Summary of Data Analysis of the YES2 Tethered SpaceMail Experiment

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The 2nd Young Engineers' Satellite (YES2) is a 36 kg student-built experiment that piggybacked on the Foton-M3 microgravity platform in September 2007. YES2 intended to demonstrate tethered SpaceMail, a concept for frequent sample return originally proposed for the International Space Station (ISS). This paper summarized the YES2 mission results. The planned tether deployment included a unique two-stage approach, a tether swing of 45 degrees and a capsule release from the bottom of the tether for increased landing precision. After a successful first stage, during the second stage the tether deployed to its full length of 31.7 km rather than the target length of 30 km due to an electrical problem. It was released at the proper time close to the nominal release point, sending Fotino some 1250 km upstream of the nominal landing point. The capsule was not yet recovered. The YES2 mission had the following scientific objectives: reconstruction of the deployment trajectory; estimation of the capsule trajectory and determination of the landing spot; assessment of the closed-loop control performance and potential landing accuracy; assessment of the deployer hardware performance for the SpaceMail application; study of tether physics and suitability of simulations and testing for planning future tether missions. All the tether mission objectives could be achieved, the novel deployment features were successfully demonstrated, any problem occurring was identified and solutions proposed. The quantity and quality of the data allows for improved understanding of tether dynamics and recommendation for future activities. Based on the lessons learned a sequel mission can be defined with promising perspectives.

Nomenclature

t	= time
T	= tension
T_0	= minimal deployment tension (tether stickiness)
θ	= in-plane angle, bending angle
f	= friction coefficient
F_{brake}	= brake force

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I	= inertia multiplier
m	= mass
n	= number of wraps (turns) around the barberpole brake
l	= tether length
ρ	= tether density [kg/m]
σ	= standard deviation
v_0	= initial velocity
Ω	= mean angular rate of Foton = $2\pi/5392.3$ rad/s

I. YES2 Background

A. Introduction

Young Engineers' Satellite (YES2) is a 36 kg student-built tether experiment that piggybacked on the Foton-M3 microgravity platform[1,2] in 2007. It featured the first space tether deployment in over a decade. The project objectives were threefold: 1. education, 2. deployment of the 31.7 km tether to accurately release a 6 kg spherical capsule into a re-entry trajectory, 3. landing of a small capsule (Fotino[3,4]) in Kazakhstan. YES2 thus intended to demonstrate SpaceMail, a concept for frequent sample return originally proposed for the International Space Station (ISS)[5]. The project could become reality through and comprehensive and careful analysis and testing of the tether system, taking into account safety aspects and concerns of critics right from the start of the project.

The tether was fully deployed on the 25th of September 2007. A wealth of data was collected, that allowed to achieve all science objectives, not only reconstruct the tether deployment, but also to cross-validate the results[6], quantify the tether deployer performance[7] and study tether dynamics by simulation matching and observing longitudinal, lateral and spring-mass oscillations in significant detail[8]. In this paper a summary of the flight results is provided.

First, an overview of the project history and particular challenges is provided. Next, the mission, science objectives and mission results are described in more detail. The paper concludes with an evaluation of success, problems & solutions and outlook.

B. A history of challenges

The YES2 project was not only a satellite design project, it also featured state-of-the-art technology developments such as the tether system, re-entry capsule and novel simulation and software technologies[9]. This made ESA's most ambitious educational project to date.

After an initial search by Delta-Utec for safe options for a SpaceMail tether deployment after completion of ESA's Tether System Experiment industrial study[10], in 2001 the Foton vehicle was selected[11]. No funding for a normal industrial approach could be found however. The YES2 project was then started in 2002 by ESA's Education Office, with education as primary objective. The original scope of the project for the Prime Contractor Delta-Utec was to set-up a university network, that would in a next phase take over the activity and lead the design, manufacturing and test of the satellite. In this first project phase, a network of 25 universities from all over Europe, Canada, Japan and Russia was set-up, and 4 Centers of Expertise were identified covering mission analysis (Samara State Aerospace University), mechanical engineering (University of Patras), tether system development (Universities of Applied Sciences in Remagen/Krefeld) and testing and re-entry capsule development (University of Modena in Reggio Emilia). About 250 students worked out initial ideas through group projects[12]. A tether mission simulator was developed based on the Delta-Utec tool MTBSim[8] by about 10 students and a tether deployment test rig was developed by about 20 students[13], as well as the first engineering model of the tether deployer hardware[14] and software. A PDR was held successfully. At the PDR it was decided that system engineering and management activity could not be effectively taken over by the universities as initially intended and should remain with Delta-Utec. Such a central lead was necessary to maintain the overview, maintain the prime focus on the project interests rather than local academic objectives and, importantly, maintain knowledge, manage and perform repeated knowledge transfer to new students, as most students are only in the project for 3-6 months. At the universities often no time was available for the guidance required to bring students up to the demands of a real space hardware project quick enough to be productive and provide significant progress in such a short period. As very little funding was available to cover for this situation, a difficult period followed, in which creative solutions were found to keep the project going. The main impact of this phase was a significant delay in the maturing of the project, leaving almost too little time to develop the system in time to meet the launch date of Foton-M3. Specifically the Centers of Expertise continued to support to the fullest extent, and also Delta-Utec continued to manage the project, largely on internal R&D. The European Commission was found to be willing to support a significant number of student internships (due to the opportunity for co-location this support was fundamental) as well as early heat-shield testing. In 2005 the funding issue for the remainder of the project was finally resolved and the project could continue. By this time some important changes with respect to the PDR design had been introduced however:

- The design, configuration item control and documentation should be upgraded to ESA standards, in particular the MAN-GPQ standard[15] that is required for all Foton payloads.
- The Fotino capsule (designed as a simple sphere with only a beacon) was to be equipped with a parachute and scientific payload.

Only at this time could negotiations with the launcher authorities start, leading to repeated upgrade of interface specifications with respect to previously held assumptions, such as full thermal isolation from the Foton spacecraft and increased number of safety features for the pyrotechnical power interfaces. The CDR was finally completed in the Summer of 2006. Only at this time, one year before launch, certainty about budget for the manufacturing and testing was obtained and long-lead items could be ordered. About 20 student interns were now co-located at Delta-Utec and ESTEC for an intense final activity, many of them new to the project. Students that had been longer in the team, some of them just graduated, supported the critical activities. Through an immense effort by the whole team in January 2007, as required, first a YES2 dummy unit was delivered to ESA and next, on time on May 2nd 2007, the flight system, having passed the EMC, thermal vacuum and shaker tests. At time of delivery the system contained a tether that had been determined by deployment testing to be out-of-spec. In the next months a new tether was developed and qualified. The tether replacement was successfully performed in July 2007 in Samara, Russia. In Samara also the interface with the Foton spacecraft could be tested for the first time, which led to a number of software changes to improve the telemetry read-out. At this moment, the actual tether mission was however still not secured. Late July 2007, a meeting was convened in Moscow discussing the safety concerns of the tether deployment with respect to the Foton spacecraft. As a result it was decided to update the flight software and reroute a number of cables in order to provide autonomous tether cutting capability in addition to the already available ground command capability. Only after successful implementation and verification of the new system in August the agreement for launch of YES2 was finally obtained and YES2 was launched only weeks later on September the 14th 2007.

At this time the first, educational objective of the project had already been achieved. Over 380 students had participated in the project, from 50 universities in 25 countries. About 180 of them contributed to the project's design documentation. 100 Students were provided an internship. The scientific/educational output of the project are about 70 conference papers and 50 thesis reports. Importantly, the project was run in an atmosphere of friendship and with shared concern of student interest, productivity, attention to technical details and quality (testing and logging, again and again), which strongly reinforced the educational value of the project. Virtually all the students left the project very satisfied. Nevertheless the overall development cost of the YES2 was limited to only about 10-15% of that of a typical industrial approach, but this feat is not necessarily repeatable.

C. Design

YES2 was built to operate from a Russian platform called Foton-M3, which carries amongst others ESA microgravity experiments, under the flag of ESA's HME Department and orbits at about 265 km altitude. The YES2 is mounted in its entirety on the outside of the Foton spacecraft (Figure 1).

Figure 1. YES2 on Foton

The YES2 design is described in detail in [2]. YES2 has three components (Figure 2):

- Fotino, the 6 kg re-entry capsule, containing a science package and a recovery system with beacon and parachute[16]
- MASS, the 8 kg tethered subsatellite Mechanical and data Acquisition Support System, with tether science instruments and transmitter
- FLOYD (Foton LOcated YES2 Deployer), 22 kg. It contains the ejection system, the tether deployer, control electronics and interface to Foton-M3 for power, data storage, telemetry and telecommand.

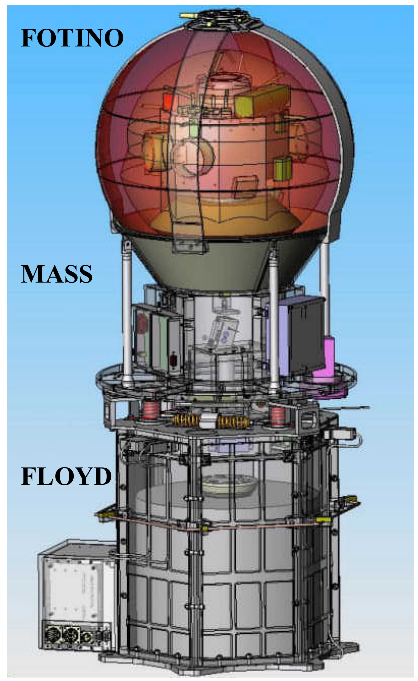

Figure 2. YES2 contains FLOYD (Foton LOcated YES2 Deployer), MASS (Mechanical and data Acquisition Support System) and Fotino, the spherical re-entry capsule.

Figure 3 provides a simplified schematic overview of the YES2 deployment hardware functionality. An ejection system initiates the deployment of the tether from a fixed spool located in FLOYD by ejecting the Fotino/MASS endmass. The spool was wound and characterized under controlled conditions before flight[7]. The tether is unwound as it is pulled over the head of the spool towards a central, small exit guide and, for each loop, crosses the Optical Loop Detection (OLD) infrared-beams. This allows the OLD electronics to register the passage and forward signals from each of the three "encoder" channels to the On-Board Computer (OBC). The OBC filters the signals to generate the length and velocity of deployment. Filtered velocity runs about 8 s behind on true velocity. The results are compared to a reference table stored on-board, and using gains and a performance model of the spool and brake system, commands are sent to the "barberpole" brake mechanism in order to control the deployment by increasing or decreasing friction (Figure 4). The level of friction is controlled by guiding the tether around a central hard-anodized pole of about 2.4 cm diameter. Each wrapping increases the effective friction by a factor of about 3 such that a large range of tension -as typically required for a tether deployment- can be controlled with little effort[14]. A mathematical model is used to estimate the friction level applied by the brake for each number of wraps. The model contains the effects of tether stickiness on the spool (T_0), tether unwinding dynamic effect (roughly proportional to the deployment speed squared, and increasing heavily when deployment approaches the solid core of the spool), and the friction effect of the wrapping of the tether around the pole. The parameters were determined from ground based tests[6]. Friction is a rather empirical process, but because of the closed-loop control, only a matching precision of model to reality precision of about a factor 3 is required.

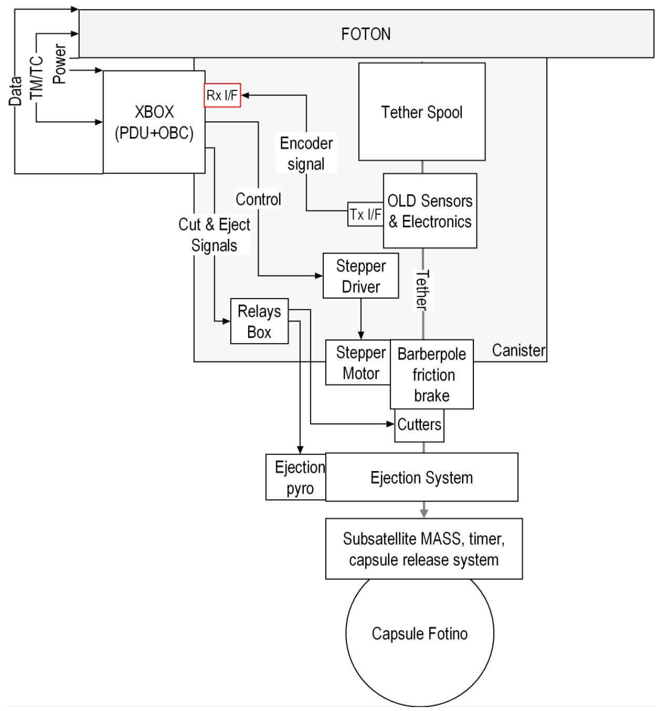

Figure 3. Simplified overview of the YES2 and tether momentum transfer system. *The system performed nominally except that during the mission, an intermittent power supply failure occurred for the Rx I/F (receiver interface) of the three OLD signals (boxed in red).*

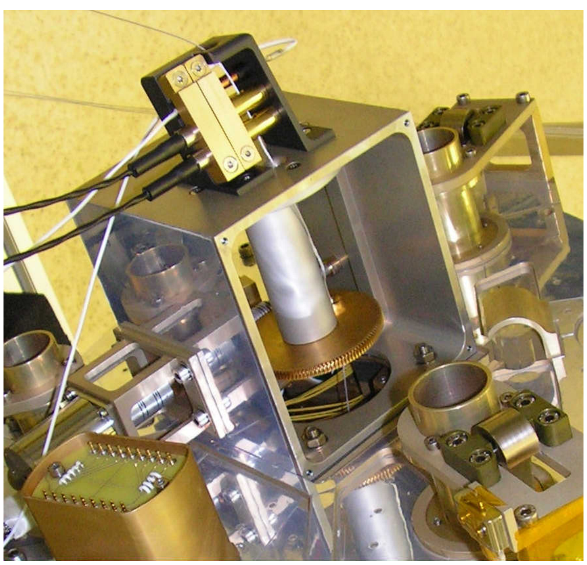

Figure 4. YES2 barberpole brake system. *Brake is in free deployment configuration (n=0). The tether cutter bracket can be seen on top, the stepper motor driving the gear in the left bottom.*

The tether, winding and deployer system is described in detail in [7]. The barberpole brake is described in [14]. The deployment measurement, controller and actuator hardware and software is described in [17] and [18]. Safety aspects are treated in [2,19].

Sensors available to track the deployment include:

- Optical Loop Detectors (OLD) in tether core on FLOYD

Allows to determine length and rate and reconstruct deployment angle and tension using a simple expression for tether dynamics[6]

- Magnetometers, tensiometer and a gyroscope on MASS
  These sensors allow to determine the subsatellite dynamics and the disturbances created by the ejection and the safety and securing features included in the first 15 meters of the tether. The simple data package[20] provided information for a range of 150 m.
- Sensitive 3-axis accelerometers and magnetometers on Foton (DIMAC experiment)[21]
  These sensors allow to derive tether tension, as well as direction of the tether near Foton (from the x and y components of the disturbing acceleration, combined with magnetometer data). A spectrograph can be used to determine the deployment rate, and a number of identifiable absolute points along the length of the tether (based on changes in the tether winding pattern).
- GPS on Foton (YES2 SSAU experiment)[20,22]
  This data would allow for in-plane angles and tether length confirmation. Data quality is good, but analysis has just started at the time of writing.
- Housekeeping information: voltages, temperatures, commanded brake position, error flags etc.

II. The mission

D. Summary

The YES2 experiment deployed a 31.7 km long, 0.5 mm diameter mechanical Dyneema® tether in 8626 seconds, downward from the 6535 kg Foton-M3 spacecraft at an altitude of about 265 km. The tether was then cut as planned at t=9364 s. By cutting the tether near the vertical (below the deployment platform), an efficient and propellantless momentum transfer between the upper and lower endmass is executed. This momentum transfer allows for a number of applications. At the same time, the YES2 deployment represents quite generically a critical stage that many future tether missions will have to go through. In fact, the YES2 deployment was somewhat more complex than may be required for other applications.

In the YES2 approach first a vertical stage of 3.4 kilometers length is deployed to stabilize, dampen any transversal oscillations and synchronize the 13.9 kg endmass with the argument of the target trajectory. In principle the time after completion of the first stage allows also for finetuning of the mission timeline (through ground control) for improved landing accuracy. A much longer second stage with relatively large gravity gradient forces can then be deployed quickly and robustly (up to the full length of 31.7 km in case of YES2). This two-stage approach was successfully performed for the first time by YES2. Deployment tension varied between 0.03 N in the first stage to 0.16 N during the hold phase between the two deployment stages, and up to 2N in the second stage. The foreseen maximum tension at the end of the second stage was 3 N, but due to over-deployment a shock of 40 N was introduced. The over-deployment was found due to an unfortunate electrical failure in the power supply to the OLD signal interface to the deployment controller (the OBC), [17], which in effect shut down the controller and lead to an open-loop completion of deployment, no smooth end-braking but instead a considerable shock of 40 N. The YES2 tether is able to withstand a 300 N shock. A passive release at about 60 N tether tension was implemented for safety, which did not trigger. In-plane angles ranged from 0 to 50 degrees (forward direction), with a final downward-backward swing from about 40 degrees amplitude (Figure 19). The deployment speed ranged from 2.2 m/s initial to a 16 m/s maximum and about 15 m/s at the end of deployment (Figure 6) [6].

The mission timeline is summarized in Table 1 and Figure 5.

Table 1. YES2 Mission Timeline

Event	Time (UTC)	Orbit #	YES2 time (seconds relative to YTK2)	Description
Launch Foton	11:00:00	1	-	14 September 2007
Upload telecommand timeline	14:00:00	163	-	24 September 2007
Switch YES2 on	2:03:00	171	-9813	25 September 2007
First relayed raw data downlink	2:07:00		-9573	Through Telescience Support Unit (data storage and forwarding) inside Foton (confirms temperature OK)
YTK10	2:13:00		-9213	Arm pyro's

TKTM	3:17:00	172	-5375	Receive telemetry (confirm arming)
YTK8	4:45:33	173	-60	Switch on MASS
YTK2	4:46:33		0	Ejection
TKTM	4:50:00		207	Receive telemetry (confirm ejection, reaching 300 m safe length)
Start hold phase	5:55:13		4120	-
YTK4	6:19:32	174	5580	Prepare for second stage
Start second stage	6:21:12		5680	-
TKTM	6:23:00		5786	Receive telemetry (confirm first stage and start second stage)
Release Fotino	7:22:17		9344	-
YTK3	7:22:37		9364	Cut tether on Foton side
Projected Fotino landing	7:57:00	175	11420	Nominal landing site 66.2E 50.6N. Ground recovery team situated downstream at 67.5E 51.6N. No beacon signal was received
TKTM	7:53:00		11186	Receive telemetry (confirm second stage deployment)
Switch YES2 off	9:16:00	176	16166	-
Last relayed raw data downlink	12:15:00	178	-	Through Telescience Support Unit (data storage and forwarding) inside Foton (full download raw data)
Landing Foton	~7:58:00	189	-	26 September

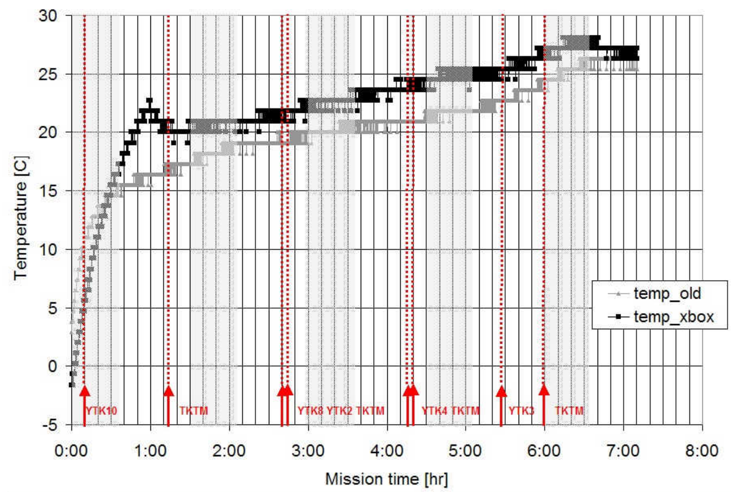

Figure 5. Temperature and telecommand history during YES2 mission. *The shaded zones indicate night time. The approximate temperature of the tether on the spool (OLD) and OBC (XBOX) are indicated.*

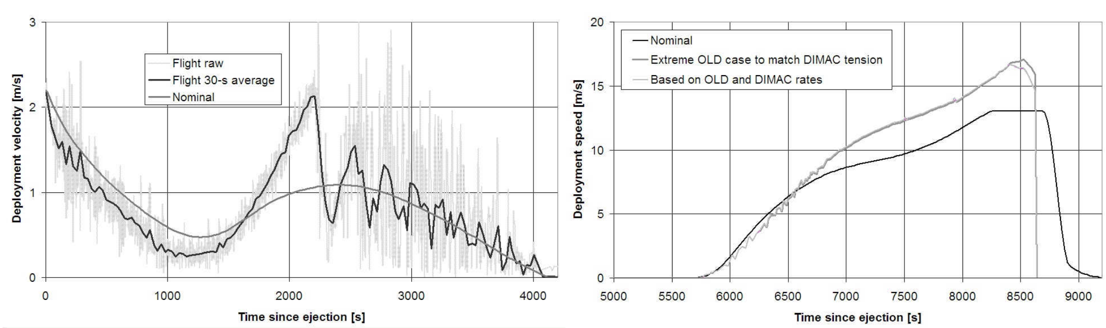

Figure 6. Deployment speed of YES2 mission vs. time and nominal in first and second stage.

E. Science objectives

The YES2 mission and data analysis had the following objectives:

- demonstrating safety of the tether deployment

- reconstruction of the deployment trajectory,
- estimation of the capsule trajectory and projected landing spot,
- assessment of the closed-loop control performance and potential landing accuracy for the SpaceMail application,
- assessment of the deployer hardware performance for the SpaceMail application,
- study of tether physics and suitability of simulations and testing for planning future tether missions.

All objectives were achieved, although due to the lack of beacon signal from Fotino the capsule's landing spot could only be estimated. The off-nominal ending of the deployment (no smooth endbrake) on one hand made it more difficult to demonstrate the real SpaceMail potential (although sufficient data is available to this purpose), on the other hand it allowed for more interesting tether dynamics and oscillations to be studied. The inofficial objective of Fotino recovery (including measurements made during its re-entry) could not yet be achieved.

F. Mission results

1. Deployment reconstruction, and Fotino trajectory

The deployment starts with ejection of the MASS/Fotino endmass. Analysis of the OLD data and fit to integration from tension measurements from both MASS and DIMAC demonstrate the (effective) ejection speed was nominal, 2.2 m/s. The pitch-off rate of the capsule could be determined from MASS gyroscope and magnetometer data to be only 1.55°/s, demonstrating excellent performance of the 40J ejection system (Figure 8). Simulations could be matched to the endmass angular dynamics for extrapolation throughout the mission, all the way into re-entry. The OLD data showed nominal unwinding behavior of the tether during most of the first deployment, although there were two periods of irregular unwinding of loops from the spool. The first period lasted for a few minutes and peaked about 30 seconds after deployment. It is likely that this irregularity was the result of endmass oscillations, that could not be tested reliably on the ground, and its study in fact represented one of the mission objectives. The On-Board Computer software uses a filter to calculate the velocity from the OLD pulses. It contains two simple checks to verify healthy performance of the OLD's. The first check verifies whether the pattern of pulses from the three channels arrives in the proper order. If this is not the case, it assumes one pulse is missed, and the software fills in the gaps. This feature performed excellently during the flight. The second feature is activated in case two subsequent pulses arrive from the same channel. Such an event can occur if the tether vibrates briefly in front of a single channel. This is what the software assumes in principle, and the noise is ignored. If the pulse interval lasts longer than a certain period of time (set based on ground tests) however, the filter assumes there was a double OLD pulse failure on two subsequent channels, and fills in the gap by counting a full loop. Analysis of the raw flight data shows that such a situation hardly ever occurs and this additional failure recovery function is therefore unnecessary. In fact, during the first period of irregular deployment, it falsely triggered several times in a row and counted about 10 or so false loops of tether. As a result, the deployment velocity was overestimated by about 10% for some tens of seconds, and the controller responded by additional braking (Figure 7). The actual deployment velocity was brought some 40 cm/s under the nominal velocity in the first minute after ejection. Normally this is not a problem, but because also the tether minimal deployment tension (stickiness to the spool) turned out to be just out-of-spec (about 4 cN compated to the maximum allowable of 3 cN), there was no possibility for smooth control. The brake was released for 2200 s during which the tether was eventually spooled out faster than nominal in order to catch up with the initial lost length. When the length was nominal again, the brake was reapplied abruptly, and a control and speed oscillation started (Figure 6), leading to a 10 degree or so in-plane oscillation at the end of the first stage (Figure 19, Figure 20). The first stage length that was obtained was determined to be nevertheless very accurate, 3378 rather than the nominal 3390 m, providing a good basis for a nominal second stage of deployment (Figure 9). Note that the following Eq. 2 was used as the first source to reconstruct both in-plane angle θ and deployment tension based on the tether length data (from OLD and other sources)[23]:

$$\ddot{\theta} + 2\frac{\dot{l}}{l}\left(\dot{\theta} - \Omega\right) + \frac{3}{2}\Omega^2 \sin 2\theta = 0$$

$$-\left(m + \rho l\right)\cdot \ddot{l} + \left(m + \frac{1}{2}\rho l\right)\cdot l \cdot \left[\left(\dot{\theta} - \Omega\right)^2 - \Omega^2\left(1 - 3\cos^2\theta\right)\right] = T = F_{brake} + \rho \dot{l}^2 \qquad \text{Eq. 1}$$

Eq. 2 is valid for light tethers with a small endmass deployed from a large platform in circular orbit and takes the shape of Hill's equations expressed in polar coordinates, slightly adapted to include tether tension and tether density aspects. These equations ignore tether flexibility aspects. For this reason, a simulation was made to match the mission data using MTBsim, an advanced tether simulator, such that the influence of these aspects could also be studied[8].

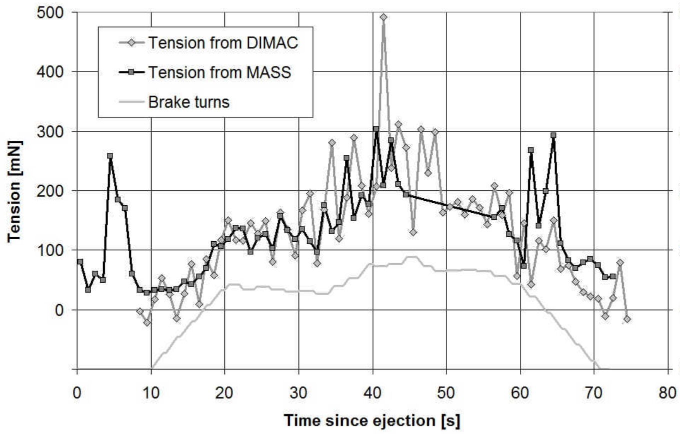

Figure 7. Tension and braking activity directly after ejection. *The initial spike is due to ripstich deployment, the stretched second increase in tension is related to the increased number of turns on the barberpole brake.*

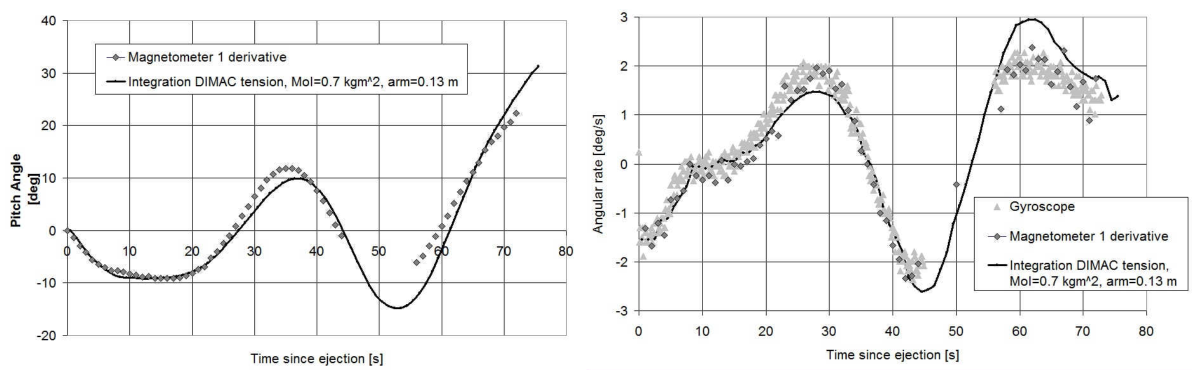

Figure 8. MASS magnetometer and gyro data directly after ejection, including simulator matching

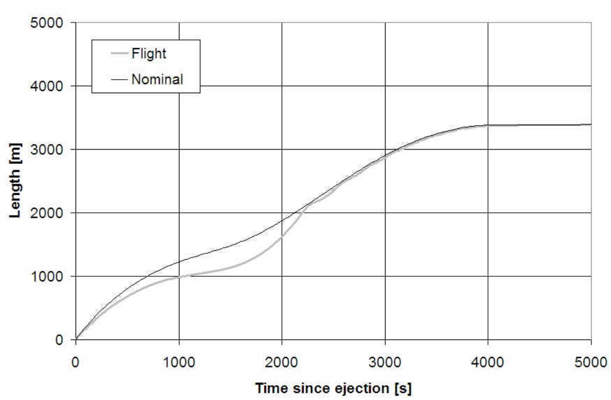

Figure 9. YES2 deployed length, first stage

The hold phase was nominal, the length was held constant with subtle adjustments by the controller meant to maintain a minimum amount of brake turns, as to allow a quick and nominal start of the second stage. The transversal oscillations dampened out for a large part.

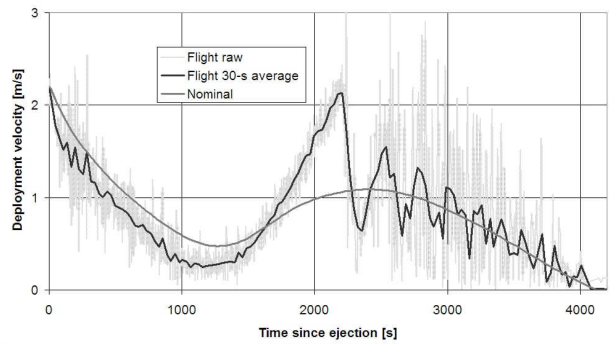

Figure 10. YES2 deployment velocity, first stage

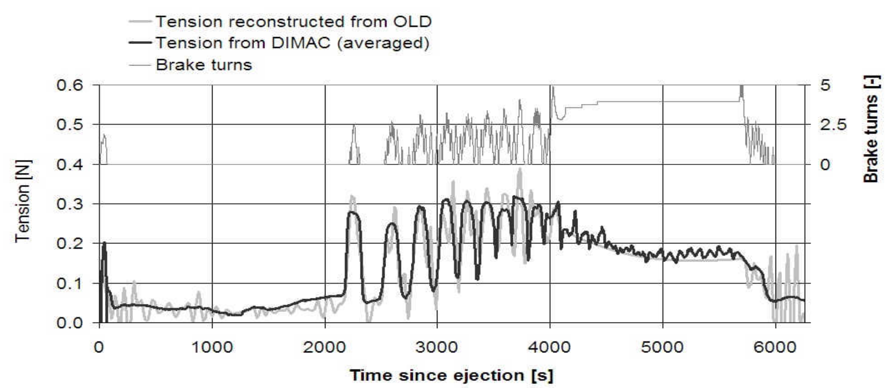

Figure 11. YES2 flight tension and brake activity from ejection to start of second stage

Some 500 s into the second stage, the OLD data as recorded by the On-Board Computer (OBC) started to break down due to a failing electronics patch that was intended to correct a broken input signal on the OBC's CPU board[17]. In response, the brake was turned to zero and the deployment continued in a free, uncontrolled manner. With the brake set to zero the deployment accelerated somewhat faster than nominal (to 16 m/s rather than 13 m/s) and overdeployed to the full length of 31.7 km rather than the target length of 30.0 km. There was no gentle deceleration near the end, the deployment stopped abruptly at about 15 m/s leaving a distinct tension signature at t = 8626 s.

Despite the incompleteness of the OLD data from 6260 to 8626 s, still sufficient data was available to determine the loop rate better than 1 Hz (about 0.3 m/s) until t = 8250 s. As the time of deployment completion was known within one second from the tension pulse, the remainder of the deployment could in principle be interpolated with a precision of about 1 m/s, confirmed with the help of a spectrograph of DIMAC-measured disturbances to the 6535 kg Foton-M3 spacecraft. Remarkably, through Fourier analysis, the rattling of the unwinding tether (weighing only 0.2 g/m) was clearly distinguished by the DIMAC experiment (Figure 12). The rate information extracted from this graph fitted neatly to the OLD rates (Figure 13). Moreover, the spectrograph reveals details of the winding pattern, such as the cyclic frequency of the winding head[7]. It is therefore possible to extract from the spectrograph four definite, absolute length measurements (Table 2), that match well with the integrated rate data. The maximum length reconstruction error during the second stage is estimated to be 0.3% or 100 m.

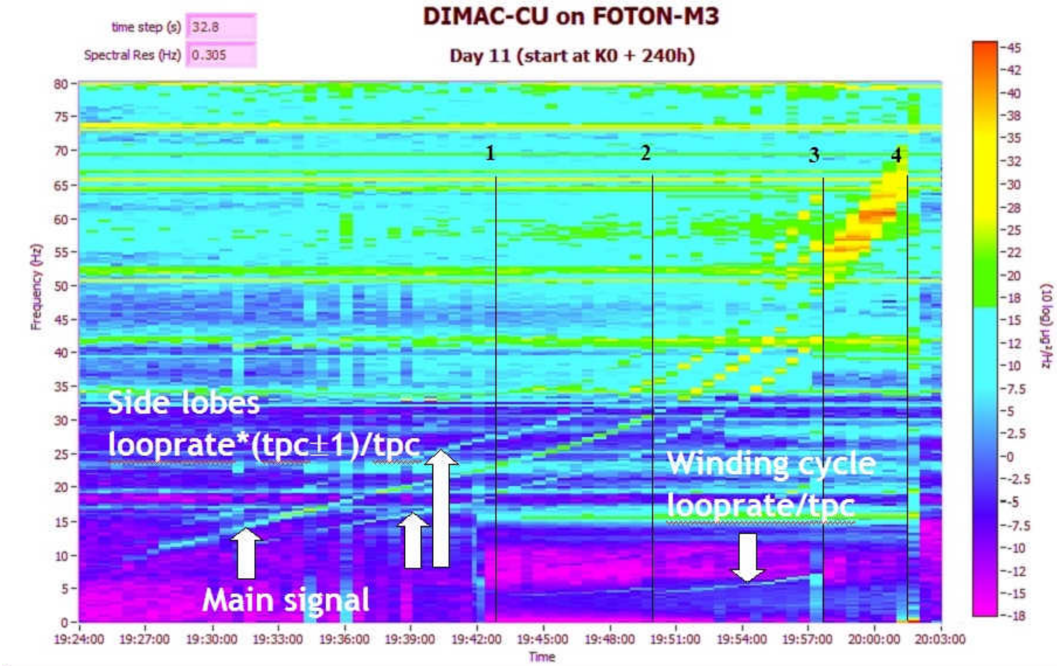

Figure 12. DIMAC spectrograph. *Edited to highlight YES2 looprate curve. Length marker events are indicated, see accompanying Table.*

Table 2. Winding events. *Recognized during deployment by DIMAC instrument, providing exact length reference*

	Winding event	t [s]	Length [m]	Loops [-]
1	*5 to 6 turns per cycle*	7512	15421	24135
2	*6 to 7 turns per cycle*	7937	21168	35754
3	*criss-cross to parallel*	8397	27979	53306
4	*end of tether*	8626	31705	66776

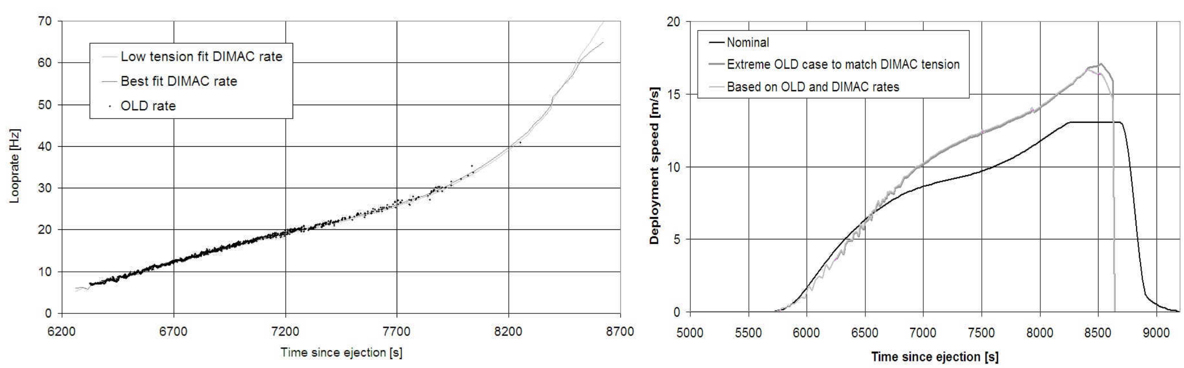

Figure 13. Looprate development during uncontrolled deployment in Stage 2, equivalent deployment speed vs. nominal. *OLD loop rates were determined based on the number of same-channel pulses received within ~0.2 s time intervals. The knick around t = 8400 is inserted to obtain a realistic fit and accounts for the winding transition from criss-cross to parallel.*

The development of in-plane angle with time should be determined precisely if the trajectory and projected landing site of the Fotino capsule is to be determined. Estimates of the in-plane angle development have so far (GPS data will be available soon) been made in two ways: through deployment reconstruction using Eq. 1 (or alternatively, the MTBSim tether simulator), and through the DIMAC three axis accelerations. During YES2 the Foton-M3 had the DIMAC x-accelerometer aligned with its body axis (in the approximate direction of the tether deployment), the y-accelerometer in-plane and the z-accelerometer out-of-plane. The angle between Foton-M3 and tether could be determined simply by taking the arctangent from the y and x measurements. Combined with the attitude of Foton (obtained mostly from the DIMAC magnetometers, except offset and angle above θ = 30º which are determined from Foton horizon sensor data) the tether in-plane deployment angle could be determined (also the out-of-plane, which was zero) to about 2-5º precision (dependent on the signal to noise ratio and the magnetometer precision). The results show that the general trend and the hold phase oscillation and the swing to the vertical are matching within the stated precision level (Figure 20). The DIMAC data shows a superimposed oscillation that is related to transversal waves and was reproduced by simulation (see Section 4).

The endshock at deployment completion occurs near θ = 40º. The release of Fotino (t = 9344 s) and tether cut (t = 9364 s) near θ = 0º. Release of the tether near the vertical is confirmed by a sudden disappearance of tether tension at t = 9364 s (Figure 23) as well as by the measurements of NORAD's ground based tracking system. NORAD found a sudden change in Foton orbital elements, and calculates the moment of divergence at t = 9364 s with an altitude impact on Foton perigee of 1100 m. This compares well with Eq. 3 assuming θ_{eff} = 40º and a fully deployed tether released at the vertical – that is, if the Foton-M3 attitude control thruster effect is taken into account. This Foton-M3 attitude control algorithm aimed to have the Foton body follow the tether but to a maximum of θ = 30º. The tether effect of Foton perigee altitude can be determined to be 950 m plus 150 m for the Foton thruster contribution.

Length and in-plane angle profiles can be combined to provide a convenient Local-Horizontal Local-Vertical view of the tether deployment (Figure 19). With the brake set to zero in most of the second stage a higher velocity than nominal could be obtained, leading to a higher in-plane angle than foreseen. Although the release of the subsatellite was close to nominal in absolute distance and direction, the increased swing velocity and tether length imparted a greater ΔV on the subsatellite and a steeper entry, considerably upstream from the nominal landing point.

A deployment matching simulation using the MTBSim mission simulator (see Section 3) with nominal Fotino release time was used to determine the most likely actual landing site of Fotino. An error ellipse around this was determined based on the identified error sources including a 150x20 km uncertainty due to atmospheric density/horizontal wind uncertainty during entry, capsule mass and drag coefficient uncertainty (due to ablation), Fotino release delay and model/matching errors. The simulations show that re-entry conditions for Fotino would have just fallen within the nominal windows for entry angle, heat flux and angular rate (Figure 15).

Figure 14 shows the resulting reconstructed landing area, about 1250 km upstream of the nominal landing point. The area dimensions are about 250x30 km, in the border region of Kazakhstan, Uzbekistan and Turkmenistan.

Figure 14. Reconstructed Fotino landing area.

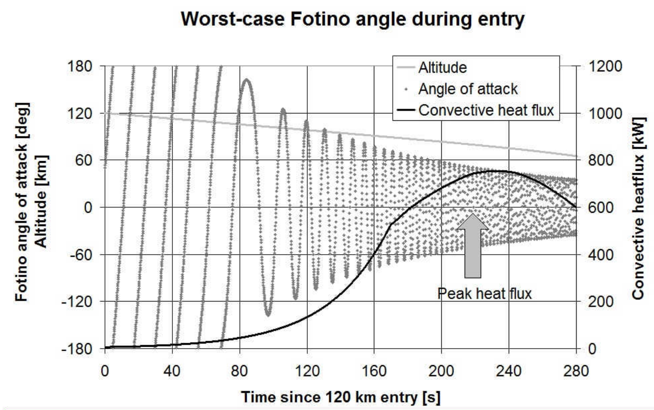

Figure 15. Fotino conditions during enty

2. Deployer performance assessment

There are three main parameters that need to be assessed for in-flight qualification of the deployer hardware, in other words, to make sure that the deployer hardware (tether spool, barberpole brake) can be sufficiently characterized on the ground to allow reliable control of deployment in space. These parameters are (Figure 16):

- Minimal deployment tension T_0 (tether stickiness to the spool), important in the early part of the first stage when gravity gradient is low and the endmass dynamics are determined by the endmass inertia and the deceleration caused by this minimal friction level. Nominal level was 0.0085 N, the acceptable level for robust control of deployment is 0.005 to 0.3 N. In flight the level was quite high and ranged from 0.027 to 0.045 N.
- Barberpole brake friction coefficient. This parameter becomes important when the deployment needs to be controlled (for better precision) or actively decelerated. Nominal value is f = 0.2. A friction level below 0.12 would require time-consuming amount of activation of the barberpole and would lead to a large number of wraps, decreasing brake effectiveness. A level above 0.3 can lead to controller resonance. A clean flight measurement was performed for the initial braking phase (Figure 7) and resulted in an excellent value of 0.175.
- The dependency of spool unwinding tension on deployed length and deployment speed, including effects of tether inertia, shock energy, compressibility of the spool etc. The criticality of this parameter I, the inertia multiplier, is not very high, as it is dominant in the high speed deployment part of the second stage, where gravity gradient is high and deployment is rather easy to control with the barberpole brake. The acceptable range is 2-20, with 8 as nominal value. The zero brake setting during the final part of the second stage setting allowed for a thorough assessment of this dynamic effect in the deployer tension model. The result showed that the dynamic effect on tension in flight was matching the preflight model excellently within 15%.

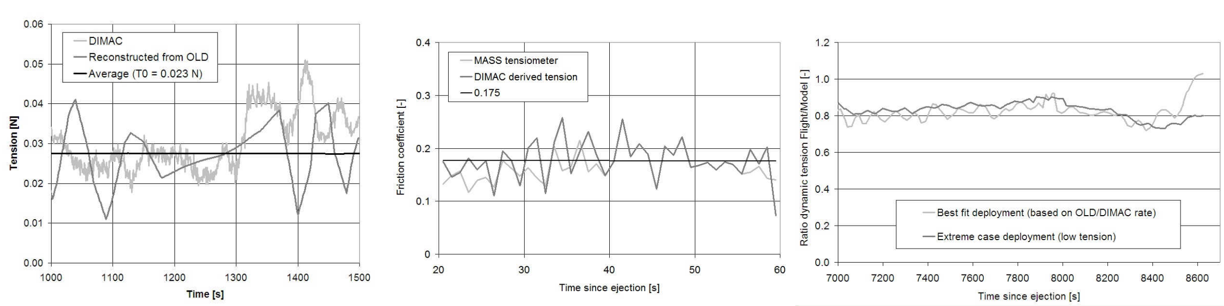

Figure 16. Quantitative evidence of suitability of tether deployer performance for the SpaceMail application. *F.L.T.R.: Tether stickiness* T_0 *during low velocity phase of Stage 1. Determination of friction coefficient* f *early into the deployment (speed about 2 m/s). Ratio of predicted dynamic tension (inertial multiplier* I*) according to ground based model over actual flight.*

3. Tether deployment data matching by simulation

MTBSim is a simulator intended for reliable simulation of complete tether missions, including capsule re-entry. MTBSim approximates the tether by a large number of spring-mass elements (including viscosity effects during bouncing). Advanced environmental models and complex aspects are integrated into the tool[8]. For example, MTBSim includes a full tether hardware and controller software model. A deployment match is simply made by setting hardware parameters close to the flight measured levels. To account for the electronics failure around t = 6200 s the deployment controller is disabled at this moment and the brake is artificially set to zero position.

The deployment rate vs. time could be matched within the precision of the available data (ranging between 5 cm/s and 1 m/s) by setting a single value for the hardware friction parameters and an improved fit was obtained by varying some of the parameters by about 10% over the mission. Because also the software controller is simulated (including its low-pass filter behavior) a representative controller-deployment resonance with resulting transversal waves was obtained (although not yet a perfect fit). Longitudinal waves were matched by increasing the tether viscosity with respect to expectations (stiffness was about nominal). Figure 17-Figure 19 show the matching results vs. flight measured/derived curves.

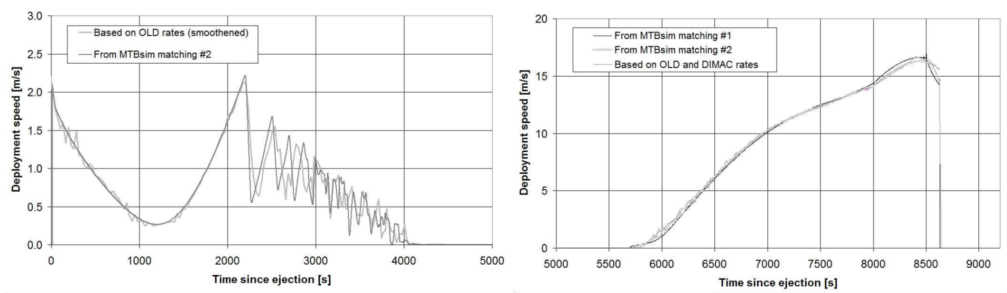

Figure 17. Matching of deployment speed (first and second stage) by simulation including controller oscillations

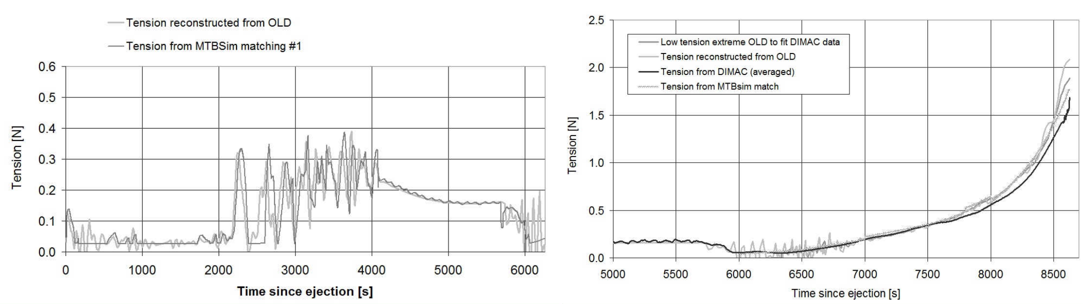

Figure 18, Matching of mission tension by simulation

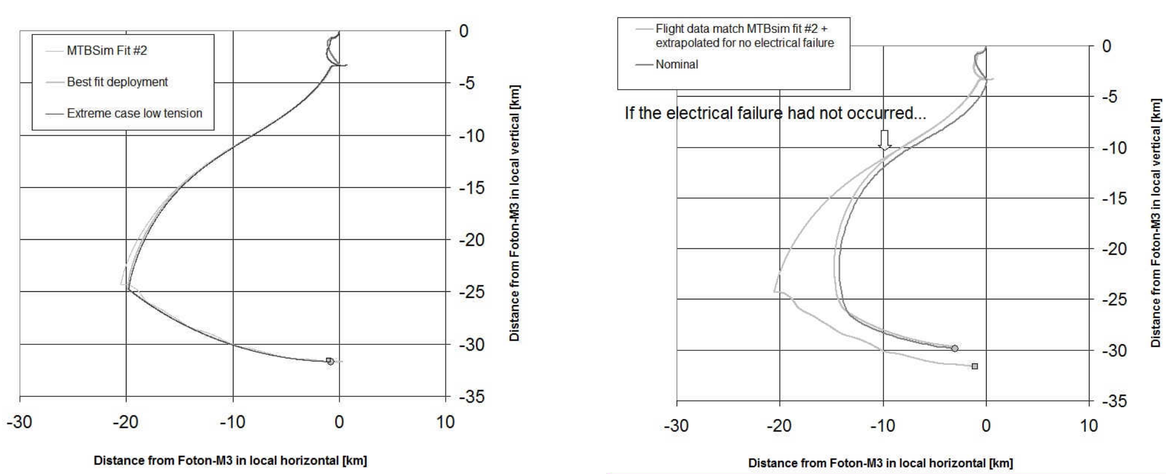

Figure 19. Matching of deployment trajectory (left), mission match and extrapolated hypothetical deployment vs. nominal in case no electrical failure had occurred (right).

4. Tether oscillations

Tether bending during deployment is normal due to Coriolis forces acting along the deploying tether. This is specifically true in early deployment if tension is low (about 3 cN in case of YES2), if deployment speed is high (YES2 maximum velocity was 16 m/s) and if tether mass is significant with respect to the endmass (YES2 endmass was 14 kg vs. 6 kg tether). Transversal waves are introduced if low tension deployment is followed by abrupt braking (as occurred in YES2 at t = 2200 s). Significant amplification of the waves after this shock was observed as a result of an unfortunate controller resonance with the deployment, Figure 25. A second event introducing transversal waves was the endshock, as the tether was brought to an abrupt stop from a speed of 15 m/s.

Transversal waves were recorded by the DIMAC instrument through their signature tension shocks (especially in the first stage), but also more directly by measurements of the angle under which the tether left Foton, Figure 20, Figure 21.

The sudden stop of the tether at deployment completion occurred at a moment that the MASS/Fotino endmass was moving away from Foton at 15 m/s and led to a stretching of the tether of more than 100 meters. As the tether relaxed, MASS/Fotino bounced back and came into a free orbital trajectory towards the local vertical below Foton. A kind of combined orbital bouncing/spring-mass oscillation was created (including also lateral and sound waves) causing repeated tension peaks of about 10 N. MTBSim reconstruction of the mission deployment matches this complex behavior qualitatively very well with proper selection of damping (ζ = 0.14-0.16 rather than 0.08 ground test) and stiffness (EA = 5000-10000 N as expected from ground tests), Figure 23.

One event recorded during YES2 showed clear impact of a sound wave echoing back and forth through the tether several times: the end shock. Figure 23 is the tension profile of the endshock recorded at Foton, the tether deployer end. The curious shape of the shock (rather than the typical sine pulse that MTBSim produces) is explained as follows. As the deploying tether is brought instantaneously to a standstill, at the site of the deployer in Foton, from about v_0 = 15 m/s, the remainder of the tether is still unaware of this event and traveling further. The information of the deployment stop travels down the full 31.7 km of tether with the speed of sound. As the deployment stop reaches any point in the tether at distance x from Foton in $\Delta t = x/a$ seconds, this point has moved $v_0\,\Delta t$ and therefore the tether has built up an additional stretch by $\Delta l = xv_0/a$. Tension according to Hooke, $\Delta T = EA\,\Delta l/l$, therefore also $T = EA\,xv_0/a/x = EA\,v_0/a$, and constant. a can be obtained through $a = 2\,l/P \sim 8.8$ km/s with P the observed time between shocks. This provides a quite precise expression for the tether stiffness from the tension measurement: $EA = 2\Delta Tl/(Pv_0) \sim 10000$ N.

After $P/2$ seconds, the standstill reaches the other end of the tether. Fotino has significant inertia and pulls on the tether. A 15 m long damping device (ripstitch) mounted near Fotino activates and reduces the tension for about a second to about 6 N. Then Fotino inertia restored and increases the tension such that the shock in the tether is reflected back to Foton where it is being measured ½ P s later as a further sudden rise. As Fotino slows down, the shock level drops, until the reflection returns again, and 7 s later a third and final time. Then Fotino has rebounced and the tether is slack. The maximum amplitude of ΔT of about 37 N is somewhat larger while the shock duration ½ P_{shock} = 14 s is significantly shorter than would be obtained simulating a spring-mass system with infinite speed of sound for which $T = v_0\sqrt{(Eam'/L)}$ = 33 N and ½ $P_{shock} = \pi/\sqrt{(EA/m'L)}$ = 24 s, using $m' = m_{Fotino}+0.34\,m_{tether}$ based on[24]. Prof. Smirnov and Ass. Prof. Alexey Malashin from Moscow M.V. Lomonosov State University have kindly provided below simulation (without damping, no ripstitch and with lower EA) for EA = 5000 N, v_0 = 14 m/s and a = 10 km/s (Figure 23) that illustrate the qualitative behavior.

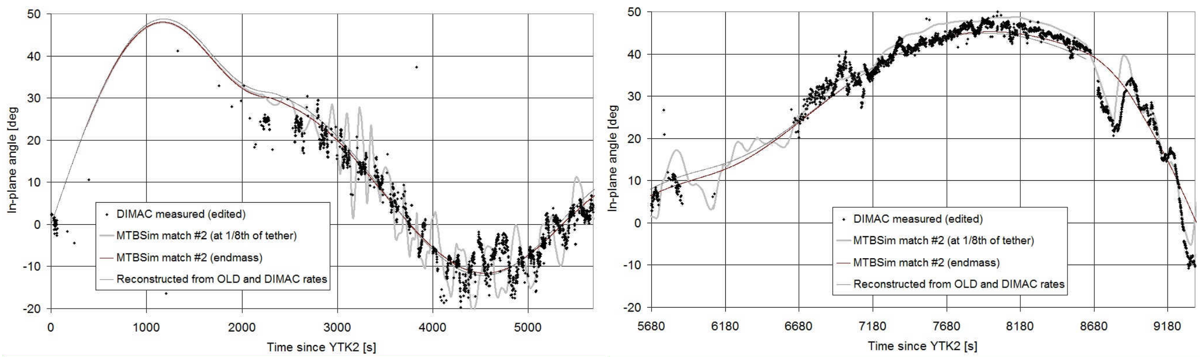

Figure 20. The measurements and simulation of the tether exit angle with respect to Foton evidence presence of transversal waves starting from 2200 s.

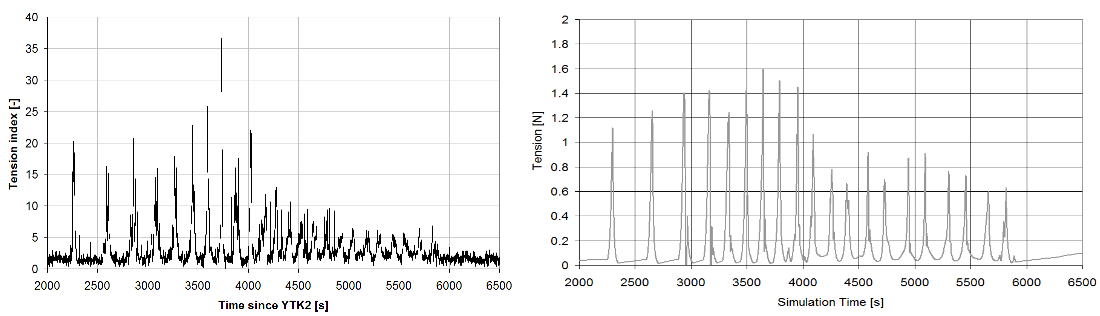

Figure 21. Tension pulses from transversal waves during first stage and hold phase. *Left: flight data, right: deployment matching simulation.*

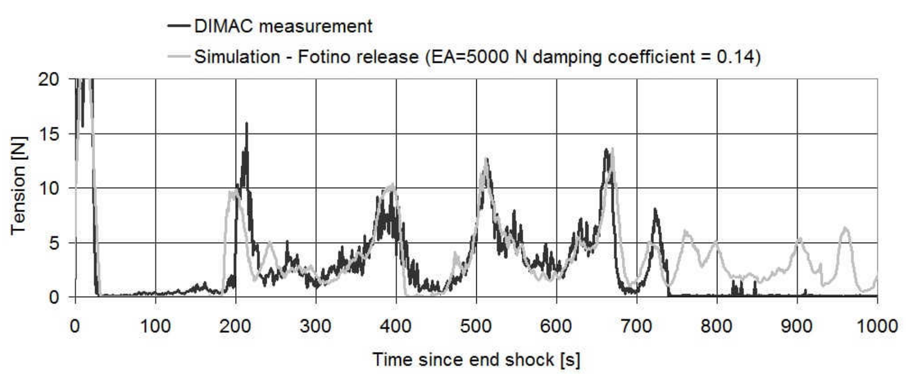

Figure 22. Matching of complex tension signature of complex wave form (mostly spring-mass) during swing-back to vertical. *Time reference is completion of deployment.* The DIMAC data shows the effect of tether cut around 740 s.

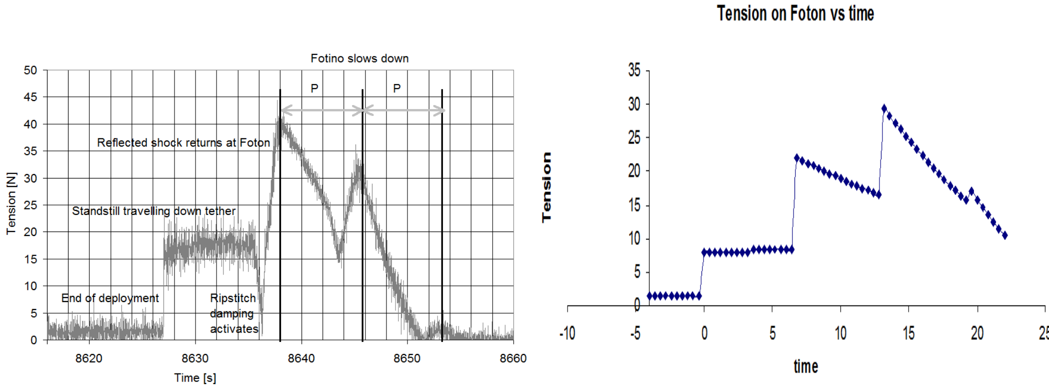

Figure 23. Measured and simulated endshock showing echo in the tether

5. SpaceMail potential

Fotino was not delivered to the ground as intended. However, more than sufficient data was gathered to assess the potential of the YES2 SpaceMail system as developed and as flown, for future applications.

Apart from the quantification of deployer performance (Section 2), the exact matching of simulation vs. flight data has also allowed to understand that the Fotino delivery failure can be fully and only attributed to the interface electronics power failure occurring around t = 6200 s. When the same deployment matching simulation is performed without (artificial) introduction of the electrical failure at t = 6200, deployment recovers smoothly from the troubled first stage and landing would still be within the nominal landing ellipse, about 150 km downstream from the nominal landing site (Figure 19, Figure 14), a performance comparable to conventional retro-rocket re-entry of ballistic light-weight capsules.

Other problems were identified and have to be fixed, but would have had only secondary impact on the mission result. They are listed with their proposed, often simple straightforward, solutions in Table 3.

Figure 24. Nominal landing area including, the hypothetical landing site of Fotino resulting from extrapolation of mission data assuming no electrical failure at *t* = 6260 s. *Also visible is the extrapolated landing site if the filter resonance problem would be resolved. The (inofficial) recovery team location at time of the expected landing is also visible.*

III. Project Evaluation

G. Successes

The achievements of YES2 can be summarized as follows:

- Highly successful as international hands-on education project, with high level of commitment from and satisfaction for hundreds of students from 25 countries, approaching ESA standards, and achieving them for all critical subsystems, producing 70 conference papers. Virtually no subsystems were purchased, all were student-developed.
- Development, implementation and qualification of innovative technologies, such as the tether system, the re-entry capsule, the mission simulator and test facilities and QA/PA software for distributed projects
- Delivery on time and at estimated 10% of industrial cost despite atypical challenges
- First tether deployment in over a decade, Guinness World Record (31.7 km)
- Extensive attention to safety aspects, development and implementation of safety systems, constructive dialogue with tether critics paid off
- First two-stage deployment, demonstrating both a controlled short first stage (3.4 km stabilizing near the vertical), restart of deployment and momentum transfer from a swinging tether.
- Successful and detailed deployment reconstruction
- Successful in-flight qualification of publicly-available tether deployer technology
- Study of tether dynamics and definition of lessons learned
- Hundreds of new tether enthusiasts in Europe and Russia with first hand experience

H. Problems, causes and solutions

An overview of all critical problems that occurred during YES2, causes and solutions is provided in Table 3.

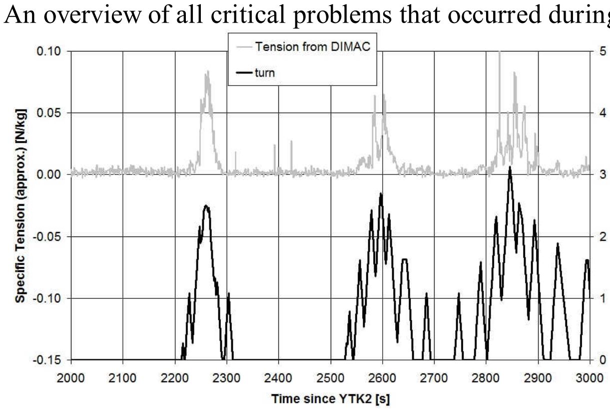

Figure 25. Brake controller causes tension pulses amplifying the transversal wave that arose from the first pulse.

Table 3. Analysis of problems occurring during YES2 and proposed solutions

Problem	Cause	Solution
Programmatic: changing requirements, lack of/staged funding, missing internal deadlines	Change of responsibles during project, insufficient broad support at start of project, insufficient know-how initially available in the team	Start only after clear and full definition (although it will raise the cost and make the project more unlikely to start). Budget for and involve senior experts from the early stages.
Tether more sticky than expected, made it more difficult to control the deployment in the first stage.	Possibly due to 11 days of tether in thermal vacuum of space before deployment	Test tether before and after full-scale exposure to representative environment. Preferably also during (costly).
Velocity filter overestimated the speed in the first minute after ejection, leading the controller to command additional braking,	Software filter parameter not properly adjusted to real-flight condition.	- remove the particular filter feature (it concerns a feature to cover for the unlikely double OLD failure case), or

which lead to a decrease of velocity		- adjust parameter based on YES2 mission data
Software controller responds poorly to first transversal wave and amplifies the waves by resonance. Effect is decreased landing accuracy potential (by about 100 km)	Software velocity filter has a delay due to averaging and low-pass filtering, which can lead (in particular circumstances) to resonance between velocity and brake control (Figure 25).	- increase stepper motor speed by a factor two, and/or - decrease friction coefficient of brake pole (now it is sandblasted for higher friction), and/or - decrease tether stickiness (see above) - optimize low-pass filter taking this problem into account, and/or - optimize feedback gains taking this problem into account
Electrical failure in OLD-OBC interface, lead to open-loop control at end of second stage and bouncing of endmass on tether after completion, 1250 km landing error	Failure on CPU board at the location of the OLD1 signal input (IRQ). The failure occurred before delivery of YES2 and was patched, but could not be sufficiently tested anymore. It was the patch that turned out faulty during flight.	Investigation of the CPU board failure, possibly selection of a more robust CPU board. More margins in testing timeline by earlier start of AIT phase.
Failure to receive signal from Fotino	Possibly failure to release properly from MASS (due to possible endmass rotation), heatshield failure or beacon failure.	Confirm release: TM, simpler capsule (no heatshield sensors, focus on redundant beacon with robust monopole antenna's). Avoid tether entanglement by center of mass position. More robust heatshield

IV. Conclusions

In September 2007 the YES2 experiment deployed a 31.7 km tether in space for the purpose of a tethered SpaceMail re-entry demonstration, featuring for the first time a two-stage deployment and release optimized for accurate entry. A rich set of data was obtained allowing for cross-validation of nearly all features of the mission. Apart from length and velocity, the in-plane dynamics could be studied. From the analysis it could be confirmed that the tether deployer and tether safety features behaved nominally. Also tether properties and wave dynamics could be studied and the measured mission dynamics could be accurately matched by simulation. The deployment was reconstructed with a precision of 20 m for the first stage of 3.4 km and about 150 m for the full length of 31.7 km. The YES2 deployment itself was mostly nominal, but ended in an off-nominal manner, after failure of sensor-to-processor interface electronics. Because of this reason, the capsule is thought to have landed 1250 km upstream of the nominal landing point. The potential for SpaceMail performance for the hardware as flown (in absence of the electrical failure) could however still be reliably quantified and found to be in accordance with expectations. About 200 km landing site precision is possible for a ballistic entry with the YES2 system, comparable to conventional retro-rocket solutions. As post-mission data analysis shows there are no major hurdles, the YES2 system can be used with only small modifications for future re-entry missions and early tether applications. The tether unwinding behavior, tether oscillation dynamics, controller behavior have been studied in detail and as a result the required modifications have been defined.

A SpaceMail follow-up mission is proposed, focusing on survival of the capsule and securing knowledge of the capsule landing location, for which the YES2 tether deployer and controller design as well as mission preparation approach and tools can be almost completely inherited. As YES2 has been an educational project, the design and test equipment is publicly available for any interested party. Such a sequel is considered of high importance to the development of tether systems aimed eventually at obtaining a sustainable space transportation system.

Acknowledgments

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