The YES2 Experience: Towards Sustainable Space Transportation using Tethers

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ABSTRACT

Today there is no common vision on sustainable space transportation. Rockets expel gasses and solid rockets often small particles. These have negative effect on the environment, but it is not understood to what extent. With ever growing demand for access to space, sustainable technology developments are to be made. In this respect a truly sustainable means of transportation seems to be the space elevator. However state of the art tether technology can already contribute today to sustainability and further tether developments are stepping stones for sustainable space transportation.

This paper provides firstly an outlook into sustainable space transportation, from a mainly European perspective. Here we address that tethers are a building block for sustainable space transportation and hence technological advancements are of key interest. Potential next steps for Europe are discussed. We then zoom in further towards the state of the art for tethers in Europe, mainly based on the results of the 2nd Young Engineers' Satellite (YES2) project, that completed a 32 km tether deployment in September 2007, and of which the technology and design is publicly available. Discussed are the YES2 tether deployer system, its scalability and supporting rigs/tools as well as the hurdles encountered on the road from concept to space demonstration such as critics' concerns about safety and simulation validity. We address tether controllability, based on mission results, showing good agreement between tests, simulations and YES2's flight measurements of the various deployment parameters. Observations of tether stiffness, damping, sound waves and lateral waves are analyzed including conclusions on scope of validity of simulation and test. We conclude that Europe can take a prominent role in sustainable space transportation development.

1 SUSTAINABLE SPACE TRANSPORTATION

Sustainability was defined at the 1987 UN conference as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

For sustainable space transportation we can substantiate two regions of interest to preserve for the next generations: Atmosphere (below 120 km) and near-Earth space (120km-GEO). For the latter a big sustainable step forward has been made when international regulations agreed at Inter Agency Debris Committee (IADC) and UNCOPUOS level to leave defunct objects in LEO with a remaining lifetime lower than 25 years (roughly 600 km). For the former region a big step has to be made: solid rockets (like the shuttle) typically expel Chlorides and Aluminum Oxide particles. More green rocket engines leave CO_2 and/or water vapor. Although there are only limited launches and pollution is minimized by the launch time selection for good weather conditions, there is a small effect on environment and greenhouse warming. The true size of this effect is hard to evaluate, but the order of particles per billion released by the Shuttle at 80km are measurable and thus could be relevant. When launch frequencies go up more sustainable technologies are to be implemented. The space elevator would be a sustainable solution, but state of the art tethers can already contribute a great deal to sustainability.

There are two types of tethers: mechanical tethers and electrodynamic tethers. Mechanical, electrically non-conductive, tethers can transfer momentum between two spacecrafts for space transportation while not losing energy or momentum by any exhaust gasses.

Electrodynamic tethers interact with the Earths magnetic field and the space plasma. An ElectroMotive Force (EMF=Voltage drop) is introduced along the conductive tether when moving through the Earth magnetic field. When no subsystems are coupled to the tether, a potential equilibrium establishes where part of the tether collects electron and part of the tether collects ions. A small current starts to flow through the tether and a Lorentz force decelerates the tether[1]. When power systems and plasma contactor subsystems are added, the current can be increased and even be reversed for orbit thrust [2, 6, 7].

Mechanical tethers have equivalent specific impulses better than double that of conventional engines and electrodynamic tethers conservatively better than double that of ion engines. Every kilogram of fuel to be saved can be replaced by 1 kilogram of useful payload.

Although a full vision on sustainable space transportation is lacking, from a sustainable perspective a continuous development on tethers seems evident. The authors have initiated two European tether missions [24,25] to allow for the first crucial European steps to be made for sustainable space transportation.

2 STATE OF THE ART TETHERS IN EUROPE

Contrary to common believe many tether missions have been largely successful in the last decades. In 2007 Europe conducted the YES2 tether mission which led to a record-braking 32km of tether deployment[13,22]. The YES2 tether actively de-orbited a small re-entry capsule and collected a large set of data. This paper evaluates the applicability of the hardware for near-term European sustainable transportation through a number of examples. Scalability is addressed.

3.1 Tether system supporting tools/rigs

To support the YES2 tether system flight hardware development, a number of tools and rigs were developed:

- winding machine [17]
- closed loop unwinding machine [20]
- advanced tether mission simulator[21]

WINDING MACHINE

In order to prepare the tether flight spools we have developed, in cooperation with the University of Remagen, a close precision winding system [Figure 1][20]. This system ensures that the tether can be wound on the core on a stable and repeatable manner. The length of each loop is accurately measured and after the tether is wound a quadratic fit for length as function of loop number is made.

UNWINDING MACHINE

Again in cooperation with the University of Remagen an unwinding machine[20] was developed with two main objectives:

- To characterize the tether hardware;
- To verify the robustness of the control algorithms and their implementation.

The unwinding machine pulls the tether of the spool with a dictated velocity. This velocity could either be manually entered or be calculated from a real-time space tether simulator. During the unwinding two tensiometers would register the tension in a low and high region range.
For the first objective, to characterize the tether hardware, one would pull the tether with a stepwise series of fixed velocities from the spool while wrapping the tether increasingly around the brake pole for each fixed velocity.
For the second objective the tether tension as established by the space tether system under test and measured by the tensiometers is fed to the real time tether simulator which calculates the state of the tether and therewith dictates the unwinding velocity. The challenge for the space tether system's control electronics is then to control the tether deployment. Results are discussed in section 3.4.

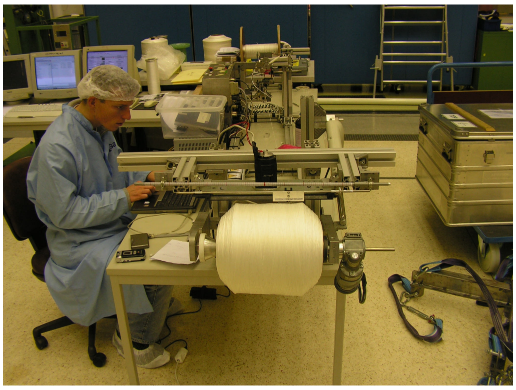

Figure 1: Tether winding system

TETHER SIMULATOR

The MTBSim[21] advanced tether simulator from Delta-Utec was further developed in order to include six DOF end-mass motion and full capability for tether mission planning (STK alike). It was validated by 6 independent parties (including ESA, TsSKB and various universities) in preparation for YES2.

A 7-step preparation for tether missions was successfully applied for YES2:

1. Characterization of deployer hardware
2. Design of deployment profile and control
3. Verification on advanced simulator
4. Monte Carlo simulations
5. Real-time test of controller software performance on flight computer using an external PC with a simple deployer hardware/tether dynamics emulator
6. Full system test using the closed loop unwinding machine
7. Late changes: verification by extreme case simulation, and test on flight computer using the emulator.

3.2 Tether deployer system

The YES2 tether deployer system concept is based on the SEDS tether deployer system[14]. The main elements of the YES2 deployer[17] are:

- the canister
- the core
- the tether
- the brake
- the cutters & melter
- Optical tether Loop Detection system (OLD)
- control electronics with control software
- ejection system

The canister [Figure 2] consists of 6 panels, a baseplate and two top plates to provide an attic with reduced EMC environment. The canister is designed to carry structural loads for small end-masses. The core is mounted on the basepate. The core and the canister can contain about 6 liters of tether.

The tether qualified for YES2 consisted mainly of 31.7 km Dyneema®, with some Kevlar and a section of tether ripstitched for safety reasons [see section 3.3].

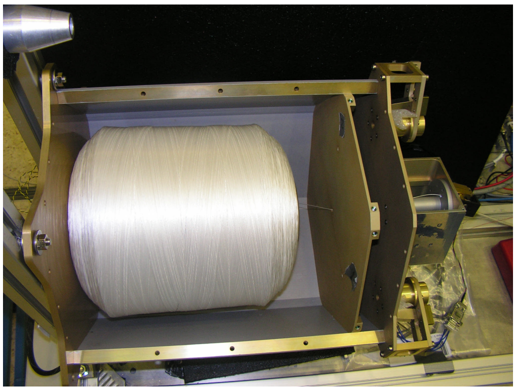

Figure 2: Tether canister

A brake system [Figure 3] is used to control the tension in the tether. It is a simple mechanism that wraps the tether around a pole in order to increase friction of a deploying tether. If the tether is not wrapped around the tether, the minimal tension (T_0) in the tether is due to stickiness of pulling the tether off the wound spool. The friction increases exponentially with each wrap around the pole. Although friction levels are noisy, control of the tether system is guaranteed by feedback algorithms [see section 3.4].

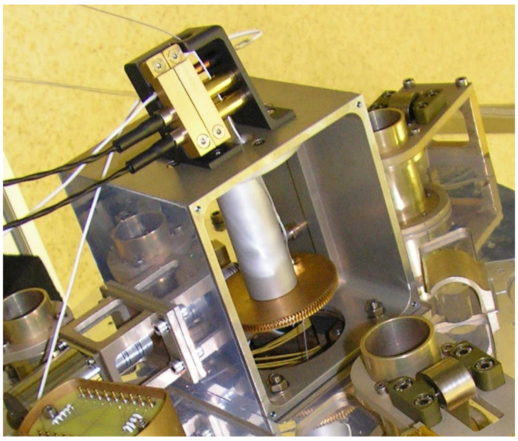

Figure 3: Brake system plus cutters

Tether cutters and a tether melter are placed on top of the brake system [Figure 3] and are the tether's exit point on the satellite into space. The function is to cut the tether at the end of the nominal mission or in off-nominal situations.

The tether length and velocity is determined by a logic based on information from 3 pairs of light emitting diodes and receivers (OLDs). The 3 receivers are in the core and the 3 diodes are in the attic plate of the canister. If the tether passes a pair, the diode's infrared beam is interrupted and a logic determines that a valid tether loop passes by. The logic takes into account noise, high frequency tether oscillation through the beam and failure of upto two of the pairs. The length of the tether is based on quadratic fits that are made during the high-precision winding [see section 3.1].

The control electronics has 4 main functions:

- Interrupt handling from the OLDs [OLD];
- Power distribution [PDU];
- Computing and datahandling [OBC][15];
- Driving a stepper motor [SD][16].

Besides the main functions the electronics have analog/digital input/output for other mission related functions.
The control software[15] is stored on the control electronics and uses input from the OLD interrupts as well as the quadratic loop/length fits to determine the deployment length and velocity. It also contains a reference deployment file with discrete information of nominal length, velocity, tension in time intervals, with some 300 values for the whole tether mission.

In order to separate the two end-masses of the tether, there is an ejection system. The 3 spring based ejection system is based on a flight proven design of the Swedish Space Corporation.

Detailed performance of the hardware is provided in[17]. The current tether system has the following specifications:

Table 1: Mass and Power specification. [including boxes and brackets]

Element	Mass [g]	Avg Power [W]
Canister	5300	-
Core	1400	-
Tether	5700	-
Brake+ motor Cutters/melter	1180	-
Electronics		
OLD	270	1
OBC	1200	5
PDU		5 (incl losses)
SD	310	10 (incl motor)
Ejection system	1650	-
Total	**17010**	**21**

The mass and power budget presented above is based on the YES2 hardware. Table 2 provides a mass and power budget based on optimized systems for a commercial system.

It can be seen in table 2 that mass savings are driven by two elements: the canister and the electronics. A non-load carrying canister which would be favorable in other configurations is considerably lighter and the control electronics system allows for further optimization (in mass, not in functionality).

Table 2: Optimized Mass and Power specification. [including boxes and brackets]

Element	Mass [g]	Avg Power [W]
Canister	3300	-
Core	1400	-
Tether	5700	-
Brake+ motor Cutters/melter	1180	- in SD-
Electronics		
OLD	50	1
OBC	300	1
PDU		4 (incl losses)
SD	200	10 (incl motor)
Ejection sys	1650	-
Total	**13760**	**16**

3.3 Safety measures implementation

In the course of working on tether systems and missions the authors find often similar concerns on tethers at any political level. As the launch review board, who signs for the launching and hence carries a responsibility, only familiarizes with the tether system when the hardware is delivered it is important to understand their potential concerns early on it the project and take timely safety related countermeasures.

The YES2 mission and system included the following safety measures:

- Orbit selection in a low orbit according to the recommended guidelines established in [1], and on an unmanned vehicle.
- Tether mission is brief and removed from orbit immediately in the nominal scenario, within days in the worst-case scenario (by downward deployment from a heavy platform).
- Nominal tether release through a triple redundant system, using two pyrocutters, each with their own double-locked latching system, and a thermal element (tether melter), powered by a dedicated battery). The cutter system shares its arming with the ejection system.
- Tether cutting is activated by timer, by direct telecommand, and, in case of deployment or sensor failure, by on-board autonomous software.
- Probability of jam is demonstrated low by a large amount of controlled deployment testing (560 km in case of YES2).
- The deployed endmass should be ejected with sufficient energy (40J in case of YES2) to overcome initial friction levels by means

of inertia until gravity gradient takes over (at about 1000 m).

- A jam in the first meters of deployment could lead to recoil of the deployed endmass and near direct impact with the deployment platform. Such an early jam would lead to a high tether tension, about 100 N. For this reason, the endmass is connected to the tether only through a sort of slipknot (Prusik knot) which is designed and tested to maintain connection during ejection shock, nominal deployment and potential shocks late in the deployment, but slip free in case of a >60 N shock, which only can occur in the first 15 meters.
- In case of an early jam (after 15 m but within the first 350 meters) recoil dynamics after an accidental jam could lead to a slow wrapping of the tether around the deployment platform. Using a damping system in the tether (ripstitching, [25]), sized to the ejection system energy and the tension shock levels that are to be expected during a jam at the critical length (here 350 m) almost all of the kinetic energy released in case of a jam is absorbed by the braking of the stitches in the ripstitch section such that the critical length interval is reduced from 350 m to about 120 m only, whereas the response time is increased to several minutes, allowing time for the on-board software to reliably detect the failure and cut the tether. Coriolis forces will secure that there is no collision on the first recoil, and the cut of the tether avoids wrapping in the subsequent orbits.
- Margin of strength in the tether should be based on testing of the braid, not on fiber strength data, should take into account bending/clamping effects and thermal load (friction braking), which can be shown to be dominant in most cases for Dyneema®. In case tether mass optimization is important, the section that will be subjected to the highest brake forces should be manufactured from e.g. Kevlar or Zylon or brake force should be reduced by deployment to a very high in-plane angle [4].

Another frequent concern of external critics is the reliability of a tether deployment: do tethers get entangled as easily in space as they do in my pocket - can their dynamics be reliably predicted, can they be controlled? This is addressed in the next section.

3.4 Reliability of the deployment

The YES2 experiment provided a large amount of data, including various independent measurements from which the deployment could be reliably reconstructed, as well as measurements of in-plane angle and tension signatures from different types of shockwaves. These data have been compared to the simulated deployment dynamics and the following could be concluded [17,21,22], Figure 4 to Figure 7:

- The tether and deployer performance was demonstrated to match largely the levels predicted in ground tests, Table 3. The notable exception was the tether minimal deployment tension (stickiness), dominant in the inertia phase (first 1000 m), for which additional thermal-vacuum testing is recommended.
- The deployment velocity filter and brake controller behavior in flight could be qualitatively reproduced in detail by simulation matching. The control as performed in flight was demonstrated to be sufficiently effective to be capable of delivering the capsule into a predetermined target trajectory with the same level of precision as a conventional rocket system, despite the high level of tether stickiness. Deployment irregularities in the first minute of deployment were unexpected and may be related to endmass dynamics interaction. Simple recommendations were identified that would make controller performance fully robust against such surprises. A controller resonance also occurred, which was reproduced in simulation, leading to a recommendation to analyze specifically and in detail controller performance in extreme cases. Measures to avoid such resonance were determined (faster brake actuation, design brake for less friction, tuned control gains).
- From Monte Carlo simulations a worst case deployment accuracy of better than 3% was predicted, comparing to the potential of the YES2 hardware as flown determined from the flight data of a deviation from target of only 0.5%.
- The simulation matching showed that the hardware model as used is sufficient to reliably predict tether deployment dynamics.
- The resulting simulated trajectory was confirmed to match the measured trajectory within the data accuracy level of 2-5° in-

plane angle, confirming proper representation of deployment dynamics.

- Complex dynamics such as those resulting from bounces and resonance, including spring mass oscillations, transversal waves and reflecting sound waves, could all be properly understood and qualitatively reproduced.
- The tether's damping coefficient seemed significantly higher than expected (0.14) based on simple ground tests (0.08), whereas the stiffness was well predicted by such tests (5000-10000 N).

Table 3. Quantified flight performance of YES2 tether and deployer vs. predictions

Property	Nominal	Acceptable	Flight
Friction	0.2	0.12-0.3	0.175-0.2
Stickiness	0.01 N	0.005-0.3 N	0.03-0.04 N
Velocity/ length dependency	8	2-20	7-8

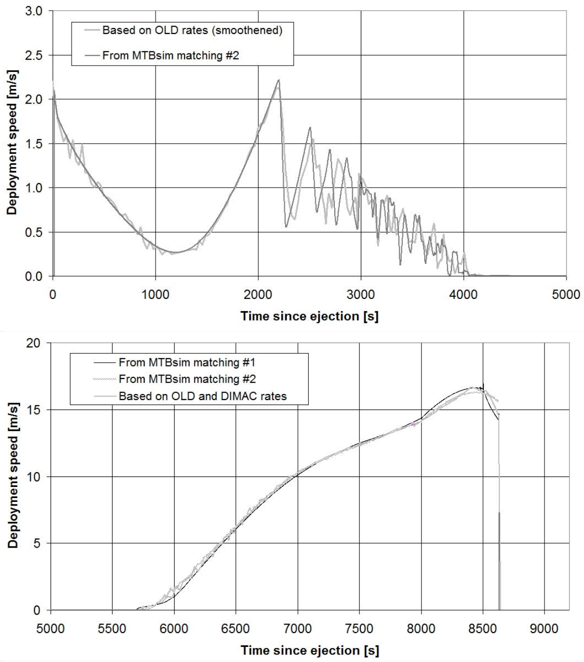

Figure 4. Reproduction of flight data of speed profile during first and second stage by simulator based on hardware model

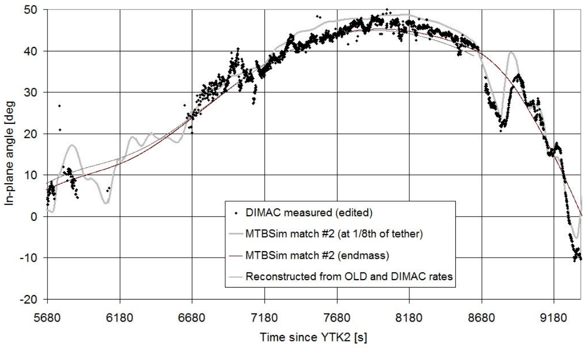

Figure 5. Matching of flight data for tether in-plane angle (measured at tether deployer) vs. reconstructed in-plane angle of endmass and simulated angle near tether deployer, evidencing transversal waves.

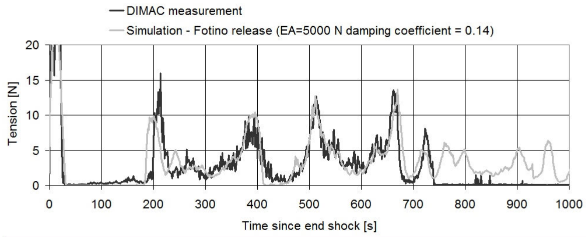

Figure 6. Match of bouncing dynamics (combined spring-mass and transversal waves) flight data vs. simulation (tether is cut at *t* = 740 s).

Figure 7. Nominal landing point and landing area from Monte Carlo run with extrapolated (hypothetical) landing point for Fotino based on flight performance of YES2 hardware.

3 APPLICABILITY AND SCALABILITY

With current tether technology a varied range of applications is already possible. In this section five examples are selected that are stepping stones for sustainable space transportation and at the same time may fit within the context of the European ambitions in space.

The Automated Transfer Vehicle (ATV) has been a major European development in space transportation for cargo transport and ISS station keeping. Today the ATV promises to be a good platform for a next step in space transportation with tethers.

EXAMPLE 1. ATV-ARV (SpaceMail)

Europe has reinitiated a SpaceMail concept; it is the initiative for the Automated Transfer Vehicle-Advanced Return Vehicle system to downmass from the ISS[3].

A promising solution would be to have this ATV-ARV capsule de-orbited from ATV by a tether with the same technology as flight proven by YES2. By decoupling the ATV-ARV de-orbit burn from the ATV de-orbit burn, a favorable entry site selection in Russia/ Kazakhstan, Woomera (or Europe) could be achieved and therewith avoid landing of the ARV in the Pacific Ocean. The advantages of such a SpaceMail system have been well described in [4].

Assume a 400kg ARV with 40 kg payload capability and compare a tether system with a conventional rocket engine.

Tether

A possible scenario for ATV before going into a destructive orbit is to circularize at a 350km orbit after leaving ISS and there perform a 32 km tether deployment.

A 14kg tether system as described in table 2, with a 32km, 0.5mm tether, could deliver a ΔV of 120 m/s and accurately deliver the ARV into a re-entry orbit. The current YES2 tether system optimized and consolidated by European industry can be used as is - no hardware scaling is required.

Rocket Engine

Alternatively, a conventional rocket engine could also be used to achieve an independent landing site. In such case, to keep the re-entry capsule simple, we assume here that ATV spins the ARV capsule before release and the rocket engine only provides the necessary deboost. For the deboost 16 kg fuel is required, plus minimal 6kg for engine, tanks valves and tubing. An ejection or release mechanism would add about 1.5kg. For now we assume control electronics are so simple that it doesn't add mass to the system (same electronics as when no separate de-boost is given). So total mass required for a non-sustainable rocket boosted de-orbit of a 400kg ARV is minimally 23.5kg.

From the perspective of the re-entry capsule there is a defining difference in de-orbiting with a tether or a rocket engine.

The rocket engine, valves and tanks would need to be accommodated and remain on the re-entry capsule and take precious mass and volume resources of the capsule, where the tether system can remain on ATV and the capsule only needs a tether attachment point. With some 40kg payload for a 400kg capsule from mass and volume perspective a rocket engine seems not acceptable, but a tether attachment point is.

From total system mass perspective the tether system favors the conventional rocket engine by 10kg for the assumed ARV capsule. This mass advantage will grow with more heavy entry capsules.

From the overall safety aspects towards ISS crew, a tether is much saver than a rocket engine as no explosive or pressurized goods need to be stored in ATV during docking.

It shall furthermore be noted that landing accuracies are similar for both systems [21].

Note:

Through tether momentum transfer a 12 tons ATV is thrown into a 350x364km orbit when ARV re-enters. If a few orbits later ATV destructively re-enters over the Pacific Ocean, a certain fraction of the 16kg fuel is required on ATV side to guarantee the right entry conditions, depending on the difference in argument between ATV and ARV landing zone. The fraction approaches 1 when landing ARV at Woomera and approaches 0 when ARV landing is at high latitudes like Northern Europe. Nevertheless this fraction of 16kg is assumed largely to be within ATV fuel margins and would not overrule the main tether system advantages.

The main argument for using a tethered re-entry for ARV should in any case be firstly Europe's advocacy for sustainability.

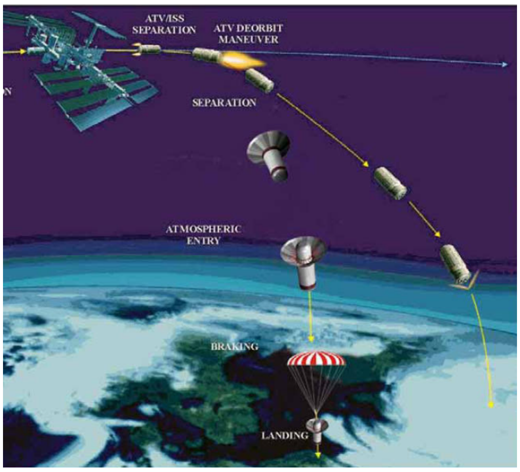

Figure 8: ATV/ PARES de-orbit scenario, where PARES (example re-entry capsule) landing side selection is limited due to shared de-orbit burn.

EXAMPLE 2. ATV-ISS (SpaceMail)

Another possibility is to de-orbit ATV itself with a momentum exchange tether from ISS. It would obviously require a thicker (~1.5mm) tether and deployment to a high angle before the momentum transfer swing is initiated. Momentum exchange of ATV would save a significant amount of fuel: about 1 ton of fuel per ATV flight. Note that the ATV represents about the largest mass that can safely be de-orbited from the ISS by tether. A deorbit of the Space Shuttle with a tether would be challenging the ISS strength and stiffness performance.

EXAMPLE 3. DEBRIS

Another field where tethers can significantly contribute is in the clean-up of defunct satellites and spent stages. To effectively remove objects from space, a tether would be a very elegant and efficient solution. The more elaborated sustainable concept to this end is presented by Pearson and Carroll, EDDE[8]. EDDE is a spinning electrodynamic tether concept that solves various classical tether system problems in a single lightweight system. On one hand the centrifugal forces of the rotation create dynamic stability and allow for large currents and hence (through large resulting Lorentz forces) short traveling times. On the other hand by modulating the current over rotation and orbit, the net force can be controlled in several directions allowing for inclination, node and altitude change at any inclination. Carroll states[9] that with 20 relatively simple systems 1600 heavy objects can be removed in 5 years, cleaning space and therewith ensuring its use in the next decennia. The system mass is estimated to be only hundreds of kilograms. As debris is an inter-agency responsibility, also the solution could be brought forward internationally. A number of small mostly passive deployers is required for the current concept that could in principle use SEDS-type hardware like that developed for YES2 [23].

EXAMPLE 4. EXPLORATION

For space exploration, rotating electrodynamic tethers are of primary interest in Jovian orbits due to Jupiter's large magnetic field[10, 11, 12]. A mission concept proposed by SanMartin [10, 12] is to use the Lorentz force to firstly lower the apojove.

Under 20 perijove passes would be required to take the spacecraft to a circular orbit at about 1.3 the Jupiter radius, below the Jovian radiation belts. Once the spacecraft is in a circular orbit, current would be controlled to allow for a slow spiralling of the orbit over a period of several months, for surface and subsurface exploration of Jupiter, and magnetic and gravimetric measurements.

A smaller and simple (<10 kg) precursor tether could be scheduled as a piggyback to Jupiter on the next Juno mission in 2011.

EXAMPLE 5. T-SERIES

A typical example that demonstrates the scalability of the tether system is the T-series upperstage, a system study performed for CNES [18, 19]. A tether system could replace a solid or liquid end stage motor and deliver through momentum transfer a micro-satellite accurately in orbit, while at the same time providing the required de-orbit service for the upper-stage over remote ocean. The T-series tether system required a 160 km tether to insert a 130kg satellite accurately in SSO orbit. We opted a system with 3 YES2-volume-size canisters to hold the tether. The canisters are in series and the tether is taped with Kapton in the canister and between the canisters. When a canister is empty the tether cuts through the Kapton and continues to deploy from the next canister. In this configuration [Figure 9] the canisters are not designed to take the structural loads and hence are lighter [3.3kg each]. Deployments in T-series upto 55 m/s and 90N tension led -for thermal reasons- to a choice of mostly Zylon [melting temp: 650˚C] as an alternative material for the high speed/high tension deployment range. The UV sensitivity of Zylon was not an issue as of the short tether mission time and hence short exposure to UV.

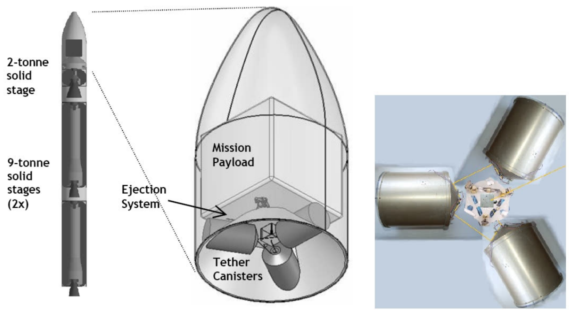

Figure 9: T-series: Tethered upperstage

The tether deployment controller is to be used to correct for the solid second stage insertion errors. Hence a third complex re-ignitable liquid stage is no longer necessary. The system is thus accurate and simple[19]. As seen in the example thermal considerations are important for scaling. The heating of the tether is linearly dependent on the brake force applied to the tether (and, for any significant level, mostly independent of velocity). Fast deployments however typically require high braking levels. As about 50% of the heat goes into the tether and 50% into the barberpole brake, also a proper cooling of the barberpole shall be evaluated at scaled up applications.

4 CONCLUSION

In this paper we elaborated on sustainable space transportation. The Space Elevator could be the only truly sustainable solution. We concluded that state-of-the-art tether systems can already contribute to sustainability and are a key building block for the space elevator. There is not yet a common vision on sustainable space transportation, but a potential for an early initiative for Europe is provided based on state-of-the-art European tether hardware. It has been demonstrated how reliable performance can be obtained using simulation, test and previous mission experience. We discussed safety features that can be implemented in tether mission proposals to help increase the probability of in-flight demonstrations and stepwise development of applications.

As such, YES2 was a first good step into sustainable tether development in Europe. It is the result of a vision of the ESA Education Office. The intention has been to plant a seed. This seed has budded and matured and must now be consolidated by further industrial developments towards a sustainable space transportation for Europe. An industrial sequel mission to YES2 is proposed to make the step to commercial applications.

ACKNOWLEDGMENTS

All students involved in YES2 have greatly contributed to the qualification of the European tether system. It is a new generation that is very aware of their responsibility in sustainability.

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