0}
\end{bmatrix}_{OR}
$$

\[ (A1-14) \]
OR frame to body fixed-reference frame B

Similar to the transformation using Euler angles from OR to T reference frame a yaw pitch roll rotation sequence \( \psi \rightarrow \theta \rightarrow \phi \) 3-2-1 expresses the body fixed reference frame [Sidi]

\[
\begin{bmatrix}
X_{OR} \\
Y_{OR} \\
Z_{OR}
\end{bmatrix} = 
\begin{bmatrix}
\cos \theta \cos \psi & \cos \theta \sin \psi & -\sin \theta \\
-\cos \phi \sin \psi + \sin \theta \sin \phi \cos \psi & \cos \phi \cos \psi + \sin \phi \sin \theta \sin \psi & \cos \phi \sin \theta \\
\sin \phi \sin \psi + \sin \theta \cos \phi \cos \psi & -\sin \phi \cos \psi + \cos \phi \sin \theta \sin \psi & \cos \phi \sin \theta
\end{bmatrix}
\begin{bmatrix}
X_{OR} \\
Y_{OR} \\
Z_{OR}
\end{bmatrix}
\]

(A1-15)

This rotation sequence has a singularity for pitch angles of 90°, if this occurs either a different rotation sequence needs to be adopted or transformations should be performed using the method of quaternions.

OR ECI reference frame transformation

Unit vector components along X,Y,Z axes of the OR frame expressed in ECI, \( x_{OR} \) directed along the velocity vector, \( Y_{OR} \) opposing orbit normal, \( z_{OR} \) opposing orbit vector \( r \).

\[
i = j \times k = \frac{\mathbf{v}}{|\mathbf{v}|}
\]

\[
j = \frac{\mathbf{v} \times r}{|\mathbf{v} \times r|}
\]

\[
k = \frac{r}{|r|}
\]

By method of Euler angle transformations [Kalis; Sidi; Wakker; Chu] simplified for \( \Omega \) and \( \omega = 0 \)

\[
\begin{bmatrix}
x \\
y \\
z_{OR}
\end{bmatrix} =
\begin{bmatrix}
-\sin \theta & \cos \theta \cos i & \sin i \cos \theta \\
0 & \sin i & -\cos i \\
-\cos \theta & -\sin \theta \cos i & -\sin i \sin \theta
\end{bmatrix}
\begin{bmatrix}
\hat{X} \\
\hat{Y} \\
\hat{Z}_{SCI}
\end{bmatrix}
\]

(A1-17)

References


APPENDIX 2 ORBIT SIMULATION

Use is made of Cartesian and Keplerian orbit elements to describe the location in orbit of SC and tether. In this appendix Keplerian orbit elements are used for orbit propagation. With the Keplerian orbit elements known they can be transformed to Cartesian elements according to [Wakker].

A2.1 Unperturbed Kepler Equation \([a, e, i, \Omega, \omega, \tau]\)

Prediction of the unperturbed orbit of the satellite tether system in the EDT Environment tool [TN.4122.12] used for determination of in orbit magnetic field strength and induced bias is performed using Keplerian elements for integration of orbit and transformed into the relevant reference frames. The systems instantaneous centre of mass is the centre of the orbital reference frame. The Kepler equation gives the relationship between the position of a satellite in a Kepler orbit and time [Wakker]

\[
E(t) - e \sin E(t) = n(t - \tau) \quad (A2-1)
\]

\[E \quad \text{– eccentric anomaly [°]}\]

With the mean anomaly given as: \(M = n(t - \tau)\)  

\[E - e \sin E = M \quad \text{(A2-2)}\]

\[M \quad \text{– mean anomaly [°]}\]

Mean motion-orbit angular rate

\[n = \sqrt{\frac{\mu}{a^3}} \quad \text{(A2-4)}\]

\[n \quad \text{– orbit angular rate [rads}^{-1}\text{]}\]

Orbital period \(P_{*} = \frac{2\pi}{n} = 2\pi \left(\frac{a^3}{\mu}\right)^{1/2}\)

\[P \quad \text{– orbital period [s]}\]

To determine the location of the satellite at a certain point in time \(t\) the root of needs to be determined [Wakker]. The integration constants \(a, e, \omega, \tau\) define size, shape and orientation of the orbital plane; integration constant \(\tau\) enables calculation of the position of the satellite at a time \(t\).

Excel

A simplified iterative method is used in the excel tool [TN.4122.12] for an initial 1-7 orbit(s) propagation [Wakker]

\[E_{i+1} = M + e \sin E_i \quad \text{(A2-6)}\]

Starting the integration with the approximation: \(E_0 = M\) for small eccentricities or \(E_0 = \pi\) for high eccentric orbits \((e > 0.8)\). With the \(E\) known the position of the satellite can be determined at a time \(t\) using equations [Wakker]

\[\tan \frac{\theta}{2} = \tan \frac{E}{2} \sqrt{\frac{1+e}{1-e}} \quad \text{(A2-7)}\]

\[\theta \quad \text{– true anomaly [°]}\]

Matlab

The Kepler equation is solved using the Newton-Raphson method to calculate root using the function, derivative and initial value. An auxiliary function is defined [Wakker]

\[f(E, M) = E - e \sin E - M \quad \text{(A2-8)}\]

The Newton-Raphson method is applied to determine an approximate root \(E_i\) of \(f(E, M)\) [Wakker]

\[E_{i+1} = E_i - \frac{f(E_i, M)}{f'(E, M)} = E_i - \frac{E_i - e \sin E_i - M}{1 - e \cos E_i} \quad \text{(A2-9)}\]
Newton-Raphson solution will converge quadratically [Adams]
1 if initial estimate of root \( f(E, M) \) is near root
2 if \( \text{abs} f'(E_0, M) \) not equal to zero; if \( f'(x_0) \) is not too small
3 if \( \text{abs} f''(E_n, M) \) is not too large near the root
Observe whether successive approximations converge to a limit and if the values of \( f \) at these approximations approach 0.

Table A2-1: Convergence of \( f(E, M) \) roots for \( e = 0.3 \); converges within 4 iterations

<table>
<thead>
<tr>
<th>M</th>
<th>1.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.3</td>
</tr>
<tr>
<td>E_0</td>
<td>1.7</td>
</tr>
<tr>
<td>n</td>
<td>E(n)</td>
</tr>
<tr>
<td>0</td>
<td>1.7</td>
</tr>
<tr>
<td>1</td>
<td>1.98642804</td>
</tr>
<tr>
<td>2</td>
<td>1.975751665</td>
</tr>
<tr>
<td>3</td>
<td>1.975737654</td>
</tr>
<tr>
<td>4</td>
<td>1.975737654</td>
</tr>
<tr>
<td>5</td>
<td>1.975737654</td>
</tr>
</tbody>
</table>

A2.2 Perturbed Kepler Orbits

The main perturbation forces are:
- Non spherical earth (non radial symmetric mass distribution Earth)
- Atmospheric drag
- 3rd body perturbations
- Solar radiation pressure
- Electromagnetic forces (Lorentz & Plasma drag)

The Gauss Planetary Equations

Using [Sidi] and rewriting for the Orbital Reference frame (OR) the Gauss Planetary equations giving an analytical expression for the differential changes in orbit elements for a known perturbing force – acceleration are given as [Sidi]

\[
\frac{da}{dt} = \frac{2}{n\sqrt{1-e^2}} \left( -e \sin \theta z_{or} + \left[ 1 + e \cos \theta \right] x_{or} \right) 
\]

\[
\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na} \left( -\sin \theta z_{or} + \left[ \cos \psi + \cos \theta \right] x_{or} \right) 
\]

\[
\frac{d\theta}{dt} = \frac{1}{na\sqrt{1-e^2}} r \cos(\theta + \omega) y_{or} 
\]

\[
\frac{d\Omega}{dt} = -\frac{1}{na\sqrt{1-e^2}} \frac{r \sin(\theta + \omega)}{\sin i} y_{or} 
\]

\[
\frac{d\psi}{dt} = \frac{\sqrt{1-e^2}}{nae} \left( \cos \theta z_{or} + \left[ 1 + \frac{1}{1+\cos \theta} \right] \sin \theta x_{or} - \frac{d\Omega}{dt} \cos i \right) 
\]

\[
\frac{dM}{dt} = n + \frac{1-e^2}{nae} \left[ -\frac{-2e}{1+\cos \theta} \right] z_{or} - \left[ 1 + \frac{1}{1+\cos \theta} \right] \sin \theta x_{or} \right) 
\]

with

\[
r = \frac{a(1-e^2)}{1+e\cos \theta} 
\]

\[
\psi = \cos^{-1} \left[ \frac{a-e}{ae} \right] 
\]
Assuming a circular orbit \( a=r; e=0 \) and using equation (A2-11) the Gauss planetary equations can be simplified assuming only Lorentz drag acting on the system as

\[
\frac{da}{dt} = \frac{2F_{Lp}}{nnm}
\]
\[
\frac{de}{dt} = \frac{2F_{Lp}}{nma} \cos \theta = \frac{2F_{Lp}}{v_m} \cos \theta
\]
\[
\frac{di}{dt} = -\frac{F_{oop}}{nma} \cos(\theta + \omega) = -\frac{F_{oop}}{v_m} \cos(\theta + \omega)
\]  

(A2-12)

Integration leads to [Tragesser]

\[
\Delta a = -\frac{2L_B \cos i}{nnm} \int_0^t \ln dt
\]
\[
\Delta e = \frac{L_B \cos i}{nma} \int_0^t 2 \cos \theta dt
\]
\[
\Delta i = -\frac{L_B \sin i}{nma} \int_0^t \ln(\cos^2(\omega+\theta)) dt
\]  

(A2-13)

For a current \( >0 \) in the tether a linear change in semi major axis occurs, DC current leads to SMA changes. A current modulation of \( \cos \theta \) induces a secular effect in the orbital eccentricity. For a DC current the \( \cos^2(\omega+\theta) \) term also induces a secular effect in the orbital inclination [Tragesser].

References
APPENDIX 3 ENVIRONMENTAL MODELS

This appendix provides for a number of environmental models used to estimate the effects of the environment on a spacecraft in low Earth orbit. The models have been implemented in the EDT Environment tool [TN.4122.12] and in part exported as an environmental database into the Tether Risk Analysis tool [TN.4122.10] and the Tether Design tool [TN.4122.19]. In table a3-1 a summary of the environment parameters considered and the models used for the detraction of the Delfi-1 environment are given. In this appendix the models used are explained in some detail including their relation to the operation of the electrodynamic tether onboard the Delfi-1 satellite.

Table A3-1: Overview of environmental models used in EDT design tools [TN.4122.12]

<table>
<thead>
<tr>
<th>Environmental Parameters</th>
<th>Model Used</th>
<th>Source</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational</td>
<td>point mass model</td>
<td>Newton</td>
<td>Circular Keplerian orbit exported to Tether Design Tool</td>
</tr>
<tr>
<td>Magnetosphere</td>
<td>Tilted Dipole</td>
<td>Tilted dipole magnetic field sheet EDT Environment Tool</td>
<td>Switch to IGRF output magnetic field strength and induced E exported to Tether Design Tool</td>
</tr>
<tr>
<td>Ionospheric</td>
<td>International Reference Ionosphere (IRI-95)</td>
<td>SPENVIS</td>
<td>Not suitable for real-time calculations exported to Tether Design Tool</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>MSISE-90</td>
<td>SPENVIS</td>
<td>exported to Tether Design Tool</td>
</tr>
<tr>
<td>Thermal</td>
<td>Equilibrium Steady State</td>
<td>Thermal sheet EDT Environment Tool and Thermal Analysis sheet Tether Design Tool</td>
<td>Predominantly located in the Tether Design Tool see Appendix 13</td>
</tr>
<tr>
<td>Micrometeoroid M</td>
<td>Grün</td>
<td>SPENVIS</td>
<td>analytical exported to Risk Analysis tool see Appendix 9</td>
</tr>
<tr>
<td>Orbital Debris OD</td>
<td>Ordem96 debris &amp; NASA90</td>
<td>SPENVIS</td>
<td>exported to Risk Analysis tool see Appendix 9</td>
</tr>
</tbody>
</table>

A3.1 Magnetic Field Model

The geomagnetic field of Earth consists of internal and external field sources. The predominant part of the magnetic field is generated internally by the outer core of the planet. External fields are generated in the ionosphere and magnetosphere due to differential flows of electrons and ions forming current systems causing short term variations in the magnetic field with intensities up to 10% of the main field [Tribble]. Other sources of magnetic fields are current flows in the crust and electrical currents flowing in the ionised upper atmosphere.

![Tilted dipole model of magnetic field](http://hyperphysics.phystr.gsu.edu)

Figure A3-1: Tilted dipole model of magnetic field [http://hyperphysics.phystr.gsu.edu]

Earth’s magnetic field can be approximated by an eccentric dipole that is tilted and translated with respect to the ECEF reference frame, similar to an electric dipole as is shown in figure a3-1. For a conservative magnetic field a scalar field potential $V_{mag}(x,y,z)$, consisting of internal and external contributions mentioned above, can be defined that the gradient of the field defines a non diverging, static vector field $\mathbf{B}$ [ECSS] expanded for Cartesian and polar coordinates as
\[ \mathbf{B} = -\nabla V_{\text{mag}} = -\left( \frac{\partial V_{\text{mag}}}{\partial x} \mathbf{i} + \frac{\partial V_{\text{mag}}}{\partial y} \mathbf{j} + \frac{\partial V_{\text{mag}}}{\partial z} \mathbf{k} \right) = -\left( \frac{\partial V_{\text{mag}}}{\partial r} \mathbf{r} + \frac{1}{r} \frac{\partial V_{\text{mag}}}{\partial \theta} \mathbf{\theta} \mathbf{x} + \frac{1}{r \sin \theta} \frac{\partial V_{\text{mag}}}{\partial \phi} \mathbf{\phi} \mathbf{z} \right) \quad (A3-1) \]

\( r \) – geocentric orbital radius \([\text{m}]\)

The scalar potential function of the magnetic field returns a scalar quantity as a function of a local coordinate and time \( t \). The gradient of the scalar potential function, \( \mathbf{B} \), is a vector normal to the isolines of the scalar field, the magnitude equals the maximum rate of change and the direction is oriented toward the maximum rate of change of the isolines, in other words the gradient is the directional derivative of the scalar field.

The scalar potential generated by dipole \( M_{\text{mag}} \) of a given strength and orientation \([\text{ECSS}]\), expanded for the polar coordinates used in figure A3-1 is

\[ V_{\text{mag}} = \frac{M_{\text{mag}} \cdot \mathbf{r}}{r^3} = -\frac{\mu_0 M_{\text{mag}} \sin \theta}{4\pi r^3} \quad \text{(A3-2)} \]

\( \theta \) – magnetic latitude \([\text{°}]\)

\( M_{\text{mag}} \) – magnitude of magnetic dipole moment \([\text{Am}^2]\)

Substituting (A3-2) in (A3-1) the magnetic flux density vector \( \mathbf{B} \) due to the dipole in spherical coordinates and Cartesian coordinates for the magnetic reference frame MAG is given as

\[ \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \frac{\mu_0 M_{\text{mag}}}{4\pi r^3} \begin{bmatrix} 3XZ \\ 3YZ \\ (3Z^2 - r^2) \end{bmatrix} \quad \text{(A3-3)} \]

Non dipolar contributions are taken into account by describing the scalar potential field numerically. Usually only the internally generated field contribution of \( V_{\text{mag}} \) is used correlating with the magnetic field for low altitudes and being a good approximation for intermediate altitudes. In a spherical coordinate system, the expansion of \( V_{\text{mag}} \) internal field sources in spherical harmonics is

\[ V_{\text{mag}} = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} \left( \frac{R}{r} \right)^{n+1} P_n^m(\cos \theta) \left[ g_n^m \cos(m\phi) + h_n^m \sin(m\phi) \right] \quad \text{(A3-4)} \]

\( \phi \) – longitude

\( \theta_c \) – co-latitude = \(90^\circ-\theta\)

\( g, h \) – Gauss or Schmidt coefficients associated with internal field sources

\( P \) – Legendre polynomials

\( R_E \) – Mean Earth radius 6378150 \([\text{m}]\)

The main mathematical model used to describe the internally generated field is the International Geomagnetic Reference Field (IGRF 2000) describing the magnetic field as a Legendre polynomial of the scalar potential function \( V_{\text{mag}} \) of the field up to \( n=m=13 \) terms \([\text{Tribble; ECSS}]\). The main contribution in the spherical harmonic expansion is by the terms of degree \( n = 1 \) describing the main dipole. Higher terms depict deviations from the ideal dipole model to eccentric tilted dipole model taking into account the tilt and offset of the dipole axis, see table A3-2.

### Table A3-2: Physical meaning of Gauss coefficients

<table>
<thead>
<tr>
<th>( n ) degree</th>
<th>( m ) order</th>
<th>Model</th>
<th>Description</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>direct dipole</td>
<td>dipole axis oriented along ( Z_{\text{ECEF}} )</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0,1</td>
<td>tilted dipole</td>
<td>rotation</td>
<td>diurnal rotation of the magnetic field</td>
</tr>
<tr>
<td>2</td>
<td>0,1</td>
<td>eccentric dipole</td>
<td>rotation and displacement</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>deforms the equatorial component of the magnetic field (dip poles)</td>
<td>perturbations of dipole subsequent terms are potentials produced by various multi-poles</td>
<td>effects are mostly apparent near Earth’s surface and decrease with increasing altitude</td>
</tr>
</tbody>
</table>
Delfi-1 operates in a low earth orbit (LEO) where the external field contributions can be discounted [Tribble], allowing for a first degree and first order (n=1, m=0,1) approximation of the field as a dipole generated by the internal geomagnetic field. The field strength at the magnetic equator at Earth’s surface $B_{eq}$ is related to the magnetic dipole moment $M_{mag}$ quantifying the amount of external magnetic field being generated by the internal magnetism for a centred dipole [Fraser-Smith]

$$M_{mag} = \frac{4\pi}{\mu_0} B_{eq} R_E^3$$  \hspace{1cm} (A3-5)

$\mu_0$ \hspace{0.5cm} – (magnetic) permeability of free space (vacuum) $4\pi \times 10^{-7}$ [TmA$^{-1}$]

$B_{eq}$ \hspace{0.5cm} – magnetic field strength at equator [T]

Combining the first order potential $V_{mag}$ (n=1, m=0,1) expansion from (A3-4)

$$V_{mag} = \left(\frac{R_E^3}{r^2}\right) \left[ g_0^0 \cos(\theta_c) + g_1^1 \sin(\theta_c) \cos(\phi) + h_1^1 \sin(\theta_c) \sin(\phi) \right]$$  \hspace{1cm} (A3-6)

With (A3-2) and (A3-5) results in the following parameters for the tilted dipole model

$$B_{eq}^2 = \left( (g_0^0)^2 + (g_1^1)^2 + (h_1^1)^2 \right)$$

$$\cos \theta_c = -\frac{g_0^0}{B_{eq}}$$  \hspace{1cm} (A3-7)

$$\tan \phi = \frac{h_1^1}{g_1^1}$$

Parameters of the centred dipole model (magnitude of $M_{mag}$ and orientation of the dipole axis ($\theta_c, \phi$) in geographical coordinates [ECEF] can be derived using the first 3 Gauss coefficients [Fraser-Smith] describing the tilted dipole, see table a3- 2. Substituting IGRF 2000 values [IAGA] the following magnetic field dipole parameters are derived.

<table>
<thead>
<tr>
<th>$g_0^0$</th>
<th>-29619.4</th>
<th>$g_1^1$</th>
<th>-1728.2</th>
<th>$h_1^1$</th>
<th>5186.1</th>
<th>[nT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-latitude $\theta_c$</td>
<td>10.46º</td>
<td>Azimuth $\phi$</td>
<td>71.57º</td>
<td>$B_{mag}$</td>
<td>30119.61</td>
<td>[nT]</td>
</tr>
<tr>
<td>$M_{mag}$</td>
<td>7.81453x10$^{22}$</td>
<td>[Am$^2$]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centred dipole intersection $Z_{mag}$ point on Earth</td>
<td>Latitude</td>
<td>79.54º</td>
<td>Longitude</td>
<td>288.43º</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The tilt of the magnetic axis leads to a diurnal precession of the magnetic dipole with respect to the Earths rotation axis as shown in figure a3- 2. For orbits with inclinations above 79.54º and below 100.46º, $i \pm \iota_m$, the rotation of the Earth and the tilt of the dipole axis of the magnetic field result in retrograde motion of the satellite during part of the orbit with respect to the magnetic field while still moving in prograde orbital direction resulting in $E$ being reversed during part of the orbit shown in figure a3- 2 for a passive deorbiting EDT the current is subsequently reversed.

Figure A3- 2: Effect magnetic field precession F$_i$; induced E 650 km-85º
In orbit variations of the magnetic field strength and its orientation to the velocity vector of the tether result in fluctuations of the induced electromotive force in the tether as can be seen in figure a3-2 for the tilted dipole magnetic field model and circular orbit with the tether oriented along the nadir.

Results for the calculated magnetic field components and induced electromagnetic field along the tether using the tilted dipole model have been verified using magnetic field models accessed through Spenvis and using ETBSim.

### A3.2 Gravity Field Model

For initial analysis of the experiment use is made of Newton’s universal law of gravitation which states that the gravitational force $F_G$ on an object of mass $m$ [kg] orbiting the Earth at an altitude of $h$ m in an Earth centred reference frame is

$$F_G = -\frac{G M_E m}{(r + h)^2} = -\frac{\mu m}{r^2}$$  \hspace{1cm} (A3-8)

- $G$ – universal gravitational constant $6.67 \times 10^{-11}$ [m$^3$kg$^{-1}$s$^{-2}$]
- $m$ – total system mass [kg]
- $M_E$ – geocentric Earth mass $5.97 \times 10^{24}$ [kg]
- $r$ – orbital radius [m]
- $\mu$ – gravitational constant $3.99 \times 10^{14}$ [m$^3$s$^{-2}$]

Gravitational scalar potential function $\Phi$ can be used to determine the acceleration of a spacecraft in orbit by taking the gradient of the geopotential function. The main gravitational perturbations due to deviations uniform gravitational field acting on the tether are:

- Earth’s oblatness $J_2$
- Superior harmonics of the geopotential
- 3rd body perturbations incl. spacecraft attraction
- Relativistic effects
- Finite tether thickness

In table a3-4 the gravitational perturbations for a L$_t$ -1000 m w- 80 mm tether of 3 kg; without an end mass $m_b$ have been calculated using approximations for the perturbations by [Beletsky]. Polar flattening caused by the planets rotation is the largest deviation from the uniform field model. The resulting perturbing acceleration due to oblatness of the Earth, $J_2$ term of the standard geopotential expansion affects the tether tension in the component of acceleration along the tether. This term increases the tether tension by a factor of approximately $2J_2 = 2 \times 10^{-3}$ when the effect of the $J_2$ in orbit is at its highest [Beletsky]. The $J_2$ contribution is ignored with respect to gravitational perturbations the EDT can be assumed to be a point mass $m$ at the mass centre c.m. [Beletsky].

**Table A3-4: Gravitational perturbations acting on tether [Beletsky]**

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>650 km</th>
<th>1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension at suspension point</td>
<td>N 1.16E-03</td>
<td>9.99E-04</td>
</tr>
<tr>
<td>$J_2$</td>
<td>N 2.31E-06</td>
<td>2.00E-06</td>
</tr>
<tr>
<td>Geopotential harmonics</td>
<td>N 1.16E-08</td>
<td>9.99E-09</td>
</tr>
<tr>
<td>Lunar</td>
<td>N 4.62E-11</td>
<td>4.00E-11</td>
</tr>
<tr>
<td>Solar</td>
<td>N 2.31E-11</td>
<td>2.00E-11</td>
</tr>
<tr>
<td>Relativistic</td>
<td>N 8.09E-13</td>
<td>6.99E-13</td>
</tr>
<tr>
<td>Vehicle attraction</td>
<td>N 2.00E-11</td>
<td>2.00E-11</td>
</tr>
<tr>
<td>Finite tether thickness</td>
<td>N 9.86E-18</td>
<td>8.95E-18</td>
</tr>
</tbody>
</table>

All other perturbations from the uniform gravity field model are significantly smaller components of force in nadir direction and are subsequently also ignored in the initial performance analysis of the EDT experiment. The gravity field is assumed to be a uniform field with Earth modelled as non-rotating, spherically symmetric mass distribution and uniform density.
Gravity Gradient Derivation

Gravity gradient force acts to restore the tether to a nadir-zenith orientation is the difference between the centripetal force \( F_C \) due to motion of system and the gravity force \( F_G \). Taken from the work of [Thoen] assuming circular Keplerian orbits

\[
F_c = m r a^2 = F_s = \frac{\mu m}{r^2}
\]

For circular orbits \( \omega^2 = \frac{\mu}{r} \)

\[
\frac{\delta F_c}{\delta r} = 2 \frac{\mu m}{r^2} = 2 m \omega^2 = \frac{\delta F_c}{\delta r} = m \omega^2
\]

\[
F_{gg} = dr \left( \frac{\delta F_c}{\delta r} + \frac{\delta F_c}{\delta r} \right) = 3 m \omega^2 dr
\]

A3.3 Atmospheric Model MSISE-90

Atmospheric data is from the Mass Spectrometer Incoherent Scatter (MSISE-90) model and can be accessed using [SPENVIS]. It determines temperature, total density, pressure, mean molecular weight and concentrations of various constituents of the atmosphere for low, mean and extremely high solar activity conditions, density variations are shown in figure a3-3. This model is used for calculation erosion effects on materials.

![Variation in atmospheric density with altitude and solar activity](image)

Figure A3-3: Variation in atmospheric density with altitude and solar activity [MSISE-90]

A3.4 Ionospheric Models LEOPOLD - IRI

Due to the Sun's UV radiation the atmospheric constituents N\(_2\), O\(_2\) and O of Earth's upper atmosphere are ionised forming a plasma between the altitudes of 70 km-1500 km. Plasma is a gas in which electrons have enough kinetic energy to remain free from ions. The ionosphere for LEO is described as low energy high density plasma, generally considered to be overall neutral, i.e., containing equal concentrations of electrons and ions with a plasma density \( n_o \). The main parameter of plasma is the kinetic energy of the constituent particles (the processes of the free particles in the plasma governed by their kinetic energy). The velocity distribution of the particles assuming each species is in thermal equilibrium with itself is Maxwellian and is determined by the temperature of the particle species \( T_p \), a measure of thermal kinetic energy per particle expressed in units of energy eV\(^{14}\) is in the order of 0.15 eV -0.28 eV for Delfi-1 orbit range. The ionosphere is non-isothermal plasma with the electrons being at a higher temperature than the ions.

Thermal velocity or thermal speed is the typical velocity of thermal motion of the particles in a gas or liquid and is a measure of temperature. It is a scalar speed (not a vector). Is a measure of the width if the peak in the Maxwell-Boltzmann particle velocity distribution. The main parameter of plasma is the energy of its constituents (ions and electrons particles). Processes in plasma primarily due to \( E_{kin} \) the mean energy of plasma is \( \frac{1}{3} T_{plasma} \). Usually \( T \) expressed in units of energy eV – J k\(_B\) T.

\(^{14}\) eV = 1.602x10\(^{-19}\) J; as a unit of temperature eVK\(^{-1}\)
Delfi-1 orbit is situated in the topside ionosphere region where H⁺ ions become the dominant species [figure a3-5]. The electron density of the ionosphere peaks at 300-350 km and decreases with increasing altitude. Densities, temperatures and ionic composition of the plasma vary diurnally, seasonally and with solar activity [ECSS].

The ionospheric plasma particles co-rotate with Earth’s magnetic field. Because of the magnetic field's influence, the particle densities also vary with latitude, being larger near the magnetic equator than near the poles at a given altitude, see figure a3-4.

![Graph showing variation in ionospheric density vs. latitude.](image)

**Figure A3-4: Variation ionospheric density vs. latitude [IRI-2007]**

The ionosphere for Delfi-1 orbit is situated above the F2 ionospheric layer and passes through the high latitude plasmasphere called the auroral and polar cap region. The auroral and polar cap region of the ionosphere density is irregular. In the auroral region plasma density can increase by a factor 100 during magnetic active periods. The polar cap region has less severe density fluctuations but is characterised by a strong winter-summer asymmetry, with density being maintained during winter by drift motion due to electric fields and a 'polar rain' consisting of an electron flux originating from the solar wind. Plasma density in the polar cap region can become very low when these two processes are depressed [ECSS].

**Table A3-5: Solar activity values**

<table>
<thead>
<tr>
<th>F10.7x10⁻²² Wm⁻² Hz⁻¹</th>
<th>Solar Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>low</td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>modest</td>
</tr>
<tr>
<td>200</td>
<td>high</td>
</tr>
<tr>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>

**LEOPOLD**

This model provides plasma parameters as a function of altitude ignoring in orbit variations of the plasma parameters due to eclipse conditions and variations due to orbit inclination. The following plasma parameters are generated as a function of altitude using [SPENVIS] and inserted in the datasheet Ionosphere in the EDT Environment tool and used for initial evaluation of EDT performance as a function of orbit altitudes and determination of Debye radius and Gyro radius for Delfi-1 orbit range.

- neutral particle density \([\text{m}^{-3}]\)
- electron density \([\text{m}^{-3}]\)
- electron temperature [K or eV]
- ion temperature [K or eV]
- average ion mass [amu or kg]
- electron thermal velocity (rms velocity) \([\text{ms}^{-1}]\)
- ion thermal velocity (rms velocity) \([\text{ms}^{-1}]\)
- spacecraft circular velocity \([\text{ms}^{-1}]\)
- electron thermal particle flux \([\text{m}^{-2}\text{s}^{-1}]\)
- ion ram particle flux \([\text{m}^{-2}\text{s}^{-1}]\)
- Debye length [m]
- mass ratio \(m_i/m_e\)
- dimensionless satellite velocity
- ion kinetic energy
Table A3- 6: LEOPOLD plasma parameters Delfi-1 orbit extremes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude h</td>
<td>km</td>
<td>650 1000</td>
</tr>
<tr>
<td>Orbital velocity v(_{\text{orb}})</td>
<td>km/s</td>
<td>7.531 7.350</td>
</tr>
<tr>
<td>Plasma density n(_o)</td>
<td>m(^{-3})</td>
<td>2.50E+11 6.00E+10</td>
</tr>
<tr>
<td>Electron temperature T(_e)</td>
<td>K</td>
<td>2800 3200</td>
</tr>
<tr>
<td>Ion temperature T(_i)</td>
<td>K</td>
<td>1850 2600</td>
</tr>
<tr>
<td>Debye length (\lambda_{\text{De}})</td>
<td>m</td>
<td>7.30E-03 1.59E-02</td>
</tr>
<tr>
<td>Electron thermal velocity v(_{\text{th},e})</td>
<td>km/s</td>
<td>291 311</td>
</tr>
<tr>
<td>Ion thermal velocity v(_{\text{th},i})</td>
<td>km/s</td>
<td>1.457 2.485</td>
</tr>
<tr>
<td>Mass ratio m(_i)/m(_e)</td>
<td>-</td>
<td>2.64E+04 1.28E+04</td>
</tr>
<tr>
<td>Electron ion collection ratio (l_e/l_i)</td>
<td>-</td>
<td>0.033571 0.042794</td>
</tr>
<tr>
<td>Gyro radius e (r_L)</td>
<td>m</td>
<td>5.1E-02 6.18E-02</td>
</tr>
<tr>
<td>Gyro radius i (r_L^+)</td>
<td>m</td>
<td>6.73 6.29</td>
</tr>
</tbody>
</table>

International Reference Ionosphere (IRI-95 IRI-2001)

IRI is an empirical model of the ionosphere for the altitude range 50-1500 km based on monthly averages for non-auroral ionosphere during magnetically quiet conditions for the following plasma parameters:
- Electron density
- Electron temperature [not for IRI-2001]
- Ion temperature
- Ion composition (O+, H+, He+, NO+, O+2)
- Ion drift
- TEC

Future versions (2007) are expected to include auroral and polar regions of the ionosphere.
http://modelweb.gsfc.nasa.gov/ionos/iri.html

Figure A3- 5: Percentages ionospheric constituents [IRI-2007] F\(_{10.7}\)-150

Figure A3- 6: Variation of ionospheric density during 1 orbit [MSISE-90]
A3.5 Micrometeoroid and Orbital Debris Models

The meteoroid and orbital debris (M/OD) environment consists of:
- (Micro) Meteoroids
- Orbital Debris (man-made)

![Figure A3-7: M/OD impact directions](image)

The debris environment is described by the flux of debris particles as a function of particle size. For meteoroids, the Grün meteoroid model is used, and for orbital debris, the NASA90 model has been used, both accessed using [SPENVIS].

**Grün Meteoroid Model**

Meteoroids are debris particles (<1 cm up to ∼10 m -50 m) in the solar system at speeds between 11 and 73 kms\(^{-1}\) originating from comets or asteroids; micrometeoroids are considered to have diameters smaller ∼10-100 µm with mass typically < 1 gram.
- Asteroidal origin ∼15 kms\(^{-1}\)
- Cometary objects ∼ 30 kms\(^{-1}\)

The Grün meteoroid model [SPENVIS] is used to estimate meteoroid particle fluxes as a function of meteoroid mass. The model gives the integral meteoroid flux averaged over a year as a function of particles per unit area per unit time that impact a randomly oriented flat plate under a viewing angle of 2π steradians for particles above a specified mass \(m\) at 1 A.U. distance from the sun in the ecliptic plane expressed in a cumulative surface area flux \(F_c(m)\) [SPENVIS]. For a given particle density, there is a one-to-one correspondence between mass and diameter (the particles are considered to be spherical). The particle size range can be entered as a mass range or a diameter range. Factors to take into account are:

- Output is cumulative surface area flux = \(\frac{1}{4}\) cross-sectional flux can be used, see figure a3-7
- Velocity distribution
- Direction distribution
- Earth shielding and gravitational focusing to obtain \(F_m(m,h)\)

The effects of the Earth on the \(F_c(m)\) need to be taken into account for M/OD calculations for spacecraft in LEO orbits. Due to Earth’s (partial) shielding, the meteoroid flux is reduced and gravitational focusing of Earth’s gravitational field increases the meteoroid flux for spacecraft in orbit. The meteoroid flux at 1 A.U. and near Earth is calculated as [Pisacane; SPENVIS]

\[
F_c(m,h) = F_c(m)\chi_i(h)G_E(h)
\]  \hspace{1cm} (A3-12)

- \(F_c\) – cumulative surface area flux \([\text{m}^2\cdot\text{yr}^{-1}(2\pi\text{sr})^{-1}]\)
- \(F_m\) – average meteoroid flux near Earth \([\text{m}^2\cdot\text{yr}^{-1}(2\pi\text{sr})^{-1}]\)
- \(\chi_i\) – Earth shielding factor [-]
- \(G_E\) – Gravitational focusing factor [-]

Assuming the flux is omni-directional \(\chi_i\) depends on the orientation of the surface to Earth’s surface, case 1 where the angle between Earth and the surface normal ≥ \(\frac{\pi}{2}\), case 2 for variable directions and case 3 with the surface normal oriented towards the surface of the Earth.
\( \chi_1 = 1 \)
\( \chi_2 = \frac{1}{2}(1 + \cos \rho_E) \) \hspace{1cm} (A3-13)
\( \chi_3 = \cos \rho_E \)

For the EDT oriented along the \( z_{OR} \) axis the Earth shielding factor is assumed be between case 1 and 2 and is calculated as [Cooke]

\[
\chi' = \frac{2\pi + \sin 2\rho_E - 2\rho_E}{2\pi} \] \hspace{1cm} (A3-14)

with \( \sin \rho_E = \frac{R_E + h_a}{R_E + h} \) \hspace{1cm} (A13-3)

\( \rho_E \) – angular radius Earth [rad]
\( h_a \) – height of atmosphere [m] [approximately 100 km, can be ignored in most calculations]

Gravitational focussing factor [-] increasing the flux is calculated as

\[
G_e(h) = 1 + \frac{R_E + h_a}{R_E + h} \] \hspace{1cm} (A3-15)

SPENVIS output of the Grün meteoroid model gives the \( F_e(m,h) \) as function of either the mass or diameter of the particles for a randomly oriented flat plate giving an Earth shielding factor of case 2 and the model also assumes an atmospheric height of 100 km.

Figure A3- 8: Earth shielding factors

**Orbital Debris Model NASA90**

For an input of orbit altitude and inclination, this model estimates debris particle fluxes as a function of particle size (diameter) giving the cumulative cross-sectional area flux. For a given particle density, there is a one-to-one correspondence between mass and diameter (the particles are considered to be spherical). The particle size range can be entered as a diameter range or a mass range. The number of debris particles in orbit around the Earth increases with time. This effect is modelled by means of two parameters the growth rate of the mass in orbit and the fragment growth rate with respect to the chosen year of epoch. The debris population also depends on the solar radio flux \( F_{10.7} \) for the year preceding the epoch. For EDT data 2000 epoch and average solar conditions \( F_{10.7} = 150 \) have been taken.
Figure A3-9: Debris flux M/OD as a function of debris particle size 650 km 70° orbit

**Trackable Orbital Debris**

Trackable orbiting objects > 10 cm with known orbital data, can be propagated along their orbit and their chance of a future collision with another spacecraft or fragment assessed. Several data sources of satellites and fragments and some analysis tools for trackable objects have been combined in the European DISCOS tool [ECSS]. Collision with trackable objects has not been analysed in this study.

**References**


[IAGA] [http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html](http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html)


[Spenvis] [http://www.spenvis.oma.be/](http://www.spenvis.oma.be/)


APPENDIX 4 SPACE CHARGING EFFECTS

The bias distribution over the floating tether is determined by space charge effects balancing the electron and ion current to the tether. Sources of passive electron and ion current collection in the ionospheric plasma charging an passive tether in orbit are [Tribble; Sanmartin]

- Thermal current collection
- Bare tether OML current collection valid for thin long cylinders (electrons over \( I_e \) and ions over \( I_i \)), see appendix 5
- Ion ram current, ions collected over \( I_i \)
- Secondary emitted electron current \( I_{se} \) (material property) \( \sim 1\% \) due to ion impact
- Secondary emitted ion current \( I_{si} \) (material property) due to electron impact \( \sim 0 \)
- Photoelectron current \( I_{ph} \) (material property), electrons emitted over \( I_e \) and \( I_i \)
- Retardation regime electrons collected over \( I_e \), ions collected over \( I_i \)

Space charging occurs when the equilibrium charge of an object in plasma is not zero, as ions or electrons are attracted to the object a sheath is formed shielding the charged object from the plasma environment. In neutral plasma the density and energy of the constituent electrons and ions is similar by approximation. Ions have a larger mass than electrons, the thermal velocity of the ions is less than the orbital velocity and the thermal velocity of the electrons is larger, the EDT is moving at mesosonic speeds relative to the plasma.

\[
\frac{v_{th}}{v_{orb}} = \sqrt{\frac{k_B T}{m_i}} > \frac{v_{th}}{v_{orb}} = \sqrt{\frac{k_B T}{m_i}}
\]

(A4-1)

\[
With \ m_i > m_e \ v_{th,i} < v_{orb,i} \sim 1.5-2.5 \text{[kms}^{-1}] < 7.5 \text{[kms}^{-1}] < \sim 200 \text{[kms}^{-1}]\]

\[
v_{th} \quad \text{thermal velocity [kms}^{-1}]\
k_B \quad \text{Boltzmann constant 1.38x10}^{-23} \text{[JK}^{-1}]\
T_{e,i} \quad \text{electron – ion temperature [K]}\
m_{e,i} \quad \text{electron – ion mass [kg]}
\]

Figure A4-1: Particles fluxes for orbit range Delfi-1

With the ion thermal velocity lower than the orbital velocity a wake is formed behind the SC without any ions, subsequently ions only impact surfaces \( A_i \) of the SC and tether oriented normal to the velocity vector, the ram side, shown in figure a4-1. Ion current is a function of the velocity, ram surfaces normal to the flight direction and the plasma density.

\[
I_i = e n_v v_{orb} A
\]

(A4-2)
Electrons impact all surfaces of the object as electron thermal velocities are larger than orbital velocity in LEO; the object immersed in the plasma collects electrons over its entire surface area $A_e$. Due to the imbalance of electron and ion flux the incident electron current to the SC and tether is larger causing charging to occur, the object charges negatively to the plasma. The particle flux intensity, a function of the mass and thermal velocity of the particles for the orbit range of Delfi-1 is shown in figure a4-1. Eventually a balance between the high electron flux and low ion flux is established when the SC and tether are charged to floating potentials. The floating potential of the SC is calculated as [Tribble]

$$V_{fl} = \frac{k_B T_e}{e} \ln \left( \frac{4v_{th,e} A_e}{v_{orb} A} \right)$$

(A4-3)

For the higher inclination range of Delfi-1 orbits the spacecraft passes the auroral and polar region where it can be exposed to accelerated polar electrons, a more negative potential is likely to occur according to [Tribble]. More research into ionospheric plasma for the polar cap region and its effects on SC charging are required.

References


APPENDIX 5 OML THEORY & REGIME

The bare tether functions as the anode and cathode collecting electrons and ions from the plasma environment. In this appendix the validity of the Orbit Motion Limited (OML) current collection model proposed for bare tether electron collection is discussed for the EDT tether and the Delfi-1 orbit range.

The maximum amount of current a tether will collect per square meter of collection area in orbit is described by the orbit motion limited current collection theory (OML). For a cylindrical probe in the OML regime the amount of current collected is a function of the bias to the surrounding plasma, the electron current collected by the probe for stationary, unmagnetised plasma is

\[
I_{\text{OML}} = \frac{4}{\pi} \left(1 + \frac{V_e - V_p}{k_B T_e} \right)^{3/2} \lambda_{\text{coll}} \left( \frac{8 k_B T_e}{\pi m_e} \right)^{1/2} I_{\text{in}}
\]

(A5-1)

\( I_{\text{in}} \) – random thermal current

Validity Theoretical OML Regime

- \( L_t >> r_t \); electron collection is a 2D process dominated by stronger gradients of the diameter, each point of the bare tether will collect current as if it were part of a cylinder uniformly polarised at the local tether bias

- Electric Shielding \( \frac{r_t}{\lambda_{De}} < 1 \)

- Magnetic Guiding \( \frac{\lambda_{De}}{r_{L,e}} \) ratio must be small

This ratio is small for \( n_0 \) above \( 10^{11} \text{ m}^{-3} \) and breaks down at low or high altitudes, this ratio is a plasma parameter not a free design parameter.

The PM (Parker Murphy) parameter \( \frac{r_t}{r_{L,e}} \) must be small to ignore the magnetic guiding effects.

For right angles of the magnetic field \( B \perp \) to tether this effect is weak, for high inclinations \( B \) is at an angle to tether these effects will increase. The gyro radius must be equal or larger than the effective diameter of the tether for current collection to be in the OML range \( \frac{r_t}{r_{L,e}} \) and \( \frac{\lambda_{De}}{r_{L,e}} < \sim 1 \)

holds when \( r_t \sim \lambda_{De} \)

- For tether potentials higher than electron and ion thermal energy velocity, effectively there is no potential barrier and the tether collects maximum OML current. Incoming electrons and ions overcome potential barrier [Sanmartin] when

\[ \frac{e \Delta V}{k_B T_e} \gg 1 \]

within the OML regime \( I_{\text{OML}} \) holds for \( e \Delta V >> k_B T_e ; k_B T_e / e \); 0.16-0.28 eV and

\[ e \Delta V > \frac{1}{2} m_i v^2 \ [\text{Ram Energy}] (-1.96-4.5 \text{ eV for Delfi-1 orbit}) \ [\text{TN.4122.12; Sanmartin}]

\[ v \] - plasma velocity (co-rotating with Earth) \([\text{ms}^{-1}]\)

- \( \frac{T_e}{T_i} \) increases then \( \frac{r_{\text{max}}}{\lambda_{De}} \) increases, so for higher altitudes an increase in tether crosswise dimensions \( r_{\text{max}} \)

Table A5- 1: OML regime parameters orbit range Delfi-1 [TN.4122.12]

<table>
<thead>
<tr>
<th>( H ) [km]</th>
<th>( \lambda_{De} ) [m]</th>
<th>( \lambda_{Ti} ) [m]</th>
<th>( k_B T_e / e ) [eV]</th>
<th>( k_B T_i / e ) [eV]</th>
<th>( \frac{1}{2} m_i v^2 / e ) [eV]</th>
<th>( T_e / T_i )</th>
<th>( \lambda_{De} / r_{L,e} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>7.30E-03</td>
<td>5.94E-03</td>
<td>0.24</td>
<td>0.16</td>
<td>4.26</td>
<td>1.61E-04</td>
<td>1.5</td>
</tr>
<tr>
<td>700</td>
<td>8.31E-03</td>
<td>6.90E-03</td>
<td>0.25</td>
<td>0.17</td>
<td>4.09</td>
<td>1.60E-04</td>
<td>1.5</td>
</tr>
<tr>
<td>750</td>
<td>8.38E-03</td>
<td>7.16E-03</td>
<td>0.25</td>
<td>0.19</td>
<td>3.91</td>
<td>1.59E-04</td>
<td>1.4</td>
</tr>
<tr>
<td>800</td>
<td>8.45E-03</td>
<td>7.40E-03</td>
<td>0.26</td>
<td>0.20</td>
<td>3.74</td>
<td>1.58E-04</td>
<td>1.3</td>
</tr>
<tr>
<td>850</td>
<td>9.84E-03</td>
<td>8.82E-03</td>
<td>0.26</td>
<td>0.21</td>
<td>3.29</td>
<td>1.57E-04</td>
<td>1.2</td>
</tr>
<tr>
<td>900</td>
<td>1.22E-02</td>
<td>1.11E-02</td>
<td>0.27</td>
<td>0.22</td>
<td>2.84</td>
<td>1.56E-04</td>
<td>1.2</td>
</tr>
<tr>
<td>950</td>
<td>1.37E-02</td>
<td>1.24E-02</td>
<td>0.27</td>
<td>0.22</td>
<td>2.40</td>
<td>1.55E-04</td>
<td>1.2</td>
</tr>
<tr>
<td>1000</td>
<td>1.59E-02</td>
<td>1.44E-02</td>
<td>0.28</td>
<td>0.22</td>
<td>1.96</td>
<td>1.54E-04</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Taking bias values from the Tether Design tool using orbit averaged values for the induced E an initial indication of validity OML theory for Delfi-1 orbit range and preliminary EDT design values is shown below.

Table A5-2: Tether Bias and OML formula Validity for orbit extremes [TN.4122.19]

<table>
<thead>
<tr>
<th>Orbit</th>
<th>$k_B T_e$ [eV]</th>
<th>$k_B T_i$ [eV]</th>
<th>$\frac{1}{2}m v^2_{orb}$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>650 km 70°</td>
<td>0.241</td>
<td>0.159</td>
<td>4.26</td>
</tr>
<tr>
<td>L_t [m]</td>
<td>anode bias [V]</td>
<td>cathode bias [V]</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.5</td>
<td>-15.0</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1.0</td>
<td>-29.9</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>1.5</td>
<td>-44.9</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>2.0</td>
<td>-59.9</td>
<td></td>
</tr>
<tr>
<td>1250</td>
<td>2.5</td>
<td>-74.9</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>3.0</td>
<td>-89.8</td>
<td></td>
</tr>
<tr>
<td>1750</td>
<td>3.5</td>
<td>-104.8</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>4.0</td>
<td>-119.8</td>
<td></td>
</tr>
<tr>
<td>2250</td>
<td>4.5</td>
<td>-134.8</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>5.0</td>
<td>-149.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Orbit</th>
<th>$k_B T_e$ [eV]</th>
<th>$k_B T_i$ [eV]</th>
<th>$\frac{1}{2}m v^2_{orb}$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 km 85°</td>
<td>0.276</td>
<td>0.224</td>
<td>1.96</td>
</tr>
<tr>
<td>L_t [m]</td>
<td>anode bias [V]</td>
<td>cathode bias [V]</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>0.09</td>
<td>-2.0</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>0.22</td>
<td>-4.0</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td>0.39</td>
<td>-6.0</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.34</td>
<td>-8.0</td>
<td></td>
</tr>
<tr>
<td>1250</td>
<td>0.43</td>
<td>-10.4</td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td>0.51</td>
<td>-11.9</td>
<td></td>
</tr>
<tr>
<td>1750</td>
<td>0.60</td>
<td>-13.9</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>0.68</td>
<td>-15.9</td>
<td></td>
</tr>
<tr>
<td>2250</td>
<td>0.77</td>
<td>-17.9</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>0.85</td>
<td>-19.9</td>
<td></td>
</tr>
</tbody>
</table>

Validity OML Regime for Tape Tethers

The domain of validity for the OML regime for un-magnetised collisionless (Maxwellian) plasma at rest is summarised in with theoretical and experimental results for thin tapes (w>>t) given below.

- The maximum valid (theoretical) width is found to be $2w_{max} = 4r_{max}$ for a cylinder [Sanmartin]. A tape allows $2A_t$ compared to wire but OML is proportional to outer perimeter $P_t (4/\pi) \sim 27\%$ increase in $I_{OML}$ max
- $I_{tape} < I_{OML}$ a tape never collects the full $I_{OML}$ current $\approx 1\%$ reduction [Sanmartin]\(^2\) for $w_c \leq 2r_{max}$ a tape collects close to OML current
- Theoretical limits of tape widths up to $4\lambda_{De}$ have been shown to collect current close to OML theory and can be considered collecting in OML regime [Estes\(^1\)]. Degradation of performance beyond the considered limit was shown to be weak for stationary un-magnetised plasma.
- Tape geometries exceeding $\lambda_{De}$ dimensions can collect current within the OML regime depending on potential and plasma temperatures. When outside the OML regime the current is expected to drop below $I_{OML}$ however effects are expected to be limited, see [Estes\(^2\); Gilchrist\(^2\); Kruifff\(^1\-2\)].
- Tape widths $w_c$ of $4-15\lambda_{De}$ have been shown to follow OML current for an equivalent cylinder with effective diameter $d_t$ in laboratory experiments [Gilchrist\(^2\); Vannaroni; Kruifff]

References


APPENDIX 6 EDT EQUIVALENT ELECTRIC CIRCUIT

In this appendix the equivalent electrical circuit of the electrodynamic tether is used to estimate voltage losses occurring reducing the effective induced EMF driving the current through the tether and effecting deorbit performance of the tether due to Lorentz drag forces. The influence of tether temperature on the Ohmic resistance of the tether is also evaluated. Finally the bias distribution for the tether used in design performance models is derived.

**System Resistance**

The resistance $R_{\text{total}}$ of the equivalent electric circuit with the EDT at floating potential is determined by Kirchhoff’s current and voltage laws and Ohm’s current law. Total resistance is determined by tether resistance, sheath resistance at the anode and cathode end and the resistance of the ionospheric plasma closing the current loop [Roozendaal; less].

$$R_{\text{total}} = R_t + R_{sh+} + R_{sh-} + R_i + R_{\text{load}} \quad \text{(A6-1)}$$

- $R_t$ – Ohmic resistance tether [Ω]
- $R_i$ – specific resistance [Ω/m]
- $R_{sh+}$ – resistance associated with ionospheric current loop [Ω]
- $R_{sh-}$ – the impedances associated with the potential jumps of the plasma sheaths between the tether terminations and the ionosphere [Ω] [less]

$$R_{sh+} = \frac{+V}{I} \quad \text{and} \quad R_{sh-} = \frac{-V}{I}$$

- $R_{\text{load}}$ – useful load [Ω]

The induced EMF equals all the voltage drops in the system

$$EMF = IR_t + \Delta V_{sh+} + \Delta V_{sh-} + \Delta V_i + \Delta V_{\text{load}} \quad \text{(A6-3)}$$

$R_i$ the ionospheric closure impedance due to Alven and whistler band wave radiation, can be ignored when compared to resistance of other elements in the circuit according to [Sanmartin]. TSS-1R showed that the impedance due to the ionospheric plasma was negligible compared to resistance of other elements [less]. These impedances are associated with the potential jumps of the plasma sheaths between the tether terminations and the ionosphere [less]. The sheaths are assumed to be negligible for the low bias voltages induced by the floating short EDT with currents dropping to zero at both ends.

For design purposes it is assumed that part of the induced bias is lost due to unknown resistances reducing the effective tether length of the system. Tether length needs to be designed with a margin capable of overcoming a voltage drop due to $R_i = 50$ Ω [Roozendaal] at orbit averaged values of $E$.  

$$I_{\text{OML max}} R_{\text{loss}} = V_{\text{loss}} \quad \text{(A6-4)}$$

$$I_{\text{loss}} = \frac{V_{\text{loss}}}{E} \quad \text{(A6-5)}$$

A maximum of 250 meters of tether could potentially be lost at 2500 m – 80 mm wide tethers for maximum OML current levels occurring in the Delfi-1 orbit range. The highest percentages tether length lost due to the 50 Ω for the orbit range for various tether configurations are shown in table a6-1.
Table A6-1: Maximum percentage of $L_t$ lost due to 50 $\Omega$ system losses for tether dimensions

<table>
<thead>
<tr>
<th>$L_t$ [m]</th>
<th>5 mm</th>
<th>10 mm</th>
<th>15 mm</th>
<th>20 mm</th>
<th>30 mm</th>
<th>40 mm</th>
<th>50 mm</th>
<th>60 mm</th>
<th>70 mm</th>
<th>80 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>500</td>
<td>0%</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>2%</td>
<td>2%</td>
<td>3%</td>
<td>3%</td>
<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>750</td>
<td>0%</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>3%</td>
<td>4%</td>
<td>4%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>1000</td>
<td>0%</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>4%</td>
<td>5%</td>
<td>6%</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>1250</td>
<td>0%</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>4%</td>
<td>4%</td>
<td>5%</td>
<td>6%</td>
<td>7%</td>
</tr>
<tr>
<td>1500</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>4%</td>
<td>5%</td>
<td>6%</td>
<td>7%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>1750</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>4%</td>
<td>5%</td>
<td>6%</td>
<td>7%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>2000</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>4%</td>
<td>4%</td>
<td>6%</td>
<td>7%</td>
<td>8%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>2250</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>4%</td>
<td>5%</td>
<td>6%</td>
<td>7%</td>
<td>8%</td>
<td>9%</td>
<td>9%</td>
</tr>
<tr>
<td>2500</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>4%</td>
<td>5%</td>
<td>6%</td>
<td>7%</td>
<td>9%</td>
<td>10%</td>
</tr>
</tbody>
</table>

**Tether Bias Distribution**

The local bias voltage of an increment of tether length $dl$ is [Sanmartin]

$$\frac{d\Delta V}{dl} = r_c I_{\text{oml}} dl \frac{E}{A_c}$$  \hspace{1cm} (A6-6)

$A_c$ – cross sectional area conducting tether [m$^2$]

Specific resistance $r_t$ [$\Omega$m] of the tether is a function of temperature, see figure a6-1

$$r_t = r_0 + \alpha r_0 (T_t - T_0)$$ \hspace{1cm} (A6-7)

$\alpha$ – temperature resistance coefficient of material [K$^{-1}$]

$r_0$ – specific resistance at room temperature [$\Omega$m]

$T_0$ – room temperature 293 [K]

$T_t$ – tether temperature [K]

![Figure A6-1 Specific conductivity of aluminium as a function of temperature](image)

For the low current levels induced in passive short tether operation the Ohmic voltage drop along the tether is considered negligible when [Kruijff; LeBreton]

$$\frac{r_t L_t}{A} I \ll L_t E$$ \hspace{1cm} (A6-8)

$I$ – current in the tether [A]

For the aluminium foil considered in figure 2.5 the Ohmic resistance $R_t$ at 20°C (room temperature) is 61 $\Omega$, Ohmic losses are 0.65 V for a maximum current $I_{\text{oml, max}} = 10.6$ mA being negligible compared to an induced bias voltage of 36 V over the tether.
Neglecting the Ohmic losses the bias between tether and plasma of equation (A6-6) is reduced to the induced EMF \( \frac{d\Delta V}{dl} = E \) resulting in an approximately constant voltage drop along the tether due to the orbital induced EMF.

This is a valid approximation for (worst case resistance high temperature R\(_{\text{t} \text{max}}\)(150°C)) 2500 m long tethers with a thickness \( t \) - 25 \( \mu m \) have a minimum factor 10 difference between induced bias and voltage loss due to tether resistance for the entire orbit range. This has been calculated using the Tether Design tool [TN.4122.19]. For a 1000 m tether 10 \( \mu m \) is sufficient thickness to ignore the voltage drop due to Ohmic losses.

Table A6-2: Aluminium resistive properties

<table>
<thead>
<tr>
<th>Conducting properties</th>
<th>Based on household aluminium foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_0 )</td>
<td>293 K</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>2.74E-08 ( \Omega m )</td>
</tr>
<tr>
<td>( \alpha_{\text{min}} )</td>
<td>3.80E-03 ( K^{-1} )</td>
</tr>
<tr>
<td>( \alpha_{\text{max}} )</td>
<td>4.40E-03 ( K^{-1} )</td>
</tr>
<tr>
<td>( T_{\text{min} \text{- max assumed}} )</td>
<td>-150° +150° ( K )</td>
</tr>
<tr>
<td>( r_{\text{max}} )</td>
<td>4.31E-08 ( \Omega m )</td>
</tr>
<tr>
<td>( r_{\text{min}} )</td>
<td>6.92E-09 ( \Omega m )</td>
</tr>
</tbody>
</table>

References


APPENDIX 7 SYSTEM DEFINITION

In this appendix a definition is given of the entire EDT system with all parameters available as variable inputs. Also the calculation of the centres and moments of inertia for the entire system in orbit are shown. These are applied in the Tether Design tool for system and tether stability analysis.

Table A7.1: EDT and Delfi-1 parameters

<table>
<thead>
<tr>
<th>System</th>
<th>Parameters</th>
<th>units</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TETHER TET</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enforced (30% w) on 1 side Kapton substrate; no coating applied</td>
<td>L&lt;sub&gt;t&lt;/sub&gt;</td>
<td>1000 m</td>
<td>Uniform d&lt;sub&gt;t&lt;/sub&gt; L&lt;sub&gt;t&lt;/sub&gt;</td>
</tr>
<tr>
<td>w</td>
<td>0.03 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>t</td>
<td>1.50E-05 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mass of the deployed tether m&lt;sub&gt;t&lt;/sub&gt;</td>
<td>1.29 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d&lt;sub&gt;l,dragouter&lt;/sub&gt;</td>
<td>1.91E-02 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d&lt;sub&gt;l,OML parameter&lt;/sub&gt;</td>
<td>1.62E-02 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;drag&lt;/sub&gt;</td>
<td>19 m&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C&lt;sub&gt;D&lt;/sub&gt;</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B&lt;sub&gt;all tether&lt;/sub&gt;</td>
<td>33 m&lt;sup&gt;2&lt;/sup&gt;/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>END MASS EM [Heijning&lt;sup&gt;15&lt;/sup&gt;]</td>
<td>1000 kgm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.0583 m</td>
<td>Thin shelled sphere r&lt;sub&gt;b&lt;/sub&gt;</td>
</tr>
<tr>
<td>ρ</td>
<td>0.00083 m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.83 kg</td>
<td></td>
</tr>
<tr>
<td>spacecraft mass m&lt;sub&gt;sc&lt;/sub&gt;</td>
<td>39 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;dragSC&lt;/sub&gt;</td>
<td>0.29 m&lt;sup&gt;2&lt;/sup&gt;</td>
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<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;total&lt;/sub&gt;</td>
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<td></td>
</tr>
<tr>
<td>C&lt;sub&gt;D&lt;/sub&gt;</td>
<td>2.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B&lt;sub&gt;all_sc&lt;/sub&gt;</td>
<td>0.016 m&lt;sup&gt;2&lt;/sup&gt;/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRAVITY GRADIENT BOOM GGB [SPC.4118.01]</td>
<td>0.05 m</td>
<td>7.735 m</td>
<td>Solid cylinder</td>
</tr>
<tr>
<td>d&lt;sub&gt;GGB&lt;/sub&gt;</td>
<td>2.55 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L&lt;sub&gt;GGB&lt;/sub&gt;</td>
<td>0.387 m&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gravity gradient boom mass m&lt;sub&gt;GGB&lt;/sub&gt;</td>
<td>0.33 m&lt;sup&gt;2&lt;/sup&gt;/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tip GGB [SPC.4118.01]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a,b,c</td>
<td>0.125 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gravity gradient boom tip mass m&lt;sub&gt;tip&lt;/sub&gt;</td>
<td>2 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B&lt;sub&gt;all_tip&lt;/sub&gt;</td>
<td>0.022 m&lt;sup&gt;2&lt;/sup&gt;/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;drag_tip&lt;/sub&gt;</td>
<td>0.02 m&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>45.6 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&lt;sub&gt;drag&lt;/sub&gt;</td>
<td>19.81 m&lt;sup&gt;2&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B&lt;sub&gt;all&lt;/sub&gt;</td>
<td>0.95 m&lt;sup&gt;2&lt;/sup&gt;/kg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>15</sup> All design parameters have variable input options in the Tether Design Tool [TN.4122.19]

<sup>16</sup> Assuming a constant tether cross-sectional area and constant density the specific tether density ρ<sub>t</sub> [kgm<sup>-1</sup>] is determined by ρ<sub>t</sub> = ∑<sub>i</sub> ρ<sub>i</sub>A<sub>i</sub>

ρ <sup>–</sup> tether material density [kgm<sup>-3</sup>]

ρ = ρ<sub>i</sub>A<sub>i</sub>
Centres of the System

The centre of mass c.m. is the point of the system where when a net force is applied the resulting motion is a translation of the system, no rotation occurs. The centre of mass of the system is calculated as the average location of subsystems weighted by their mass [Gere]

$$\bar{z}_{\text{cm}} = \frac{\sum m_i z_i}{\sum m_i} = \frac{m_w \frac{1}{2} z_w + m_{\text{GB}} (z_w + \frac{1}{2} z_{\text{GB}}) + m_{\text{tip}} (z_w + z_{\text{GB}} + \frac{1}{2} z_{\text{tip}}) + m_r \frac{1}{2} z_r + m_b (z_r + \frac{1}{2} z_b)}{m_w + m_{\text{GB}} + m_{\text{tip}} + m_r + m_b}$$  \hspace{1cm} (A7-1)

For orbit simulations the system is modelled as a point mass located at the c.m. of the system with the position of the c.m. \( r_{\text{cm}} \) located at

$$r_{\text{cm}} = \frac{m_w r_w + m_{\text{GB}} r_{\text{GB}} + m_{\text{tip}} r_{\text{tip}} + m_r r_r + m_b r_b}{m_w + m_{\text{GB}} + m_{\text{tip}} + m_r + m_b}$$  \hspace{1cm} (A7-2)

The centre of aerodynamic and solar pressure of the entire system, c.a.p. and c.s.p., are the points where sum of aerodynamic forces or the sum of radiation pressure forces act on the system producing a translation of the object, no rotation. The centre of aerodynamic pressure [see section 2.3.3] of the system weighted by area

$$\bar{z}_{\text{c.a.p.}} = \frac{\sum A_i z_i}{\sum A_i} = \frac{z_w \frac{1}{2} z_w + d_{\text{GB}} L_{\text{GB}} (z_w + \frac{1}{2} z_{\text{GB}}) + z_{\text{tip}} (z_w + z_{\text{GB}} + \frac{1}{2} z_{\text{tip}}) + \pi r_b^2 \frac{1}{2} z_r + \pi r_b^2 (z_r + \frac{1}{2} z_b)}{A_w + A_{\text{GB}} + A_{\text{tip}} + A_r + A_b}$$  \hspace{1cm} (A7-3)

The centre of solar radiation pressure of the system weighted by reflectivity

$$\bar{z}_{\text{c.s.p.}} = \frac{\sum A_i (1 + \bar{f}) z_i}{\sum A_i (1 + \bar{f})} = \frac{z_w \frac{1}{2} z_w (1 + \bar{f}_w) + d_{\text{GB}} L_{\text{GB}} (1 + \bar{f}_{\text{GB}}) (z_w + \frac{1}{2} z_{\text{GB}}) + z_{\text{tip}} (1 + \bar{f}_{\text{tip}}) (z_w + z_{\text{GB}} + \frac{1}{2} z_{\text{tip}}) + \pi r_b^2 (1 + \bar{f}_r) \frac{1}{2} z_r + \pi r_b^2 (1 + \bar{f}_r) (z_r + \frac{1}{2} z_b)}{A_w (1 + \bar{f}_w) + A_{\text{GB}} (1 + \bar{f}_{\text{GB}}) + A_{\text{tip}} (1 + \bar{f}_{\text{tip}}) + A_r (1 + \bar{f}_r) + A_b (1 + \bar{f}_b)}$$  \hspace{1cm} (A7-4)

\( \bar{f} \) — material reflection coefficient specular reflection only

Moments of Inertia of the System

Table A7-2: Subsystem moments of inertia

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Model</th>
<th>Mol [Gere]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC and TIP</td>
<td>solid block</td>
<td>( I_{xx} = \frac{1}{12} m \left(x^2 + z^2\right) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( I_{yy} = \frac{1}{12} m \left(y^2 + z^2\right) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( I_{zz} = \frac{1}{12} m \left(x^2 + y^2\right) )</td>
</tr>
<tr>
<td>EDT</td>
<td>uniform rod</td>
<td>( I_{yy} = \frac{1}{12} mL^2 )</td>
</tr>
<tr>
<td>EM - GAS</td>
<td>thin shell sphere</td>
<td>( I_{yy} = \frac{2mr^2}{3} )</td>
</tr>
<tr>
<td>GGB</td>
<td>Solid cylinder</td>
<td>( I_{xx,yy} = \frac{1}{12} m \left(3r^2 + L^2\right) )</td>
</tr>
</tbody>
</table>

References

APPENDIX 8 EQUATIONS OF MOTION

In this appendix the gravity gradient stabilised equations of motion are given. Using the Lagrange equations the tether equations of motion are also derived for both in plane and out of plane motion.

Linearised Equations of Motion for Passive Gravity Gradient Stabilisation

\[ T_{DIST_x} = I_x \ddot{\phi} + 4 \omega^2 \left( I_y - I_z \right) \phi - \omega \left( I_x + I_z - I_y \right) \psi \]
\[ T_{DIST_y} = I_y \ddot{\theta} + 3 \omega^2 \left( I_z - I_x \right) \theta \]
\[ T_{DIST_z} = I_z \ddot{\psi} + \omega^2 \left( I_y - I_x \right) \psi + \omega \left( I_x + I_z - I_y \right) \phi \]

(A8-1)

Characteristic equation pitch motion \( \theta \) about \( y \)-axis using Laplace transformation

\[ s^2 + 3 \omega^2 \left( \frac{I_x - I_z}{I_y} \right) = 0 \] with roots \( \sqrt{\frac{3(I_z - I_x)}{I_y}} \)

(A8-2)

The amplitude of the oscillation \( C (T_{dy}/(I_x-I_y)) \div T_{dy} \ ; \theta \)

\[ C = \frac{T_{dy}}{3 \omega^2 (I_x-I_y)} \]

(A8-3)

Tether Equations of Motion

Using the equation of Lagrange the complete set of differential equations describing the motion of the tether is derived. These equations of motion are limited to describing the libration modes of the tether as a rigid tether is assumed.

**In Plane Motion:** \( \phi = 0 \)

Energy of \( m_2 \) with respect to \( m_1 \)

\[ T = \frac{1}{2} m_2 V \quad V = \frac{1}{2} m_2 \left[ i^2 + l^2 (\dot{\theta} - \omega_2)^2 \right] \]

\[ V = \frac{1}{2} m_2 \omega_2 l^2 (1 - 3 \cos^2 \theta) \]

(A8-4)

Lagrange equations of motion are described as

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = \frac{\partial T}{\partial \dot{q}_i} - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} = Q_i \]

(A8-5)

With generalised coordinates

\[ q_1 = \theta \]
\[ q_2 = l \]

\[ \ddot{\theta} + \frac{l}{m_2} (\dot{\theta} - \omega_2)^2 + 3 \omega_2 \sin \theta \cos \theta = \dot{\theta} + 2 \frac{l}{m_2} (\dot{\theta} - \omega_2)^2 + \frac{3}{2} \omega_2 \sin 2 \theta = \frac{Q_\theta}{m_2 l^2} \]

\[ \ddot{l} (\dot{\theta} - \omega_2)^2 + 2 a_2 l (1 - 3 \cos^2 \theta) = \frac{Q_l}{m_2} = -\frac{T}{m_2} \]

(T – tether tension [N]

For a deployed tether the operational tension for in plane motion is

\[ T = -Q_l = m_2 l a_2 \left( 2 \dot{\theta} + 3 \frac{\dot{l}}{l} \right) \]

(A8-6)

These results have been verified using [Leamy]
In Plane and Out of Plane Motion

\[ T = \frac{1}{2} m_v \dot{v} = \frac{1}{2} m_v \left[ i^2 + l^2 (\dot{\theta} - \omega_o)^2 \cos^2 \phi + \dot{\dot{\phi}} l^2 \right] \]  
(A8-8)

\[ V = \frac{1}{2} m_v \omega_o^2 l^2 (1 - 3 \cos^2 \theta \cos^2 \phi) \]

With generalised coordinates

\[ q_1 = \theta \]
\[ q_2 = \phi \]
\[ q_3 = l \]

\[ \dot{\theta} + 2 \frac{i}{l} (\dot{\theta} - \omega_o) \phi \tan \phi + 3 \omega_o^2 \sin \theta \cos \theta \cos \phi - \dot{\phi} + 2 \frac{i}{l} (\dot{\theta} - \omega_o) \phi \tan \phi + \frac{3}{2} \omega_o^2 \sin 2\theta = \frac{Q_o}{m_j l^2 \cos \phi} \]

\[ \dot{\phi} + 2 \frac{i}{l} \phi + (\dot{\theta} - \omega_o)^2 \cos \phi \sin \phi + 3 \omega_o^2 \cos^2 \theta \sin \phi \cos \phi = \ddot{\theta} + 2 \frac{i}{l} \dot{\phi} + \frac{1}{2} (\dot{\theta} - \omega_o)^2 \sin 2\phi + \frac{3}{2} \omega_o^2 \cos^2 \theta \sin 2\phi = \frac{Q_o}{m_j l^2} \]  
(A8-9)

\[ \ddot{\phi} - l (\dot{\theta} - \omega_o)^2 \cos \phi + \omega_o^2 l (1 - 3 \cos^2 \theta \cos^2 \phi) = \frac{Q_o}{m_j} = - \frac{T}{m_j} \]

For a deployed tether the operational tension subsequently is

\[ \ddot{\theta} - 2 (\dot{\theta} - \omega_o) \phi \tan \phi + \frac{3}{2} \omega_o^2 \sin 2\theta = \frac{Q_o}{m_j l^2 \cos \phi} \]

\[ \ddot{\phi} + 2 \frac{i}{l} \phi + 3 \omega_o^2 \cos^2 \phi \sin \phi = \frac{Q_o}{m_j l^2} \]

\[ \ddot{\phi} - l (\dot{\theta} - \omega_o)^2 \cos \phi = \frac{Q_o}{m_j} = - \frac{T}{m_j} \]  
(A8-10)

These results have been verified with [Beletsky; Pascal; Pelaez], equation (A8-9) linearised for small angles results in the following simplified set of equations of motion

\[ \ddot{\phi} + 2 \frac{i}{l} \phi + 4 \omega_o^2 \phi = \frac{Q_o}{m_j} \]  
(A8-11)

\[ \ddot{\phi} - 3 \phi = \frac{Q_o}{m_j \omega_o^2 l} \]

No current or other perturbing forces in the system reduces to the conservative GG stabilisation similar to (A8-1)

\[ \theta + 3 \dot{\theta} = 0 \]

\[ \ddot{\phi} + 4 \dot{\phi} = 0 \]  
(A8-12)

Generalised Forces

Non-conservative forces acting on the tether and the end masses are the deployment force and the electrodynamic Lorentz force \( F_i \) and \( F_{ad} \) and \( F_s \). The deployment force is assumed to act at \( m_e \) end and that the magnetic field dipole axis coincides with the rotation axis of the earth so use can be made of the following force equations.

\[ \begin{bmatrix} Q_o \\ Q_s \\ Q_t \end{bmatrix} = \begin{bmatrix} -F_{ad} - F_s - BIL \cos i \\ BIL \cos (\phi + \omega_o) \sin i \\ -T \end{bmatrix} \]  
(A8-13)

References


APPENDIX 9 MICROMETEOROID AND ORBITAL DEBRIS RISK

In this appendix the use of the Poisson distribution for calculating the risk of impact by micrometeoroids and orbital debris is given. The general Poisson distribution is adapted taking various sizes of debris into account of which not all sizes result in a critical tether impact. Two geometric models are used describing the projected area of the tether exposed to the debris fluxed.

Poisson Distribution

The Poisson distribution determines the chance $p$ of an event occurring for uncorrelated events with an assumed known average rate of events over a fixed time interval and is written as

$$p(k, \lambda t) = \frac{1}{k!} (\lambda t)^k e^{-\lambda t}$$  \hspace{1cm} (A9-1)

$k$– number of events
$\lambda$– average number/unit of time
$t$– time
$\lambda t$– shape parameter

The probability of one or more impacts occurring during time t is

$$p(k \geq 1, \lambda t) = 1 - p(0, \lambda t) = 1 - e^{-\lambda t}$$  \hspace{1cm} (A9-2)

Using the flux density $F$ the average number of particles larger than mass $m$ per unit of time equals

$$\lambda = F(m)A$$  \hspace{1cm} (A9-3)

$F(m)$ – average flux density of particles of mass $> m$; [#particles s$^{-1}$ m$^{-2}$]
$A$ – area of interest [m$^2$]

$$p(k, F_c(m)At) = \frac{1}{k!} (F_c(m)At)^k e^{-F_c(m)At}$$  \hspace{1cm} (A9-4)

$F_c$ – cumulative (surface) area flux [m$^{-2}$ yr$^{-1}$ (2πsr)$^{-1}$ m$^{-2}$ yr$^{-1}$]

Both M and OD fluxes combined $F_{m+d}(m) = F_m(m) + F_d(m)$

$$p(k, F(m)At) = \frac{1}{k!} (F_{m+d}(m)At)^k e^{-F_{m+d}(m)At}$$  \hspace{1cm} (A9-5)

$F_d$ – average debris flux [m$^{-2}$ yr$^{-1}$]

Effective Projected Diameter Tape Tether

For a tape tether the chance of a cut occurring is a function of the angle of the impacting particle. The projected diameter is used with tape tether dimensions $w, t$ [Kruijff]

$$d_{proj} = w \cos \delta + t \sin \delta$$  \hspace{1cm} (A9-6)

with $\delta$ ranging from [0-1/2π]

Anz-Meador geometric model [NASA/JSC ISTI/CNR], see [Tether Risk Analysis(2.0)], source [Pardani; Oishi]

$$P_{cut}(d) = (1 - 2\alpha[1.0 + \beta]) \Theta(\beta - \alpha)$$  \hspace{1cm} (A9-7)
\( \alpha \) - 'gouging factor'

\[
\alpha = \frac{d - d_{in}}{2d}
\]  
(A9-8)

\[
\beta = \frac{d}{d_i}
\]

\[
\Theta = \begin{cases} 
0 & \beta - \alpha < 0 \\
1 & \beta - \alpha > 0
\end{cases}
\]

\[
A(d) = L_i (d_i + d)
\]

\[
A_{mod。(d)} = P_1 (d) A_2 (d) = L_i (d_{in} + d)
\]  
(A9-9)

References


This appendix provides an overview of candidate instruments for use onboard the Delfi-1 mission to realise the scientific objectives of the EDT experiment. Also the workings of a Langmuir Probe are shortly outlined to derive instrument performance requirements.

**Orbital Drag Effects on Delfi-1 Satellite Orbit**

Drag will reduce the orbital altitude, leading to changes in the semi major axis (SMA). Typical changes calculated for the Delfi-1 satellite are given in the table below.

Table A10- 1: SMA and orbital period change during 9 months for Delfi-1

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>650 km</th>
<th>700 km</th>
<th>750 km</th>
<th>800 km</th>
<th>850 km</th>
<th>900 km</th>
<th>950 km</th>
<th>1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 ) [m]</td>
<td>7028150</td>
<td>7078150</td>
<td>7128150</td>
<td>7178150</td>
<td>7228150</td>
<td>7278150</td>
<td>7328150</td>
<td>7378150</td>
</tr>
<tr>
<td>( P_{orb} ) [s]</td>
<td>5864</td>
<td>5926</td>
<td>5989</td>
<td>6052</td>
<td>6116</td>
<td>6179</td>
<td>6243</td>
<td>6307</td>
</tr>
<tr>
<td>( \Delta SMA ) [N]</td>
<td>4401</td>
<td>2461</td>
<td>1407</td>
<td>741</td>
<td>508</td>
<td>325</td>
<td>217</td>
<td>152</td>
</tr>
<tr>
<td>( \Delta SMA ) [N]</td>
<td>819</td>
<td>434</td>
<td>248</td>
<td>155</td>
<td>104</td>
<td>75</td>
<td>57</td>
<td>45</td>
</tr>
<tr>
<td>( \Delta SMA ) [N]</td>
<td>139</td>
<td>88</td>
<td>61</td>
<td>45</td>
<td>35</td>
<td>28</td>
<td>22</td>
<td>18</td>
</tr>
</tbody>
</table>

**GPS Receiver**

A number of GPS receivers suitable for operation onboard micro satellites are compared in the table below.

Table A10- 2: Various GPS receivers

<table>
<thead>
<tr>
<th>Designation</th>
<th>SGR-05U</th>
<th>SGR-05P</th>
<th>SGR-10</th>
<th>EURO4</th>
<th>Phoenix-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company</td>
<td>SSTL</td>
<td>SSTL</td>
<td>SSTL</td>
<td>NovAtel</td>
<td>DLR 2004</td>
</tr>
<tr>
<td>Type</td>
<td>Single frequency</td>
<td>Single frequency</td>
<td>Dual frequency</td>
<td>Dual frequency</td>
<td>Single frequency</td>
</tr>
<tr>
<td>Dynamic capability</td>
<td>8 kms(^{-1}); 2 g</td>
<td>8 kms(^{-1}); 2 g</td>
<td>8 kms(^{-1}); 2 g</td>
<td>8 kms(^{-1}); 2 g</td>
<td>8 kms(^{-1}); 2 g</td>
</tr>
<tr>
<td>Position accuracy</td>
<td>m</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Velocity accuracy</td>
<td>ms(^{-1})</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Time accuracy</td>
<td>( \mu s )</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>TTFF</td>
<td>s</td>
<td>60 s warm 9 min cold</td>
<td>60 s warm 9 min cold</td>
<td>90 s warm 7 min cold</td>
<td>2 min warm &lt;30 s hot</td>
</tr>
<tr>
<td>Channels</td>
<td>#</td>
<td>12 channels L1 C/A code</td>
<td>12 channels L1 C/A code</td>
<td>12</td>
<td>12 x 2</td>
</tr>
<tr>
<td>Output frequency</td>
<td>Hz</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Attitude</td>
<td>°</td>
<td>-</td>
<td>-</td>
<td>0.2°</td>
<td>0.4°</td>
</tr>
<tr>
<td>Power consumption</td>
<td>W</td>
<td>0.5 - 0.8@5V</td>
<td>1 @ 3.3V</td>
<td>5.3@28V</td>
<td>4.5</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>°C</td>
<td>0 to +50</td>
<td>-20 to +50</td>
<td>-25 to +50</td>
<td>-40 to +75</td>
</tr>
<tr>
<td>Dimensions</td>
<td>mm</td>
<td>70x45x10</td>
<td>105x65x12</td>
<td>160/295x160x50</td>
<td>208 x 111 x 54</td>
</tr>
<tr>
<td>Mass incl shields</td>
<td>g</td>
<td>40</td>
<td>60</td>
<td>950 (2x50)</td>
<td>980</td>
</tr>
<tr>
<td>antenna</td>
<td>g</td>
<td>12</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qualified for space</td>
<td></td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>√</td>
</tr>
<tr>
<td>Random vibration</td>
<td>g rms</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>
Rad | kRad | 10 | 10 | 10 | 10 | 15
---|-----|----|----|----|----|----
Supply Voltage | V | 5 | 18-38 | 10-36 | 5 |
Data interface | 3.3V TTL UART | 3.3V TTL UART | RS-422, CAN, PPS | RS-232C; RS-422 UART TTL |
Extra components required | Signal amp; RS-485 conv | Signal amp; RS-485 conv | Signal amp; RS-485 conv | Signal amp; RS-485 conv |
Number of antenna | # | 1 | 1 | 1-2 | 2 | 1 |
Availability | | 3 months | | |
Cost | | unknown | unknown | 10000 USD | |
Source | [SSTL] | [SSTL] | [Unwin] | [Gill; Montebruck] |

Extra components [TBC 47]
- power converter
- data interface
- housing
- does the receiver have an integrated microprocessor
- pre amplifier
- RF cables connecting antenna on zenith panel to the receiver

**Turn Counter Types**
Angular position devices consist of [Jongkind]
- Rotary Potentiometer, high power, low cost, low accuracy 0.3%-5%
- Encoders [readout capacitive, magnetic, optics, contact]
  - Absolute measures absolute position
  - Incremental measure the change in angular position
- Electrical Transformers high accuracy, resolver or synchro [more complex signal processing performed on chip], requires input signal
  - RVDT accuracy ± 0.25-0.5% full scale limited angular range ±40°-60°
  - Synchro
  - Resolver

Table A10-3: Angular displacement devices overview

<table>
<thead>
<tr>
<th>Type</th>
<th>Characteristics</th>
<th>Main disadvantage</th>
<th>Main advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potentiometer</td>
<td>Analog output</td>
<td>Lower accuracy and resolution</td>
<td>Cheap simple, low data</td>
</tr>
<tr>
<td>Encoder</td>
<td></td>
<td>Distance output</td>
<td></td>
</tr>
<tr>
<td>Incremental</td>
<td>Speed Direction</td>
<td>Counts turns digital data output</td>
<td>Simple, low data rate, 2-3 data lines</td>
</tr>
<tr>
<td>Absolute</td>
<td>Speed Direction</td>
<td>Counts turns digital data output</td>
<td>Compared to incremental encoder more expensive and higher data rates</td>
</tr>
<tr>
<td>Electrical Transformer</td>
<td></td>
<td>Relatively heavy, complex</td>
<td></td>
</tr>
<tr>
<td>RVDT</td>
<td></td>
<td>operational limits mostly within ±30°; theoretically operate between ±45°</td>
<td>low sensitivity to temperature, primary voltage &amp; frequency variations</td>
</tr>
<tr>
<td>Synchro</td>
<td></td>
<td></td>
<td>Rugged environment</td>
</tr>
<tr>
<td>Resolver</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Tension Transducer Load Rating**

The net force acting on the roller including a margin of 2 for transients is calculated as [Dover Flexo]

\[
\text{Net Force} = 4T \sin \left( \frac{B}{2} \right) \pm W \cos (A)
\]

(A10-1)

With

- \( T \) – maximum web tension [g]
- \( B \) – wrap angle [°]
- \( W \) – roller weight [g]
- \( A \) – angle between tension force \( F_T \) acting on the roller and vertical

**Accelerometer**

Table A10- 4: Accelerometers

<table>
<thead>
<tr>
<th>Dynamic Range</th>
<th>Resolution</th>
<th>Sensitivity</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pm 10 \text{ mg} )</td>
<td>80 ( \mu \text{g} )</td>
<td>0.5 ( \text{Vg}^{-1} )</td>
<td>±20mg 10( \mu \text{g} ) 16 bit ADC \nRange ±2mg ±20mg ±200mg \nYES Triad 442T accelerometer \nSEDS [Wijnans5b] \n3-axis accelerometer 8 Hz sample rate \nRange ±1mg ±5mg ±50mg \nResolution 8.3( \mu \text{g} ) 42( \mu \text{g} ) 0.42 mg</td>
</tr>
<tr>
<td>( \pm 0.085 \text{ mg} )</td>
<td>0.7 ( \mu \text{g} )</td>
<td>2.5 ( \text{Vg}^{-1} )</td>
<td>\nATEx [Wijnans5b] \n3-axis accelerometer 8 Hz sample rate \nRange ±1mg ±5mg ±50 mg \nResolution 8.3( \mu \text{g} ) 42( \mu \text{g} ) 0.42 mg \nToo heavy tether unlikely to fly</td>
</tr>
<tr>
<td>( \pm 1.5 \mu \text{g} )</td>
<td>10 ( \text{ng} )</td>
<td>2780 ( \text{Vg}^{-1} )</td>
<td>TBD 47</td>
</tr>
</tbody>
</table>

**Temperature Sensors**

Table A10- 5: Types of temperature sensors [Jongkind; various Temp Sensors]

<table>
<thead>
<tr>
<th>Type</th>
<th>Range [°C]</th>
<th>Characteristics</th>
<th>Main disadvantage</th>
<th>Main advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTD</td>
<td>Wire wound</td>
<td>Sensitive to strain and shock, react slow, Linearity</td>
<td>\text{expensive}</td>
<td>When linearity is required</td>
</tr>
<tr>
<td>Film</td>
<td>-200 +800</td>
<td>Accurate, repeatable over a wide operating range, maintain stability over years</td>
<td></td>
<td>Accuracy ± 0.06-0.012% at (0°C)</td>
</tr>
<tr>
<td>Thermistors</td>
<td>-250 -300</td>
<td>Accurate over a limited temperature range, high sensitivity, Non linear Resolution better than thermocouple or RTD’s Power source</td>
<td>susceptible to permanent decalibration and self heating errors tendency to drift even if within temp range</td>
<td>High sensitivity required</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>fragile</td>
<td>Accuracy ± 1% at 25°C to ±15% at 0°C</td>
</tr>
<tr>
<td>Thermocouple</td>
<td>-245 +2350</td>
<td>Cheap, Robust, Range Non linear; High temp Self powered</td>
<td>Tendency to drift</td>
<td>High temp required</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Accuracy ± 2°C</td>
</tr>
<tr>
<td>Silicon Temperature Sensors</td>
<td>-55 +125</td>
<td>Not in temp range</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Current to a Langmuir Probe

![Idealised I-V curve with the left curve expanded x10 to show ion current [Chen]](image)

**Figure A10-1:** Idealised I-V curve with the left curve expanded x10 to show ion current [Chen]

Current to a spherical probe at floating potentials

\[
I_e(V) = \frac{1}{4} n_e e \pi r_{LP}^2 \sqrt{\frac{8k_B T_e}{\pi m_i}} \left(1 + \frac{e(V_{LP} - V_p)}{E_{sat}^i}\right) \quad (A10-2)
\]

\( r_{LP} \) – probe radius [m]

Negatively biased probe collects ions according to [Kruijff; Chen]

\[
I_i(V) = n_i e \pi r_{LP}^2 V_i \left(1 + \frac{e(V_{LP} - V_p)}{E_{sat}^i}\right) \quad (A10-3)
\]

\( V_{LP} \) – LP potential [V]

With the ions are at mesosonic (supersonic) speeds in the spacecrafts reference frame and the current is subsequently independent of the particles thermal energies \( kT_i \). Total current collected by the probe in the transition region

\[
I_{tot}(V) = \frac{1}{4} n_e e \pi r_{LP}^2 \sqrt{\frac{8k_B T_e}{\pi m_i}} \left(1 + \frac{e(V_{LP} - V_p)}{E_{sat}^i}\right) \quad (A10-4)
\]

For positive biased probe the current is due to electrons in the electron saturation region

\[
I_e(V) = \frac{1}{4} n_e e \pi r_{LP}^2 \sqrt{\frac{8k_B T_e}{\pi m_e}} \left(1 + \frac{e(V_{LP} - V_p)}{E_{sat}^e}\right) \quad (A10-5)
\]

References


[SSTL-27433] Data Sheet SGR05-U and P GPS Receiver [http://www.SSTL.co.uk](http://www.SSTL.co.uk)


[Wijnans\textsuperscript{ab}] Instruments Past Experiments, technical note, AE4-S02 essay, June 2007

[DELFI.1.TN.4122.15b]
APPENDIX 11 TETHER PROPERTIES

This appendix an overview of material properties and handling loads to be considered for the tether are shown. Important properties for a conductive tether are the materials resistance and mass. Preferably a low specific conductivity material is used having a low mass density. Strength is of less importance as the tension loads in orbit are expected to be low however a tether failure is critical for the mission and adequate margins of safety are required including verification tests. Handling loads are expected to play a more significant role in the tether design. The material properties will also influence tether dynamics through stiffness-elasticity of the material. Thermal and optical properties of the materials predicting how the material behaves under the significant temperature extremes it will experience in orbit are also listed in this appendix. Some characteristics of various substrate materials, adhesives are also listed.

Table A11- 1: Conductive material properties [Kruijff; Jainandunsing; Beletsky; Gere]

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity @23°C [nΩm]</th>
<th>Density ρ [kg/m³]</th>
<th>Specific conductivity [m²Ω·kg⁻¹]</th>
<th>σₚₜ [MPa]</th>
<th>σₚᵣᵢₙ [MPa]</th>
<th>E [GPa]</th>
<th>Ductility % elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>17</td>
<td>8933</td>
<td>6585</td>
<td>230-380</td>
<td>55-330</td>
<td>110-120</td>
<td>++</td>
</tr>
<tr>
<td>Aluminium</td>
<td>27.4</td>
<td>2700</td>
<td>13500</td>
<td>60-75</td>
<td>26</td>
<td>62-76</td>
<td>++ 39-60%</td>
</tr>
<tr>
<td>Beryllium (toxic)</td>
<td>32.5</td>
<td>1850</td>
<td>16630</td>
<td></td>
<td></td>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Beryllium-Copper</td>
<td>32</td>
<td>8830</td>
<td>3539</td>
<td>830</td>
<td>760</td>
<td>120</td>
<td>--</td>
</tr>
<tr>
<td>Silver</td>
<td>15.9</td>
<td>10500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>++</td>
</tr>
<tr>
<td>Steel</td>
<td>97</td>
<td>7900</td>
<td></td>
<td>200</td>
<td>280-700</td>
<td>190-210</td>
<td>++</td>
</tr>
<tr>
<td>Titanium</td>
<td>40</td>
<td>4600</td>
<td>900-970</td>
<td>760-900</td>
<td>100-120</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Availability</th>
<th>Cost</th>
<th>Space</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>++</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>++</td>
<td>++</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Beryllium (toxic)</td>
<td>--</td>
<td>-</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Beryllium-Copper</td>
<td>--</td>
<td>-</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>--</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>--</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Designing a tape tether as thin as possible requires the handling-manufacturing loads to be taken into account to assure the final tether design is producable and manageable. To derive a handling load requirement various foil products and their estimated ultimate strength have been gathered.

Table A11- 2: Aluminium foil Handling loads requirement

<table>
<thead>
<tr>
<th>Type-Manufacturer</th>
<th>lᵢ [µm]</th>
<th>wᵢ [mm]</th>
<th>Tᵢᵢ [N]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDDE</td>
<td>38</td>
<td>30</td>
<td>85</td>
<td>[Pearson]</td>
</tr>
<tr>
<td>Household Foil</td>
<td>15</td>
<td>300</td>
<td>342</td>
<td></td>
</tr>
<tr>
<td>Impol</td>
<td>8</td>
<td>250</td>
<td>152</td>
<td></td>
</tr>
<tr>
<td>Aluminium Foil Strip</td>
<td>60</td>
<td>10</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>5</td>
<td>2.3</td>
<td><a href="http://www.cnaljh.com/en_slb.html">http://www.cnaljh.com/en_slb.html</a></td>
</tr>
<tr>
<td>Alcoil aluminium Foil</td>
<td>6</td>
<td>30-60</td>
<td>13.6-27</td>
<td><a href="http://www.alcoil.com">http://www.alcoil.com</a></td>
</tr>
<tr>
<td>Hangzou</td>
<td>5</td>
<td>100</td>
<td>38</td>
<td><a href="http://www.alibaba.com/product-gs/407065735/thin_aluminium_foil_strip.html">http://www.alibaba.com/product-gs/407065735/thin_aluminium_foil_strip.html</a></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>76</td>
<td>40</td>
<td><a href="http://www.pharmaceuticalfoil.com/light-gauge-converter-foli.htm">http://www.pharmaceuticalfoil.com/light-gauge-converter-foli.htm</a></td>
</tr>
</tbody>
</table>

The foil rolling process creates a highly polished finish. To produce thin foil < 12-50 µm economically two layers are normally rolled together and then separated, the inner surfaces taking on a mat finish. Single rolled aluminium foil can also be made in thinner gauges and produces a bright finish on both sides [Alufoils]. Bare aluminium optical properties range from [Kruijff]

\[
\alpha_{alu} = 0.2 – 0.55 \quad \text{[oxidised bare aluminium]} \quad \alpha_{alu} \quad 0.03 – 0.55 \quad \text{[TBD 34]}
\]

\[
\varepsilon_{alu} = 0.03 – 0.2
\]

\[
\omega_{alu} / \varepsilon_{alu} = 2.4 – 11
\]
Kapton® substrate optical properties [Wertz] [TBD 35]

\[ \alpha_{\text{sub}} \approx 0.38 - 0.45 \] EOL

\[ \varepsilon_{\text{sub}} \approx 0.03 - 0.67 \]

Table A11-3: Materials thermal properties [Matweb]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>( \alpha )</th>
<th>( \varepsilon )</th>
<th>CTE linear ( \mu \text{m-m}^{-1}\text{°C}^{-1} )</th>
<th>( c_p ) ( \text{[Jkg}^{-1}\text{K}^{-1}] )</th>
<th>( k ) ( \text{[Wm}^{-1}\text{K}^{-1}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL General</td>
<td>0.2-0.3</td>
<td></td>
<td>24</td>
<td>900</td>
<td>210</td>
</tr>
<tr>
<td>AL 1000</td>
<td>0.04-0.05</td>
<td></td>
<td>23.6-25.5</td>
<td>900-904</td>
<td>218-243</td>
</tr>
<tr>
<td>Kapton\textsuperscript{®} HN50</td>
<td>0.38-0.45</td>
<td>0.03-0.67</td>
<td>20</td>
<td>1090</td>
<td>0.12</td>
</tr>
<tr>
<td>Kapton\textsuperscript{®} VN50</td>
<td>0.38-0.45</td>
<td>0.03-0.67</td>
<td>20</td>
<td>1090</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Types of dielectric substrates available are

- Polyimide films; thickness 7.5 \( \mu \text{m} \) to 125 \( \mu \text{m} \) widths up to 1.5 m
- Polyester films: lower temperature capabilities and less dimensional stability compared to polyimide films; 6.3 \( \mu \text{m} \)
- Aramids: very hygroscopic up to 13% moisture absorption possible 50 \( \mu \text{m} \)
- Reinforced composites: dimensional stability excellent, high temp resistance, low moisture absorption much less flexible and lower tear initiation strength than non enforced substrates and relatively expensive
- Fluorocarbons: poor dimensional stability at higher temperatures

Common adhesives used in printed circuit board (PCB) laminate foils (flexible electrical laminates) are

- Polyester adhesives (sheet or roll products)
  - Low temperature thermoplastic polymers
- Epoxy (sheet or roll products) low outgassing [NASA outgassing] often used
- Acrylic (sheet products)
  - High temperature thermoplastic polymers
- Phenolies not used for dynamic applications (flexibility limited)
- Polyimide
  - Highest thermal properties up to 370°C, low bond strength and less flexible than acrylics
- Fluorocarbons
  - Thermoplastic material, good flexibility high temperature

Coatings to Prevent Atomic Oxygen (AO) Erosion

Below the erosion due to Atomic Oxygen (AO) is shown for materials used in space applications. As can be seen erosion effects decrease with increasing altitude being considered a design issue for materials in orbits below 700-750 km. The effect of applying a protective coating (700 angstrom) is shown to reduce the mass loss due to AO for Kapton\textsuperscript{®} for a number of types of coating in de right figure.

![Figure A11-1: AO Erosion for various materials on panels facing sun and effect of protective coatings [Silverman]](image-url)
Two manufactures of coatings that meet (general) requirements for a bare tether are [Kruijff]
- Triton Inc. ProSeds tether
- Aeroplas NASA SBIR phase I contract for investigating coatings for electrodynamic space tethers produce $\alpha/\varepsilon \approx 1$

TOR$^\text{TM}$ polymer based resins developed by NASA used to produce films, coatings, threads and fabrics. Phosphine oxide containing polymers when exposed to AO the phosphine oxide forms a protective oxide layer on the base polymer decreasing AO erosion by a factor 10-15 [Kruijff; Schuler].

TOR-LM$^\text{TM}$ [Schuler]:
- $\alpha$ 0.2 - 0.41
- $\varepsilon$ 0.64 - 0.76
- $\alpha/\varepsilon$ 0.312 - 0.263
- AO Yield 1-2e-25
- Thermal expansion similar to polymides $10^{-5}$ [ppm °C]
- Outgassing TML 2.32% CVCM 0.01%
- R - 1.6e16 $\Omega$ per cm volumetric resistance
- Tear Strength 0.02 [lbf]

The TOR-BP$^\text{TM}$ conductive coating consisting of a biphenyl resin to coat wires conductive or non conductive when flexibility is of importance [Kruijff].
- $\alpha/\varepsilon$ 0.95 – 1.10
- 0.35 mil on 1100 Al $\alpha$-0.844 $\varepsilon$-0.832
- 0.4 mil on 1100 Al $\alpha$-0.879 $\varepsilon$-0.835
- Surface resistivity film 2.46e5 [$\Omega$m$^{-2}$]
- AO and UV resistant
- more flexible than TOR-LM$^\text{TM}$

In the table below an overview of various types of adhesive available is shown.
Table A11- 4: Adhesives [IPC-FC-233A]

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature resistant</th>
<th>Electrical properties</th>
<th>Adhesion</th>
<th>Flexibility</th>
<th>Cost</th>
<th>Moisture absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>Fair</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Low</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Acrylic</td>
<td>Very good</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
<td>High</td>
<td>Good</td>
</tr>
<tr>
<td>Modified Epoxy</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Moderate</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Polyimide</td>
<td>Excellent up to 370 °C</td>
<td>Good</td>
<td>Very good</td>
<td>Fair</td>
<td>Very high</td>
<td>Poorly</td>
</tr>
<tr>
<td>Fluor Carbon</td>
<td>Very good</td>
<td>Good</td>
<td>Very good</td>
<td>Excellent</td>
<td>Moderate</td>
<td>Excellent</td>
</tr>
<tr>
<td>Butyral/phenolic</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Moderate</td>
<td>Fair</td>
<td>Fair</td>
</tr>
</tbody>
</table>

In the table below the total mass loss (TML) and collected volatile condensable material (CVCM) properties of some materials is listed. These indicate the amount of material and contaminants a material produces due to outgassing effects in space. Materials selected for a mission must adhere to the TML and CVCM requirements to reduce the risk of (optical) systems failing due to contaminants being outgassed.

Table A11- 5: Total Mass Loss (TML) and Collected Volatile Condensable Material CVCM percentages for Kapton$^\text{®}$, Mylar$^\text{®}$ and adhesives [Tribble]

<table>
<thead>
<tr>
<th>Material</th>
<th>TML [%]</th>
<th>CVCM [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton$^\text{®}$</td>
<td>0.77</td>
<td>0.02</td>
</tr>
<tr>
<td>Adhesives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ablebond$^\text{®}$</td>
<td>0.19</td>
<td>0.00</td>
</tr>
<tr>
<td>RTV$^\text{®}$</td>
<td>0.10</td>
<td>0.02</td>
</tr>
<tr>
<td>Scotchweld$^\text{®}$</td>
<td>1.25</td>
<td>0.08</td>
</tr>
<tr>
<td>Solithane$^\text{®}$</td>
<td>0.66</td>
<td>0.04</td>
</tr>
<tr>
<td>Trabond$^\text{®}$</td>
<td>1.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>

References
[AluFoils]  
http://www.aluminumfoils.com/  
http://allfoils.thomasnet.com/item/aluminum/aluminum-foil/pn-1001?


[IPC-FC-233A] PCB Adhesives


APPENDIX 12 TETHER REEL DIMENSIONS

In this appendix the calculation of the reel/spool dimensions is outlined. These are used to calculate the storage dimensions of the tether on the reel. The method was derived from [Thoen]

\[ V_{\text{tether}} = L \cdot \rho \]  \hspace{1cm} (A12-1)
\[ V_{\text{axel}} = \frac{1}{4} \pi D_a^2 L_a \]  \hspace{1cm} (A12-2)

\[ D_a \quad \text{– reel axel diameter [m]} \]
\[ L_a \quad \text{– reel axel length [m]} \]

\[ D_R = \sqrt{\frac{4 \cdot (V_{\text{tether}} + V_{\text{axel}})}{\pi L_a}} \]  \hspace{1cm} (A12-3)

\[ D_R \quad \text{– reel outer diameter [m]} \]

The number of windings \( N \) of the tether on the reel is calculated as

\[ N = \frac{L_t}{\pi \left( \frac{D_a + D_R}{2} \right)} \]  \hspace{1cm} (A12-4)

References

APPENDIX 13 THERMAL MODEL

To determine the steady state temperature extremes of the tether in orbit a thermal model has been developed calculating the solar, albedo and IR fluxes on the tether for the Delfi-1 orbit range. In this appendix the basis of the model is outlined consisting of the geometric calculations including view factors and environmental radiation fluxes. For this model the following assumptions have been made

- Tether is oriented along nadir-zenith direction (SC-tether geometry as viewed by the sun and Earth constant)
- Isothermal tether, no temperature gradients assuming this is valid for thin Kapton® films and non enforced aluminium tether
- Albedo and Solar radiation same spectrum ($\alpha_s = \alpha_a$)
- No Penumbra only Umbra shadow cone in eclipse
- Uncertainty margin of ±15 K [ECSS²] design phase A
- Thermal connection between SC structure and tether is conductive [REQ.4122.STS.04] - 2 nodes connecting the SC and tether; SC will act as a heat sink / source for the tether limiting extreme temperatures

Geometrical Mathematical Model (GMM)

Input:
- Geometry
- SC orbit altitude

Output:
- Sun out of plane angle $\beta$ extremes
- Eclipse duration
- View factors F calculations
- Environmental fluxes
- Conductive Coupling: Bus and payload shall have a thermal conductive connection

Sun Out of Plane Angle

Defining the Sun out of plane angle $\beta$ as being the angle between the solar vector of the Sun and the orbit plane of the SC. Varying the angle $\beta$ between min and max values will give range of environmental heat fluxes the tether will encounter in orbit.

The absolute value of the $\beta$ angle varies from 0° to orbit inclination + maximum declination of the sun $\varepsilon$ (23.5°), for orbits with $I > 66.5°$ $\beta$ ranges from 0-90°[Cosmo]. For the hot case with the tether in the full sun $\beta$ - 90° and for the cold case the orbit with $\beta$ - 0°. For thermal orbit geometry the sub solar point is located at true anomaly $\theta_s = 0°$. 

Figure A13- 1: Flux geometry
Eclipse Data

The angles at which eclipse occurs can be calculated as follows [Wertz]

\[ \theta_{\text{eclipse\_begin}} = 180 - a \sin \left( \frac{R_E}{R_E + h} \right) \]
\[ \theta_{\text{eclipse\_end}} = 180 + a \sin \left( \frac{R_E}{R_E + h} \right) \]

\[ T_{\text{ecl}} = P \frac{\Phi}{2\pi} \text{ with } \cos \left( \frac{\Phi}{2} \right) = \frac{\cos \rho_E}{\cos \beta} \]

\( \Phi/2 \) – half rotation angle corresponding to the eclipse duration [rad]

\( \beta \) – Sun out of plane angle [rad]

\( \rho_E \) – angular radius Earth [rad]

Angular radius of Earth: \( \rho_E = a \sin \left( \frac{R_E}{r} \right) \)

Table A13-1: Eclipse data for \( \beta - 0^\circ \)

<table>
<thead>
<tr>
<th>altitude h</th>
<th>650000 m</th>
<th>1000000 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius r</td>
<td>7028150 m</td>
<td>7378150 m</td>
</tr>
<tr>
<td>period P</td>
<td>98 min</td>
<td>105 min</td>
</tr>
<tr>
<td>angular radius Earth ( \rho_e )</td>
<td>65.16 °</td>
<td>59.82 °</td>
</tr>
</tbody>
</table>

| \( \theta_{\text{eclipse\_begin}} \) | 114.8 ° | 120.2 ° |
| \( \theta_{\text{eclipse\_end}} \) | 245.2 ° | 239.8 ° |

| \( \Delta \theta \) in eclipse | 130.3 ° | 119.6 ° |
| part orbit | 0.36 | 0.33 |
| max time in eclipse | 35.4 min | 34.9 min |

The Delfi-1 orbit range produces the following eclipse conditions [SLR 133]

Orbital Period P: 97.7 – 105.1 min

Maximum Eclipse Time: 34.9 – 35.4 min

Earth View Factors \( F \)

Earth view factor \( F \) is a function of the angle between the surface normal vector and the solar vector, albedo is assumed to only occur in the daylight time of the orbit. View factor \( F \) of infinitesimal sphere viewing finite sphere [Wertz]

\[ F_{\text{sphere}} = \frac{1 - \cos \rho_E}{2} = \frac{1 - \sqrt{1 - F_{\text{down}}}}{2} \]

View factors for a tether in LEO are taken from [Cosmo]

\[ F_{\text{side}} = \left( \rho_E - \sin \rho_E \cos \rho_E \right) \]

\[ F_{\text{bottom}} = \sin^2 \rho_E = \left( \frac{R_E}{r} \right)^2 \]

\[ F_{\text{up}} = 0 \]

Figure A13-1: Earth View Factors Tether [Cosmo]
Table A13- 2: Geometry and view factors tether

<table>
<thead>
<tr>
<th>Orbit altitude h</th>
<th>650 km</th>
<th>1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_e$</td>
<td>1.13</td>
<td>1.04</td>
</tr>
<tr>
<td>$F_{\text{down}}$</td>
<td>0.824</td>
<td>0.747</td>
</tr>
<tr>
<td>$F_{\text{side}}$</td>
<td>0.241</td>
<td>0.194</td>
</tr>
<tr>
<td>$F_{\text{up}}$</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>$F_{\text{sphere}}$</td>
<td>0.29</td>
<td>0.249</td>
</tr>
</tbody>
</table>

Environmental Fluxes

Sources and sinks of radiation to and from a spacecraft in LEO are:
- Solar radiation flux
- IR Earth radiation flux
- Albedo radiation flux
- Radiation to space from the SC and EDT
- Internal heat sources
- Aero-thermal heat Fluxes

Solar radiation varies with solar activity Earth around the sun. Albedo radiation depends on part of the Earth that is illuminated by the Sun and seen by the spacecraft (clouds, ocean and surface properties) and is a function of the sun out of plane angle $\beta$ and the solar-zenith angle $\alpha_s$ of the surface to the solar vector. Earth’s infrared (IR) radiation is more constant with its largest diurnal variations occurring over deserts amounting to 20% [ECSS]. Aerodynamic heating, a convective heat source can be neglected for orbits above 140 km [Cosmo]. Other environments to be considered are the pre-launch environment, ascent heating and ascent free molecular heating (after fairing jettisoning). These will be neglected in this report, but the model will be designed to handle variable conditions and thus they can be included at a later time.

The amount of solar energy absorbed by the satellite depends on the amount of area of the tether or SC that is exposed to the sunlight $A_s$, the material’s absorption properties ($\alpha$). The solar energy absorbed is equal to

$$Q_s = k_s \alpha_s A_s S_s$$  \hspace{1cm} (A13-7)

**Solar Heat Flux Density**

$$S_s = \frac{P_s}{4\pi r_s^2}$$  \hspace{1cm} (A13-8)

- $S_s$ – solar heat flux density 1366 [Wm$^{-2}$]
- $P_s$ – power output of the sun $3.84 \times 10^{26}$ [W]
- $r_s$ –average distance from the sun taken at 1 A.U.[m]

The amount of albedo radiation absorbed equals [Pisacane$^2$]

$$Q_a = k_a \alpha_a A_a aFS_s \cos \phi_1 \cos \theta_s$$  \hspace{1cm} (A13-9)

Angular deviation from subsolar point
- $\phi_1$ – ecliptic angle assumed $0^\circ$
- $\theta_s$ – orbit angle w.r.t. subsolar point
Albedo Flux

\[ S_a = S_a F \]  \hspace{1cm} (A13-10)

- Earth reflectance 0.34\(^{17}\) [-] [Wertz]
- Earth view factor

Infrared Flux

The Earth itself is an energy source and is a source of heat transfer from the Earth’s atmosphere to the satellite in a LEO. The Earth emits approximately a maximum of 258 Wm\(^{-2}\) and a minimum of 216 Wm\(^{-2}\) in eclipse conditions. The intensity of the IR radiation is a sinus distribution between these two extremes. The received IR radiation from the planet for a satellite at an altitude h km is given as

\[
S_{IR\text{max}} = 258 \left( \frac{R_E}{R_E + h} \right)^2 \sin^2 \rho_E
\]

\[
S_{IR\text{min}} = 216 \left( \frac{R_E}{R_E + h} \right)^2 \sin^2 \rho_E
\]  \hspace{1cm} (A13-11)

Similar to solar and albedo radiation the amount of Earth infrared radiation absorbed is calculated as

\[ Q_{ir} = \alpha_a A_r FS_{\nu} \]  \hspace{1cm} (A13-12)

Internal heat generation tether due to Ohmic resistance losses

\[ Q_{int\text{oml}} = I_{oml}^2 R_i \]  \hspace{1cm} (A13-13)

The background temperature of space is a heat sink at 3-4 K it allows the satellite to radiate as a black body into space

\[ Q_{out} = \varepsilon \sigma T^4 \]  \hspace{1cm} (A13-14)

\[ \sigma = \text{Stephan Boltzmann constant} \ 5.67 \times 10^{-8} \text{[Wm}^2\text{K}^{-4}\text{]} \]

The extreme values of the fluxes encountered in orbit are summarised below

Table A13-3: Environmental fluxes

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux Density [Wm(^{-2})]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Solar Flux (S_s)</td>
<td>1316 [ECSS]</td>
<td></td>
</tr>
<tr>
<td>Maximum Solar Flux (S_s)</td>
<td>1428 [ECSS]</td>
<td></td>
</tr>
<tr>
<td>Average Solar Flux (S_s)</td>
<td>1366 [ECSS]</td>
<td></td>
</tr>
<tr>
<td>Albedo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Albedo Flux (S_a) a=0.05</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Maximum Albedo Flux (S_a) a=0.6</td>
<td>246</td>
<td></td>
</tr>
<tr>
<td>Average Albedo Flux (S_a) a=0.34</td>
<td>139 [ECSS]</td>
<td></td>
</tr>
<tr>
<td>Infrared</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(I_{ir\text{max}})</td>
<td>237</td>
<td></td>
</tr>
<tr>
<td>IR flux (S_{IR\text{max}})</td>
<td>258 (\sin^2 \rho_E) (650 km)</td>
<td></td>
</tr>
<tr>
<td>IR flux (S_{IR\text{min}})</td>
<td>216 (\sin^2 \rho_E) (1000 km)</td>
<td></td>
</tr>
</tbody>
</table>

\(^{17}\) Averaged albedo only applicable for short duration analysis
References

[SLR 133] DELFI.1.TN.5200.04 Eclipse Times


APPENDIX 14 NEUTRAL GAS RELEASE

The release of a neutral gas in the vicinity of the electrodynamic tether may enhance the deorbiting capability of the electrodynamic tether by increasing the tether current levels. Nitrogen gas selected for use in the cold gas thrusters (CGT) designed for the tether deployment system has a reasonably low ionisation potential and energy making it suitable for use in the neutral gas cathode for the EDT current enhancement experiment. In this appendix the performance equations of the CGT are outlined.

The characteristics of the cold gas thruster used for the deployment system are given in table A14-1.

Table A14-1: Cold gas thruster characteristics [Heijning2; Heijning3]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank temperature $T_T$</td>
<td>K</td>
<td>293</td>
</tr>
<tr>
<td>Pressure loss $\varepsilon_p$</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>Universal gas constant $R$</td>
<td>Jk molK$^{-1}$</td>
<td>8.314</td>
</tr>
<tr>
<td>Nozzle pressure ratio $p_c/p_e$</td>
<td>-</td>
<td>1/3907</td>
</tr>
<tr>
<td>Exit diameter $d_e$</td>
<td>m</td>
<td>1.00E-03</td>
</tr>
<tr>
<td>Exit area $A_e$</td>
<td>m$^2$</td>
<td>7.85E-07</td>
</tr>
<tr>
<td>Throat diameter $d_t$</td>
<td>m</td>
<td>1.00E-04</td>
</tr>
<tr>
<td>Throat area $A_t$</td>
<td>m$^2$</td>
<td>7.85E-09</td>
</tr>
<tr>
<td>Molar mass $M$</td>
<td>kg mol$^{-1}$</td>
<td>2.80E-02</td>
</tr>
<tr>
<td>Specific heat ratio $\gamma$</td>
<td>-</td>
<td>1.40E+00</td>
</tr>
<tr>
<td>Van den Kerckhove parameter $\Gamma$</td>
<td>-</td>
<td>0.685</td>
</tr>
<tr>
<td>Exhaust velocity $v_e$</td>
<td>ms$^{-1}$</td>
<td>742.76</td>
</tr>
<tr>
<td>speed of sound</td>
<td>ms$^{-1}$</td>
<td>349.01</td>
</tr>
</tbody>
</table>

Equations used to calculate the performance of the CGT have been derived from the work of [Zandbergen2]. The temperature dependant exit velocity for a isentropic expansion using a gas nozzle

$$v_e = \sqrt{\frac{2\gamma RT}{M\left(1 - \left(\frac{p_e}{p_c}\right)^{\gamma-1}\right)}}$$

(A14-1)

$p_c$ – chamber pressure [Nm$^{-2}$]

$p_e$ – nozzle exit pressure [Nm$^{-2}$]

The speed of sound for an ideal gas is calculated as

$$c = \sqrt{\frac{\gamma RT}{M}}$$

(A14-2)

$R$ – universal gas constant 8.314 [J mol$^{-1}$ K$^{-1}$]

With

$$\rho_e = \frac{p_e M}{RT_c}$$

(A14-3)

$p_c = \varepsilon_p p_T = 0.9 \times 40e5 = 36e5$ [Nm$^2$]

$p_T$ – tank pressure [Nm$^2$]
\[ p_r = \frac{nRT_r}{V_r} \] (A14-4)

\[ n \quad - \text{moles of gas [-]} \]
\[ V_r \quad - \text{tank volume [m}^3\text{]} \text{ assumed constant 0.00483 [m}^3\text{]} \]

\[ \frac{\rho_r}{\rho_e} = \left( \frac{p_r}{p_e} \right)^{\frac{1}{\gamma}} \] (A14-5)

\[ \rho_e \quad - \text{propellant mass density chamber [kgm}^{-3}\text{]} \]
\[ \rho_c \quad - \text{mass flow density at the nozzle exit [kgm}^{-3}\text{]} \]

\[ \rho_c = \rho_r \left( \frac{p_r}{p_e} \right)^{\frac{1}{\gamma}} = \rho_r \left( \frac{1}{3907} \right)^{\frac{1}{\gamma}} \] (A14-6)

Assuming ideal gas (neglecting compressibility) the ideal gas law states

\[ p_rV_r = \frac{m_{\text{gas}}RT_r}{M} = nRT_r \] (A14-7)

Number of particles per second

\[ N = \frac{nR}{k_B} = \frac{mR}{Mk_B} \] (A14-8)

\[ k_B \quad - \text{Boltzmann constant 1.38x10}^{-23} \text{[JK}^{-1}\text{]} \]

References
[Heijning\textsuperscript{3}] Deployment Profile Determination v1.0
[Zandbergen\textsuperscript{3}] Zandbergen, B.T.C., Rocket Propulsion, Lecture Notes Ae4-S01, Faculty of Aerospace Engineering, Delft University of Technology, January 2001.
### EDT SYSTEM REQUIREMENTS SPECIFICATION

<table>
<thead>
<tr>
<th>PUID</th>
<th>Title</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.SC.01</td>
<td>Bare EDT</td>
<td>Prove de-boost capability of a bare electrodynamic tether by deorbiting the system 80-200 m in 2 weeks</td>
<td>TBC 16</td>
</tr>
<tr>
<td>4122.SC.02</td>
<td>Flat EDT</td>
<td>Deployment and operation of a Flat ED tether 15-20 mm wide; 16-22 µm thick conducting tape</td>
<td>see UR.01</td>
</tr>
<tr>
<td>4122.SC.03</td>
<td>Gas Release</td>
<td>Demonstrate effect of gas release on current in tether [TBC]</td>
<td>TBD 4</td>
</tr>
<tr>
<td>4122.SC.04</td>
<td>Auroral Effects</td>
<td>Observe the auroral effects [TBD]</td>
<td>-</td>
</tr>
<tr>
<td>4122.SC.05</td>
<td>Self accelerating rotation</td>
<td>Demonstrate self-accelerating rotating tether concept</td>
<td>-</td>
</tr>
</tbody>
</table>

#### Science Requirements

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.UR.01</td>
<td>Operating Altitude</td>
<td>The experiment shall be performed at an altitude below the ISS (350km) (17-06-03)</td>
</tr>
<tr>
<td>4122.UR.02</td>
<td>Educational</td>
<td>The EDT shall be developed by students</td>
</tr>
<tr>
<td>4122.UR.03</td>
<td>Development Location</td>
<td>The EDT shall be developed at TUD</td>
</tr>
</tbody>
</table>

#### User Requirements

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.M.10</td>
<td>Cost</td>
<td>The EDT Experiment shall adhere to cost budgets total cost €1.6 to €2.2 M, EDT development, manufacture, assembly and testing shall cost less than €236,000</td>
</tr>
<tr>
<td>4122.M.20</td>
<td>Schedule Requirements</td>
<td>The EDT Experiment shall adhere to schedule requirements stated in Delfi-1 Project timeline</td>
</tr>
<tr>
<td>4122.M.21</td>
<td>manufacturing qualification model schedule</td>
<td>Ready for manufacture qualification model December 2005</td>
</tr>
<tr>
<td>4122.M.22</td>
<td>production schedule</td>
<td>Production shall take place September 2005 - August 2006</td>
</tr>
<tr>
<td>4122.M.23</td>
<td>assembly schedule</td>
<td>Final assembly completed begin August 2006</td>
</tr>
<tr>
<td>4122.M.24</td>
<td>testing and redesign schedule</td>
<td>Testing and redesign during August-November 2006</td>
</tr>
<tr>
<td>4122.M.25</td>
<td>Integration schedule</td>
<td>Ready for integration end November 2006</td>
</tr>
<tr>
<td>4122.M.26</td>
<td>Integrated tests schedule</td>
<td>In 2007 6 months integrated satellite tests</td>
</tr>
<tr>
<td>4122.M.27</td>
<td>Operations schedule</td>
<td>Operations start 2008</td>
</tr>
</tbody>
</table>

#### Mission Requirements

<table>
<thead>
<tr>
<th>Title</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.EDT.01</td>
<td>Ground Storage</td>
<td>The payload shall be storable on ground for at least 1+ 2 years</td>
</tr>
<tr>
<td>4122.EDT.02</td>
<td>Integrated onto the Delfi-1 Bus</td>
<td>Design effort to integrate on standardised bus design of Delfi-1</td>
</tr>
<tr>
<td>4122.EDT.03</td>
<td>Integrated tests-checkout</td>
<td>The EDT shall facilitate an integrated test program for Delfi-1 bus</td>
</tr>
<tr>
<td>4122.EDT.04</td>
<td>Survive launch loads</td>
<td>Launch loads as below shall not decrease operational capabilities of EDT</td>
</tr>
<tr>
<td>4122.EDT.04a</td>
<td>Fundamental Frequencies</td>
<td>The EDT design shall be able to withstand the following quasi-static flight limit loads: Lateral: -6.0/6.0 g (TBC 3 Delfi-1) Longitudinal: -5.5/7.5 g ('-' sign indicates compression,)</td>
</tr>
<tr>
<td>4122.EDT.04b</td>
<td>Quasi Static Loads</td>
<td>The EDT design shall be able to withstand the following sine vibration flight limit loads see Table 1 see SPC.01 document</td>
</tr>
<tr>
<td>4122.EDT.04c</td>
<td>Sine Vibrations</td>
<td>The EDT design shall be able to withstand the following random vibrations see Table 2 see SPC.01 document</td>
</tr>
<tr>
<td>4122.EDT.04d</td>
<td>Random Vibrations</td>
<td>The EDT design shall be able to withstand the shock spectrum in Figure 1. see SPC.01 document</td>
</tr>
<tr>
<td>4122.EDT.04e</td>
<td>Shock Load</td>
<td>The EDT design shall be able to withstand the acoustic loads in Table 3. see SPC.01 document</td>
</tr>
<tr>
<td>4122.EDT.04f</td>
<td>Acoustic Vibrations</td>
<td>Storage onboard Delfi-1 during its 1 yr mission shall not decrease operational capabilities of EDT</td>
</tr>
<tr>
<td>4122.EDT.05</td>
<td>Onboard storage</td>
<td>Storage onboard Delfi-1 will have a system preventing premature deployment of the tether and gas release</td>
</tr>
<tr>
<td>4122.EDT.06</td>
<td>Prevent Premature Deployment</td>
<td>The EDT shall have a design life of at least 1 year</td>
</tr>
<tr>
<td>4122.EDT.07</td>
<td>Design Life</td>
<td>The payload shall require an operational life of no more than 1 year</td>
</tr>
<tr>
<td>4122.EDT.08</td>
<td>EDT Operational Level</td>
<td>Remain operational during each operational phase, environment and loads</td>
</tr>
<tr>
<td>4122.EDT.10</td>
<td>Absolute Pointing Error</td>
<td>The EDT shall require an absolute pointing error of no better than +/- 5º around x and y axes of the spacecraft frame [SLR 71].</td>
</tr>
<tr>
<td>4122.EDT.10b</td>
<td>Absolute Rate Error</td>
<td>1-3º /s (TBD 7 Delfi-1)</td>
</tr>
<tr>
<td>4122.EDT.59</td>
<td>SC Pointing Direction</td>
<td>The SC shall be oriented with the ZS/Corb-axis pointed to the Earth centre in the experiment operations phase be able to provide pointing in the experiment operations phase.</td>
</tr>
</tbody>
</table>

**Interface Requirements**

| 4122.EDT.11 | EMC Compatibility | The payload shall be designed to achieve electromagnetic compatibility according to the EMC Plan (TBW 2 Delfi-1):  · Between payload and all other subsystems within the spacecraft.  · In the presence of its self-induced environment.  · In the presence of the external electromagnetic environment. (TBD 2) |
| 4122.EDT.12 | Electrostatic Charging | EDT design and configuration shall be such to ensure that no parts of the spacecraft are charged to high potentials. The differential charging potential shall not exceed 10 V as a design goal. (TBD 31) |
| 4122.EDT.12b | Arcing | Tethers which contain electrical conductors have special considerations in order to prevent arcing or discharge of electricity from the tether. |
| 4122.EDT.13 | Disturbance Torque | Payload mechanisms shall not induce a disturbance torque of more than Nm (TBD 2) |
| 4122.EDT.14 | Disturbance Time | Payload mechanisms shall not induce a disturbance torque longer than xxx s. (TBD 2) |
| 4122.EDT.15 | Disturbance force | Payload mechanisms shall not induce a disturbance force exceeding xxx N (TBD 2) | |
| 4122.EDT.16 | Influence on SC Stability | during the EDT storage, deployment and operational phase nominal tether operations will ensure the SC bus ADCS is able to maintain 5deg pointing attitude requirement keeping the bus operational. |
| 4122.EDT.17 | Residual Magnetic Dipole | The EDT shall not compromise the ability of the SC magnetic dipole to be less than 1 Am² (TBC 5 Delfi-1). |

**Technical Budgets and Constraints**

| 4122.DS.01 | Design Philosophy | ECSS and Delfi-1 project based |
| 4122.DS.02 | Design Margins | 23% on budgets for Loads see DELFI-1 |
| 4122.DS.03 | Material and Component Selection | ECSS |
| 4122.EDT.18 | Mass | EDT experiment is limited to a total mass of 6kg <11.5 kg |
| 4122.EDT.19 | Dimensions | remain within envelopes PL platforms - modules 410 x 410 x 135 mm |
| 4122.EDT.20 | Physical location onboard the satellite | Design effort to locate on standard PL platform; Special PL module location is mission specific |
| 4122.EDT.21 | Payload Platform Location | The payload platform in the spacecraft shall have dimensions of 450*450 mm2, with a height of 140 mm |
| 4122.EDT.22 | Payload Module Placement | The Payload Modules shall be placed in a support structure on the Payload Platform as specified in the Payload Platform Design Description [SLR 124] |
| 4122.EDT.23 | Outside Area | The payload antenna modules [SLR 117] shall use no more than 25% of the outside area of one side of the spacecraft |

**Operational Requirements**

| 4122.EDT.24 | Operating Orbit Altitude | 650 - 1000 km |
| 4122.EDT.25 | Operating Orbit Inclination | 70°-110° => 70°-85° and 95°-110° |
| 4122.EDT.26 | Operating Orbit Eccentricity | 0 |
| 4122.EDT.27 | Off Mode | The EDT will have an Off Mode with no power to experiment |
| 4122.EDT.28 | Off Mode timeline | EDT will remain in Off Mode during 275 days with intervals of Standby Mode for CHECKOUT |

**Payload Platform Size**

| 450*450 mm², with a height of 140 mm |

**GGB Tip Platform Size**

| 130x 270 x 75 mm³ |

**Special PL module volume**

| 3.2x10⁵ mm³ |

**Antenna PL outside area**

| 506.25 cm² Volume unknown m = 0.1kg |

**Technical Budgets and Constraints**

| ECSS and Delfi-1 project based |

**Design Margins**

| 23% on budgets for Loads see DELFI-1 |

**Material and Component Selection**

| ECSS |

**Dimensions**

| remain within envelopes PL platforms - modules 410 x 410 x 135 mm |

**Payload Platform Location**

| The payload platform in the spacecraft shall have dimensions of 450*450 mm², with a height of 140 mm |

**Payload Module Placement**

| The Payload Modules shall be placed in a support structure on the Payload Platform as specified in the Payload Platform Design Description [SLR 124] |

**Outside Area**

| The payload antenna modules [SLR 117] shall use no more than 25% of the outside area of one side of the spacecraft |
4122.EDT.29 Safety Mode  The EDT will have a Safety Mode Payload is partially activated to check health status

4122.EDT.30 Standby Mode  The EDT will have a Stand by Mode Payload is Listening for Activation Signals

4122.EDT.31 Deployment Mode  EDT Mission Mode first phase: Deployment mode the tether experiment will be deployed to operational status

4122.EDT.32 Operational Mode  EDT Mission Mode second phase: Operational mode the EDT experiment will perform scientific objectives

4122.EDT.33 Termination Mode  In Termination Mode the EDT experiment will shut down and return to Off Mode after (un)-intentional release of the tether or expiration of the operational experiment time

4122.EDT.34 Checkout  Checkout data in combination with experiment data determine when the system changes its operational mode.

4122.EDT.35 Operational Timeline  Operational Timeline as specified TBW 3

4122.EDT.36 Payload Control  The EDT shall be controlled and operated by the bus

4122.SC.12- EDT Reference frames  The EDT system reference frames will be compatible with Delfi-1

4122.EDT.37 Operational Limits  the EDT shall remain within operational limits during required experiment time of 3 months total

4122.EDT.38 Total Mass loss  To limit damage to the spacecraft due to outgassing effects, materials used on the spacecraft shall have a total mass loss of less than 1%

4122.EDT.39 Volatile Condensing Material  To limit damage to the spacecraft due to outgassing effects, materials used on the spacecraft shall have a volatile condensing material of less than 0.1%

**Environmental Requirements**

4122.EDT.40 EDT Operating Environment  If not specified, the EDT shall be able to function as designed within the space environment specified in Spacecraft System Requirements Specification [SLR 114].

4122.EDT.41 Magnetic Field  $B_{avg} = 2.88e-5 - 3.45e-5 \text{ [T]}$, $B_{avg} = 1.27e-5 - 1.6e-5 \text{ [T]}$

4122.EDT.42 EMF  $0.008 - 0.062 \text{ [Vm}^{-1}\text{]}$

4122.EDT.43 Atmospheric density  $1e-15 - 4e-12 \text{ [kgm}^{-3}\text{]}$

4122.EDT.44 Plasma parameters  $n_e = 6e10 - 2.5e11 \text{ [m}^{-3}\text{]}$  
$T_e = 2800 - 3200 \text{ [K]}$  
$T_i = 1850 \text{ [K]}$  
$2850 \text{ [K]}$  
$\lambda_0 = 4.6 - 10.7 \text{ [mm]}$  
$L_e = 48 - 58 \text{ [mm]}$

4122.EDT.45 Atomic Oxygen  All materials considered for use on the external surfaces of the spacecraft shall be evaluated for their resistance to atomic oxygen

4122.EDT.46 Micro gravity

4122.EDT.47 Temperature  The EDT shall be able to function at an operating temperature of no more than 328 K and no less than 253 K.

4122.TET.10 Tether Temperature  The TET shall be able to operate between -100°C [TBC] +100°C

4122.EDT.48 Radiation Dose  The EDT shall be able to withstand a radiation dose of at least 5 kRad without loss of function.

4122.EDT.49 External Air Pressure  The EDT shall be able to withstand any external air pressure between 0.115 Mpa and 1·10^{-9} Pa.

4122.EDT.50 Pressure Drop  The EDT shall be able to withstand a depressurisation of 4.5 kPa/s.

4122.EDT.51 Humidity  The EDT shall be able to withstand a maximum relative humidity without performance degradation of 55 %.

4122.EDT.52 Particulates  The effect of impacts by micrometeoroids and debris on materials shall be reviewed and assessed on a case-by-case basis

4122.EDT.53 Contamination  The EDT shall be designed for class 100,000 cleanliness levels

**RAMS & Safety Requirements**

4122.EDT.54 Integration time  The EDT experiment shall be entirely replaceable within 4 hrs

4122.EDT.56 Failure Effect  Payload equipment failure shall not have a mission critical effect on spacecraft operations

4122.EDT.57 Collision Avoidance  The total number of avoidance/alert situations for operational spacecraft should ideally be equal or of lesser order of magnitude than for normal space debris in orbit

4122.EDT.58 Collision Avoidance  Experiment orbits must not be densely populated with spacecraft $h < 350 \text{ km}$
## Experiment Data

<table>
<thead>
<tr>
<th>PUID</th>
<th>Title</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.SC.06</td>
<td>Experiment time</td>
<td>Experiment time 3 Months (EOL Delfi-1) 2 weeks measurable effects</td>
<td></td>
</tr>
<tr>
<td>4122.SC.07</td>
<td>Data Availability</td>
<td>A minimum of (TBD) % of the generated payload data with an accuracy of (TBD) shall be available for the PI’s.</td>
<td>TBD 9</td>
</tr>
<tr>
<td>4122.SC.08</td>
<td>Data Format</td>
<td>The payload data shall be available to the PI’s in a (TBD 10) format.</td>
<td>TBD 10</td>
</tr>
<tr>
<td>4122.SC.09</td>
<td>Post Processing</td>
<td>The experiment data shall not be post processed before transferring the data to the PI</td>
<td></td>
</tr>
<tr>
<td>4122.SC.10</td>
<td>Delivery Time</td>
<td>The generated experiment data shall be given to the PI (TBD 11 period) maximum after the data was generated by the experiment.</td>
<td>TBD 11</td>
</tr>
<tr>
<td>4122.SC.11</td>
<td>GS contact time</td>
<td>Mean time between GS contact 247 min; max time 597 min; min 87 min</td>
<td></td>
</tr>
<tr>
<td>4122.SC.13</td>
<td>Delfi Doppler accuracy 2 km</td>
<td>Delfi Doppler accuracy 2 km</td>
<td></td>
</tr>
</tbody>
</table>

## TET REQUIREMENTS

<table>
<thead>
<tr>
<th>PUID</th>
<th>Title</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.TET.01</td>
<td>Drag force</td>
<td>The TET shall generate ED drag force $F_D = 1.6e-6$ [N]</td>
<td></td>
</tr>
<tr>
<td>4122.TET.02</td>
<td>Bias</td>
<td>The TET shall induce sufficient bias to perform Scientific Objectives $V_{\text{ion}} \leq 25$ V ionisation gas</td>
<td></td>
</tr>
<tr>
<td>4122.TET.03</td>
<td>Current</td>
<td>The tether shall have a bare segment acting as an anode collecting current $I_{\text{out}} \leq I_{\text{opt}}$</td>
<td></td>
</tr>
<tr>
<td>4122.TET.04</td>
<td>Deployability</td>
<td>The TET shall remain deployable after storage time of at least 15 months</td>
<td></td>
</tr>
<tr>
<td>4122.TET.04a</td>
<td>Residual Reel Storage</td>
<td>Effects The tether shall be designed to ensure the tether will operate smoothly through the DEP mechanisms following a 6 months integrated tests + 9 months in space storage period on the reel</td>
<td></td>
</tr>
<tr>
<td>4122.TET.05</td>
<td>TET mass</td>
<td>1.6 kg incl. contingency margin 23 % 1.3 kg</td>
<td></td>
</tr>
<tr>
<td>4122.TET.06</td>
<td>Tether Geometry</td>
<td>The tether shall have a tape geometry</td>
<td></td>
</tr>
<tr>
<td>4122.TET.07</td>
<td>Nominal TET operation</td>
<td>The tether librations shall be within ±20° during nominal tether operation</td>
<td></td>
</tr>
<tr>
<td>4122.TET.08a</td>
<td>Tether Integrity</td>
<td>Resistance to mechanical load (dynamic or static) electrical load and resistance to combined actions of the environment and loads (stress corrosion, cracking, thermo-elastic behaviour, cold welding etc.)</td>
<td></td>
</tr>
<tr>
<td>4122.TET.08b</td>
<td>Tether Integrity</td>
<td>95% chance of tether surviving M/OD being maintained during EDT experiment duration</td>
<td></td>
</tr>
<tr>
<td>4122.TET.09</td>
<td>Tether Area-Life time</td>
<td>The tether must be designed to spend a minimal time in the operational satellite environment (when cut) the area time product or sweep volume needs to be minimised</td>
<td>TBD 12</td>
</tr>
<tr>
<td>4122.TET.10</td>
<td>Tether Temperature range</td>
<td>-150°C +100°C</td>
<td></td>
</tr>
<tr>
<td>4122.TET.11</td>
<td>Flight Tether Handling</td>
<td>Tether handling during ground storage; integration; tests shall not in any way compromise the integrity of the tether</td>
<td></td>
</tr>
<tr>
<td>4122.TET.12</td>
<td>Area Youngs modulus AE</td>
<td>Stiffness Large variations of AE have been noted when operating at low tension fractions and AE increases significantly as operating tension increases. AE increased on TSS and SEDS tethers as temperatures decreased and vice versa.</td>
<td>TBC 48</td>
</tr>
<tr>
<td>4122.TET.13</td>
<td>Thermal Expansion</td>
<td>CTE of the TET is [TBD 49] Tested for operating temperatures</td>
<td>TBD 52</td>
</tr>
<tr>
<td>4122.TET.14</td>
<td>Proof-test of flight</td>
<td>$PF = 2.0$ End-to-end on the maximum predicted tether load and in the appropriate environment.</td>
<td></td>
</tr>
<tr>
<td>4122.TET.15</td>
<td>Qualification test</td>
<td>$FS\text{ult} = 5.0$ Basic tether, splice, and repair methods = 2.0 Off-nominal tether condition on the maximum predicted tether load and in the appropriate environment.</td>
<td></td>
</tr>
<tr>
<td>4122.TET.16</td>
<td>Gas release tether</td>
<td>Trapped gasses in the tether should be avoided because they can be excited and ionized by radio frequency or alternating current in the tether. This could lead to a breach in the insulation, causing mechanical failure of the tether.</td>
<td>TBC 49</td>
</tr>
<tr>
<td>4122.TET.17</td>
<td>Tether Length</td>
<td>$L = 500-900$ m</td>
<td></td>
</tr>
<tr>
<td>4122.TET.18</td>
<td>Tether width</td>
<td>$w, 5-40$ mm</td>
<td>TBC 4</td>
</tr>
<tr>
<td>4122.TET.19</td>
<td>Tether Thickness</td>
<td>$t, \mu$m based on voltage drop and handling loads</td>
<td></td>
</tr>
<tr>
<td>4122.TET.20</td>
<td>Tether conducting</td>
<td>High Conductivity [alloy 1xxx or 8xxx] Temperature Range -150°C+50°C [C] Ductile [alloy 1xxx, 3xxx, 5xxx, 6xxx] QUANTIFY High fracture toughness</td>
<td>TBD 43</td>
</tr>
</tbody>
</table>
### Tether enforcement

- **Temperature Range**: -150 to +100 °C
- **High emittance factor**: ε [TBC 41]
- **Low outgassing TLM 1%; CVCM 0.1%**
- **Low UV and Particle Radiation susceptibility**
- **CTE**: 20e-6 to 30e-6 [mm°C⁻¹]
- **Poisson Ratio**: ν ∼ 0.3

### Tether coating

- **Conductive Surface Resistance**: R_coating < 10⁶ [Ωm⁻²] [TBC 47] [Kruijff]
- **Survive deformations during winding, storage and deployment**
- **Temperature Range**: -150 to +100 °C
- **AO resistant Erosion Yield**: AO < 0.1e⁻²⁴ [cm⁻³]
- **Low outgassing**
- **CTE**: 20e-6-30e-6 [°C⁻¹]
- **Friction static and dynamic** [TBC 48]

### Tether maximum current levels

- **Fig. 5.2**: I_{max} = 4I_{OML}

### Tether Voltage Loss

- **r_L/A_c << L_E** by a factor 10 over entire orbit range

### Total Mass loss

- To limit damage to the spacecraft due to outgassing effects, materials used on the spacecraft shall have a total mass loss of less than 1% (TBD 7).

### Volatile Condensing Material

- To limit damage to the spacecraft due to outgassing effects, materials used on the spacecraft shall have a volatile condensing material of less than 0.1%.

### Adhesive Properties

- **Temperature Range**: -150 to +100 °C
- **Low outgassing TLM 1%; CVCM 0.1%**
- **Low UV and Particle Radiation**
- **CTE**: 20e-6 to 30e-6 [mm°C⁻¹]
- **Poisson Ratio**: ν ∼ 0.3

---

<table>
<thead>
<tr>
<th>PUID</th>
<th>Keyword</th>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.TLM.01</td>
<td>voltage</td>
<td>The TLM will handle all the experiment HK data, experiment data and commands</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.02</td>
<td>measurements</td>
<td>The TLM will perform required measurements of the EDT experiment</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.03</td>
<td>CDHS Interface</td>
<td>The TLM will interface with the CDHS</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.04</td>
<td>CDHS</td>
<td>The TLM will receive and send digital payload data to the bus consisting of House Keeping data (HK data) Science data Commands</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.05</td>
<td>Sample Size</td>
<td>The TLM shall use a maximum sample size of 8 bits</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.06</td>
<td>Data Format</td>
<td>The TLM shall use a data format consistent with Delfi-1</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.07</td>
<td>Protocol</td>
<td>The TLM shall have CDHS - SW protocol compatible with Delfi-1 protocol and EDT resulting digital data shall be compatible with the adapted Delfi protocol [SLR 17] in order to be processed by the bus.</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.08</td>
<td>Data Connectors</td>
<td>The TLM shall be connected to the data bus by 2 connectors with the RS-485 standard per connection. These connectors can be combined with power connectors.</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.09</td>
<td>TLM mass</td>
<td>1.0 kg incl margin 23 % 0.8 kg</td>
<td>TBC 25</td>
</tr>
<tr>
<td>4122.TLM.10</td>
<td>Data rate</td>
<td>The payload shall generate an average data rate of no more than 210 bps [160 bps design target]</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.11</td>
<td>Health Check</td>
<td>During each operational mode except for the Off Mode the TLM &amp; CDHS will perform system health checks</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.12</td>
<td>sensor location</td>
<td>All sensors shall be located at the Delfi-1 bus implicating environment for onboard and tether connection</td>
<td></td>
</tr>
<tr>
<td>4122.TLM.13</td>
<td>Power budget TLM system</td>
<td>4 W (3.1W) 0.66 W (0.5 W)</td>
<td></td>
</tr>
<tr>
<td>Requirement</td>
<td>Details</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GPS Performance and Integration Requirements</strong></td>
<td>mass &lt; 150 [g]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume &lt; 1 PL &lt; 1 APL</td>
<td>High dynamic environment ability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>power &lt; 1 [W]</td>
<td>operational velocity 7531 [ms⁻¹]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>- real time position &lt; 20 [m]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- velocity 0.06 – 1 [ms⁻¹]</td>
<td>Single Frequency Receiver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to first fix (TTFF) cold and warm</td>
<td>Number of channels &gt; 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time offset [TBD 21]</td>
<td>Output frequency 1 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output data</td>
<td>- Position Cartesian ECI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Velocity Cartesian ECI</td>
<td>- Time signal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Raw Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Turn Counter Optical</strong></td>
<td>Resolution # counts per turn 1 – 2 – 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotational speed 21-98 [RPM]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>calibration deployed length</strong></td>
<td>Measure the temperature T₁ and tension T of the tether during deployment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>to calibrate the amount of tether deployed for each turn</td>
<td>for deployment conditions required for post processing of the number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of turns to tether length deployed.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>pitch and roll attitude angles Delfi-1 sat</strong></td>
<td>access to data required EDT PL</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>sun sensor data</strong></td>
<td>access to data required EDT PL</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>magnetic cleanliness</strong></td>
<td>&lt; 20 nT</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Langmuir probe performance</strong></td>
<td>Tₑ Range 2200 – 3200 [K]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy ±10% [Cosmo]</td>
<td>Resolution 50 K [Cosmo]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range 3e10 – 2.5e11 [m⁻³]</td>
<td>Accuracy &lt; ±10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>Resolution I-V acquisition 0.1-0.2 [V]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current levels range from 1.6e-9 to 2.8e-4 [A]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LP reference ground</strong></td>
<td>The LP will be referenced to the SPG of the spacecraft chassis</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>calibration turn counter</strong></td>
<td>Calibration is required when switched on to obtain the null position</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of the sensor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Command and Data Handling GPS</strong></td>
<td>The CDHS is required to perform checks on the operation of the GPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>system and be able to reset the GPS system if required</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GPS antenna placement</strong></td>
<td>The antenna module containing the GPS antenna is required to have a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a clear view of space and needs to be attached to the zenith panel of</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>the satellite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tether bias measurement performance</strong></td>
<td>Range ±0.17 – ±1[0V]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution 0.5 [mV] – 0.05 [V]</td>
<td>Tether electrically isolated from sc chassis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency 1 [Hz]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RTD sensor performance</strong></td>
<td>Range ±150 ° C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resolution 2°C</td>
<td>Frequency 0.1 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LP configuration requirements preliminary</strong></td>
<td>Deploy the sensor head(s) with a deployable boom of 10 [cm] [20 incl.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>design margin from the spacecraft; Lₑ &gt; 0.1-0.2 [m]</td>
<td>Probe location a function of ram – wake effects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not mounted on a surface directly in sun</td>
<td>During storage and operational phase in flight recalibration will be</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disturbance RF antenna’s and tether Power &lt; 2 [W]</td>
<td>applied to instruments sensitive to degradation by using known inputs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensions:</td>
<td>requiring to be calibrated before operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probe dimensions &lt;1 antenna module</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electronics dimensions &lt;1 PL module</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EMC-Grounding</strong></td>
<td>Delfi-1 bus shall preferably have a positive or floating ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set up experiment (electronic connections) so failure of onboard</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electronics will not influence operation of tether. Isolate tether</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>termination from satellite ground</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise Quite conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>calibration Instrumentation</strong></td>
<td>All instruments are required to be calibrated pre-flight for entire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>expected operating range.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>During storage and operational phase in flight recalibration will be</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>applied to instruments sensitive to degradation by using known inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>requiring to be calibrated before operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>sample frequency</strong></td>
<td>All sample frequencies are TBC</td>
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<td></td>
</tr>
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</table>

TBD 19

TBD 20

TBD 21

TBD 22

TBD 23

TBD 24

TBD 25

TBD 26

TBD 27

TBD 28

TBD 29

TBD 30

TBD 31
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<th>PUID [Heijning]</th>
<th>Keyword</th>
<th>Requirement</th>
<th>Status</th>
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<tbody>
<tr>
<td>4122.DEP.01</td>
<td>Storage</td>
<td>The DEP shall store the TET and maintain deployability</td>
<td>test</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>using a single movie reel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.02</td>
<td>Ejection</td>
<td>The DEP shall eject the TET and EM; GAS using CGT</td>
<td>go</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(pending on analysis slack Springs an option)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.03</td>
<td>Control</td>
<td>Passive; deployment according to predetermined</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>deployment profile resulting in nominal tether θ ≤ 20° of length L_t</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.04</td>
<td>rotate</td>
<td>The DEP shall initiate system rotation by retraction of tether if SC bus cannot provide initial rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.05</td>
<td>termination</td>
<td>The DEP shall release or retract the EDT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.06</td>
<td>REQ.4122.TDS.79</td>
<td>Mass</td>
<td>1.1 kg design margin 0.88 kg</td>
<td></td>
</tr>
<tr>
<td>4122.DEP.07</td>
<td>Deployment</td>
<td>The EDT shall not be deployed in the same direction as the GGB unless integrated on the GGB platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.07a</td>
<td>Direction</td>
<td>Nadir Opposing to the GGB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.07b</td>
<td>Direction</td>
<td>The floating tether shall be deployed in a nadir</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>direction to minimise the differential potential between payload and SC bus to &lt; 10 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.08</td>
<td>REQ.4122.TDS.75</td>
<td>Deployment Timeline</td>
<td>Deployment shall not occur during transition from solar to eclipse or vice versa</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>The deployment shall take place in solar part of orbit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.09a</td>
<td>Deployment</td>
<td>&gt; 651 [s] contingency margin xx</td>
<td>TBC 8</td>
<td></td>
</tr>
<tr>
<td>4122.DEP.09b</td>
<td>Time</td>
<td>&lt; 3738 [s] contingency margin xx</td>
<td>TBC 33</td>
<td></td>
</tr>
<tr>
<td>4122.DEP.10</td>
<td>REQ.4122.TDS.78</td>
<td>No Slack</td>
<td>avoid slack build up of the tether T&gt;0 [N]</td>
<td></td>
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<tr>
<td>4122.DEP.11</td>
<td>REQ.4122.TDS.72</td>
<td>Deployment Momentum</td>
<td>≤ 0.18 [Nm]</td>
<td>TBD 2</td>
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<tr>
<td></td>
<td></td>
<td>Deployment Impulse</td>
<td>≤ 50 [Ns]</td>
<td></td>
</tr>
<tr>
<td>4122.DEP.13</td>
<td>Verification</td>
<td>deployment at all tether temperatures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.14</td>
<td>REQ.4122.TDS.90</td>
<td>Reel Dimensions</td>
<td>D_h ≤ 200 [mm]</td>
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<tr>
<td>4122.DEP.15</td>
<td>max initial</td>
<td>Deployment velocity</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Tip off Rates</td>
<td>max tip off rate ensuring tether does not entangle with debus</td>
<td>TBD 37</td>
<td></td>
</tr>
<tr>
<td>4122.DEP.16</td>
<td>Velocity max</td>
<td>Table 6.32</td>
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<tr>
<td>4122.DEP.17</td>
<td>Energy Dissipation</td>
<td>resulting in tether libration angles &lt; 20°</td>
<td>TBD 38</td>
<td></td>
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<tr>
<td>4122.DEP.18</td>
<td>Deployment</td>
<td>Deployment Profile Tool (1.0)</td>
<td>TBD 53</td>
<td></td>
</tr>
<tr>
<td>4122.DEP.19</td>
<td>Initial Deployment</td>
<td>Errors</td>
<td>TBD</td>
<td></td>
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<tr>
<td>4122.DEP.20</td>
<td>Errors During Deployment</td>
<td>TBD</td>
<td>TBD</td>
<td></td>
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<tr>
<td>4122.DEP.21</td>
<td>Arcing</td>
<td>The tether path through the deployer system should be free from conducting</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>paths which could lead to electrical arcing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4122.DEP.22</td>
<td>Power</td>
<td>0 - 2 W</td>
<td></td>
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</tbody>
</table>

**4122.TLM.31** overload capacity tension transducer

Overload capacity: 300% allowing up to 15 [N]

**4122.TLM.32** MAG performance

Range: ±64 to ±100 [µT]
Sensitivity: 100 [µV/µT]
Accuracy: 0.64 [µT] to 0.75 [µT]
Power: < 1 [W]
Data rate: < 100 [bps]

**4122.TLM.33** TEN performance

Range: 0 - 7.38e-4 N / 4.39e-2 N
Resolution: 5 µN, 0.5mN
Frequency: 1-8 Hz

Fixed idle roller: integrated with deflection roller DEP
<table>
<thead>
<tr>
<th>PUID</th>
<th>Keyword</th>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.GAS.01</td>
<td>Function Gas Cathode</td>
<td>Time Tagged gas release</td>
<td></td>
</tr>
<tr>
<td>4122.GAS.02</td>
<td>Gas Cathode Mass</td>
<td>1.0 kg (\rightarrow) 0.5 kg</td>
<td>TBC 49</td>
</tr>
<tr>
<td>4122.GAS.03</td>
<td>System and Tether stability</td>
<td>APE: \pm 5° &amp; 6&lt;20° including a margin of 3 Tgas &lt; Nm</td>
<td>TBC 53</td>
</tr>
<tr>
<td>4122.GAS.04</td>
<td>gas cathode breakdown voltage</td>
<td>25 V</td>
<td>TBD 48</td>
</tr>
<tr>
<td>4122.GAS.05</td>
<td>(I_{gas})</td>
<td>40 mA</td>
<td>TBC 51</td>
</tr>
<tr>
<td>4122.GAS.06</td>
<td>Gas discharge time schedule</td>
<td>solar part of orbit</td>
<td></td>
</tr>
<tr>
<td>4122.GAS.07</td>
<td>mass flow rate gas cathode</td>
<td>1.6e-6 kgs(^{-1})</td>
<td>TBC 52</td>
</tr>
<tr>
<td>4122.GAS.08</td>
<td>Deorbit performance GAS</td>
<td>Increase deorbit during gas release by 20-40 m</td>
<td>TBC 18</td>
</tr>
</tbody>
</table>

**EM Requirements**

<table>
<thead>
<tr>
<th>PUID</th>
<th>Keyword</th>
<th>Requirement</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>4122.EM.01</td>
<td>End Mass EM stabilisation</td>
<td>Stabilise tether system</td>
<td></td>
</tr>
<tr>
<td>4122.EM.02</td>
<td>platform</td>
<td>provide platform for required subsystems</td>
<td></td>
</tr>
<tr>
<td>4122.EM.03</td>
<td>EM mass budget</td>
<td>0.83 – 1.83 kg required value feasible configurations 1.1-1.5 kg</td>
<td>TBC 7</td>
</tr>
</tbody>
</table>

**EPS Requirements**

<table>
<thead>
<tr>
<th>PUID</th>
<th>Keyword</th>
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</tr>
</thead>
<tbody>
<tr>
<td>4122.EPS.01</td>
<td>Electrical Power System EPS</td>
<td>The EPS shall supply sub systems required power to operate</td>
<td></td>
</tr>
<tr>
<td>4122.EPS.02</td>
<td>Electrical Interface</td>
<td>The EPS will interface with the EPS of Delfi-1 bus</td>
<td></td>
</tr>
<tr>
<td>4122.EPS.03</td>
<td>Voltage</td>
<td>The EDT shall use voltages of 28 V, which will be provided by the bus</td>
<td></td>
</tr>
<tr>
<td>4122.EPS.04</td>
<td>Power Connectors</td>
<td>The EDT shall have 2 power connectors per payload connection. (TBC 4) These connectors can be combined with data connectors</td>
<td></td>
</tr>
<tr>
<td>4122.EPS.05</td>
<td>EPS mass</td>
<td>0.6 kg</td>
<td></td>
</tr>
<tr>
<td>4122.EPS.06</td>
<td>Power average</td>
<td>6 W and 1 W eclipse</td>
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</tbody>
</table>

**STS Requirements**

<table>
<thead>
<tr>
<th>PUID</th>
<th>Keyword</th>
<th>Requirement</th>
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</thead>
<tbody>
<tr>
<td>4122.STS.01</td>
<td>Structure System STS</td>
<td>The STS shall consist of all required structural components and harnessing not part off other systems</td>
<td></td>
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<tr>
<td>4122.STS.02</td>
<td>Connector locations</td>
<td>The power/data connectors shall be placed on the cover plate of the payload modules as specified in Payload Module Design Description [SLR 117]</td>
<td></td>
</tr>
<tr>
<td>4122.STS.03</td>
<td>Interface with STS</td>
<td>EDT shall interface with the Delfi-1 structure via the PL Platform</td>
<td></td>
</tr>
<tr>
<td>4122.STS.04</td>
<td>Thermal Interface</td>
<td>The STS shall be conductive with structure</td>
<td></td>
</tr>
<tr>
<td>4122.STS.05</td>
<td>STS mass</td>
<td>0.7 kg</td>
<td></td>
</tr>
</tbody>
</table>

References

DELF1.1.SPC.4122.01-02 EDT System Requirements Specification (2.0)