Abstract

This paper discusses the tethered re-entry mission of the 2nd Young Engineers Satellite with a particular focus on the approach to mission planning, safety, risks and contingency. As an introduction, the major safety aspects and lessons learned from YES1 are discussed. YES2 aims at a tethered sample return demonstration using an inherently-safe inflatable capsule, possibly landing in Europe. It is completely student built.

The paper provides a summary overview of and references for the evaluations behind design choices such as the selection of landing site, deployment scheme, optimisation of the cut time, mission timeline and contingency planning. The system hardware and control algorithms are driven by a minimalist design for simplicity and reliability. In addition, it discusses and quantifies the approach to safety issues such as meteoroid cutting risk, deployment failure scenarios, tether contingency lifetime and atmospheric entry/ground impact risks.

1. Two inherently-safe YES satellites

In May 2002 the European Space Agency kicked off a hands-on educational project called Young Engineers Satellite 2, managed by Delta-Utec in Leiden, Holland [1,2]. The YES2 is building on the experience and success of YES & TEAMSAT, launched on Ariane 502 in 1997 [3].

This first YES, a 200 kg satellite built in only 6 months, had the objective to deorbit a dummy mass from GTO by a 3 km rotating tether. A late change in nominal Ariane orbit increased the risk of accidental collision with other satellites to a non-negligible level, it was decided to not deploy the tether.

Many experiments on TEAMSAT & YES were performed successfully (GPS, radiation sensors, cameras, commercial technology, sunsensors), but some important systems ran into problems.

After the flight, a careful analysis was made of potential design flaws and the events that led to them, revealing three major causes[3]:

1. Human interaction under pressure
2. Off-nominal satellite orbit & attitude,
3. System complexity, providing on one hand useful redundancy, but also additional failure modes.

Annex 1 reports in more detail about the technical challenges and solutions regarding safety of the tether mission in particular.

There are significant differences between the two projects: YES1 was built in an intense effort, by a small group of co-located youngster working (nearly) full-time. For the YES2 project the students are working within the university curriculum, the focus is generally less intense. The project lasts longer too, so students will have to transfer tasks to a new generation from time to time. However there are more students involved and there is more time available, so more time and effort can be spent on careful analysis and testing.

For YES2, students from all over Europe and Canada are now building a satellite with the objective to demonstrate two attractive new technologies:

A 30 km long, 0.5 mm, 5 kg Tether
An Inherently-safe Re-entry capsule, AIR

Late 2006 YES2 is to be launched on Foton-M3, a Russian carrier. The 30 km of tether will be deployed from the carrier. At the other end, the AIR capsule is located. There is no conventional de-orbit burn: it is the tether that will accurately swing the capsule towards the Earth. The two technologies serve to demonstrate the SpaceMail application: a frequent sample return capability for the International Space Station9. Here, quick access and delivery to the customer is of importance.

Conventional re-entry capsules are however landing in remote areas for reasons of safety. The concept behind YES2 is, if all goes to plan, the capsule will land so softly that it does not pose any risk to the population. We are designing AIR light and slow enough to land in mainland Europe (primary focus Sweden 60-63 degrees North), although alternative landing sites are considered as back-up.

Such a mission must be inherently safe: even if something fails, it should still be safe, e.g. a failing capsule can be designed to burn in the atmosphere and therefore be of no threat.

The principle approach for safety of YES2 is:

Simplicity
Increased reliability by having simple, well-understood or well-tested systems with few interfaces.

Inherent safety
Student built satellites cannot be expected to be as highly reliable as their professional equivalents.

Therefore, mission and design concepts must be selected such that single failures do not lead to hazards. This also allows for highly attractive experiments such as the 30 km tether deployment or a capsule landing in Europe.

Understanding your hardware
Hardware performance is modelled, simulated (Monte Carlo etc.) and tested. Particularly, An advanced testing system has been built for realtime tether deployment simulation with hardware-in-the-loop, mission simulation and reentry simulations.

Awareness of risk & contingencies
The system know-how needs to be translated in an overview of primary and secondary risks, failures and abort options.

2. The YES2 mission and safety approach

In this section we give a short introduction into the YES2 mission [2.1] and subsequently discuss the tether related safety aspects [2.2], the capsule related safety aspects [2.3], the flight operations and landing concerns [2.4].

2.1 YES2 Mission plan

YES2 will be launched as a piggy back on FOTON in 2006 at ~ 280 km altitude (Fig. 1-[2]). YES2 consists of 2 satellite parts, connected by a tether Fig. 1-[3]: FLOYD (Foton Located Yes Deployer, Fig. 1-[4]) and AIR (An
Inherently-safe Re-entry vehicle, Fig. 1-[5]).

After initial downward ejection of AIR by a spring system, inertia and gravity gradient are used to deploy the tether between the two parts and AIR is stabilized 3.5 km below FOTON Fig. 1-[6]. This takes about 1.5 hours. Possibly, AIR will be inflated at this stage. When synchronization with the projected landing site is achieved several hours later, deployment is continued (t2=0). The increased gravity gradient accelerates the capsule exponentially to ~60 km/hr. A Coriolis force builds up and the tether swings forward below and ahead of the FOTON Fig. 1-[7]. With the 30 km tether fully deployed (t2 ~ 2200 s), it becomes a pendulum and swings back to the vertical, below FOTON, where it is cut at FOTON-side (t2 ~ 3100 s). This cut releases the AIR and tether from FOTON Fig. 1-[8]. The reduced altitude and velocity send AIR into a reentry trajectory. The tether may still be attached to AIR and assist in initial orientation Fig. 1-[9].

Eventually the tether is released, together with all superfluous hardware, the so-called Mechanical and data-Acquisition Support System (MASS). MASS provides stiffness during launch, contains the ejection interface, the inflation system, and possibly a GPS and telemetry unit. AIR is now ultra-light (~5-15 kg) and inflated such to obtain a very low ballistic coefficient. It will slow down already in the very upper layers of the atmosphere and remain relatively cool Fig. 1-[10]. It will come down to Earth softly as a balloon and may therefore be used to land even in inhabited areas of Western Europe Fig. 1-[11]. If the AIR balloon fails to inflate, it will burn, thus creating an inherent level of safety. The tether itself is dragged along to burn or will re-enter soon after due to atmospheric drag.

The total mission duration is several hours up to a day (depending on the duration of the synchronization phase Fig. 1-[6]).

Fig. 1 shows the mission stages and telecommands from different viewpoints.

2.2 Tether mission safety

The YES2 tether deployment safety approach is characterized by the following points, providing a multi-level safety:
1. System well understood
2. Reliability through simplicity
3. Opportunities for evaluation and safe abort during mission, robust deployment
4. Orbital dynamics provide inherent safety
5. Low impact on Foton if failure

These points will now be discussed in detail:

System well understood

The deployer hardware is based on a flight proven tether deployer concept, derived from the SEDS missions (Fig. 2). The following steps are followed to fully characterize the tether hardware:

**Fig. 1:** YES2 sample return mission. Foton moves to the right. See text for numbers.
<table>
<thead>
<tr>
<th>Hardware modelled, tested and characterized in detail.</th>
<th>This includes e.g. the tether spool unwinding characteristics inside the canister (Fig. 2) as well as the friction brake performance. For the YES2 brake, mathematical models were developed (Fig. 3b, [5,10,11]) and friction tests were performed, [5,6] also in zero-gee. Tests in thermal vacuum are planned.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics &amp; effect of disturbances studied extensively.</td>
<td>Validated 3D Tether simulator MTBSim ([5,7]). Unknowns in orbit parameters are modelled as having normal distributions with conservative standard deviations: Environment (airdrag), initial conditions (ejection speed and direction), control measurement errors, brake friction performance parameters, etc.</td>
</tr>
<tr>
<td>Monte Carlo simulations quantified deployment control response</td>
<td>Standard deviations based on results of testing, literature etc. See also Fig. 4.</td>
</tr>
<tr>
<td>Realistic breadboard testing performed</td>
<td>With real-time hardware-in-the-loop and closed loop control [8]. The results show that a better than 0.5% deployment accuracy can be obtained with the current system, in both length and deployment angle. The lessons learned could be directly applied into design improvements. The results also indicate how the Monte Carlo simulations indeed provide results typical for real hardware systems [8].</td>
</tr>
<tr>
<td>YES2 team designed improved test rig [16], also simulates the mission.</td>
<td>Improvements based on the results of above tests. It includes a display of the 3D deployment as actually achieved by the hardware. It can be used for the full range of deployment tension and velocities. Includes EGSE and can also be used to test flight software.</td>
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**Reliability through simplicity**

The tether deployer concept and hardware is chosen for its simplicity, to avoid as much as possible failure modes. There are no moving parts, nor open guides required for the unwinding there is an axial deployment from a spool head as depicted in Fig. 2) and the single thin smooth tether is thus contained.

The so-called barberpole brake (Fig. 3a) is a simple snag-free friction-brake design: the friction acts a viscous damping force rather than a (destructive) clamping or inertia force.

Also the control feedback is designed for simplicity: *Only length measurement is required for feedback.*

It has been demonstrated there is no need for differential GPS, angle measurement or tension measurement, even not if accurate landing is a requirement [8,9,12].

Furthermore there is no need for communication between the capsule and Foton. The length is measured on the Foton-side, where the control computer is housed in a pressurized, thermally

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**Fig. 2:** Left: FLOYD: YES2 Deployer, SEDS derived. Middle: YES1 tether spool. Right: YES2 tether
controlled environment. The unwinding of the tether is monitored by optical sensors, counting the number of deployed loops. From a table, the deployed length is calculated and velocity is derived by a filter[5].

\[ T = (T_0 + I \cdot \frac{P \cdot l^2}{A_{rel}} e^{(f_0 |\theta_0 - \theta|)} e^{2\pi \cdot f_n \cdot n} \]

Fig. 3b: Barberpole friction brake behaviour: the applied friction is proportional to the exponential function of the number of turns wrapped around the central pole. The pole itself is positioned by a stepper motor through a feedback based on length measurements. A simplified mathematical model is shown (more advanced models were derived in [5,10,11]). Measurements of tension versus turns performance are shown below, from which the friction parameters in the model can be derived. At high velocities, the tension resulting from the unspooling rises as well (see formula, with at least the square of velocity). This means there will be an inherent tendency for passive braking.
**Simple & robust control algorithm:**

A reference deployment is stored on board containing: tether length, angle and brake position as a function of time.

This reference deployment is designed to have:
1. good robustness (no very low velocities (<0.3 m/s) during deployment to avoid risk of getting stuck,
2. a nominal tension level with sufficient margin to control in either direction with the brake position
3. a tension level high enough to avoid bending of the tether as a result of Coriolis forces
4. smooth end brake and tether length margin to avoid jerks and slackness when the tether is fully deployed.

A feedback will be applied with respect to the brake position from the reference file. Because of the non-linear dynamics of tethers in space, an Energy Feedback was devised and tested. For this, the onboard computer converts length and velocity into a system energy measure based on a mathematical model of the tether system (potential & kinetic)[12]. If the system has too much energy, extra energy is dissipated by applying additional brake turns.

The mission operations are kept simple and are minimized for real-time human interaction. There are no telecommands other than switch on/off, (time tagged) eject, start of second stage & cut tether. In order to allow safety for the Foton carrier, the Russian controller will have full control and/or override possibility (Fig. 10c).

For example, the tether is cut autonomously, at a fixed time since start of second stage deployment: t2 = tcut. This time can be pre-fixed before launch, or sent after launch by time-tagged telecommand (TITTC), when the orbital parameters are more precisely known. During the tether deployment itself, no telecommands will be sent (other than abort). The cut-time has been determined at a specific point in the swing back (Fig. 1-8), some degrees before the vertical chosen such that robustness with respect to system noise is maximal[9].

**Opportunities for evaluation and safe abort during mission, robust deployment**

Fig. 10c shows the reference mission control. Because the deployment is in two stages (Fig. 1), there is the opportunity to evaluate the mission success during the stable synchronization phase. Now the 2-stage deployment was developed not only for this purpose. At 3 km distance between Foton and the capsule, the difference in gravity is sufficiently large to quickly accelerate the capsule. Therefore the second stage of deployment is less sensitive to noise and more predictable. In this way, the robustness of the tether deployment is significantly increased [9],[13].

**Orbital dynamics provide inherent safety**

As explained above the concept of the barberpole and axial spool deployment makes it unlikely that the
tether would get stuck and introduce a sudden stop. The following discussion should be considered in such event.

The first tens of meters of the tether can be designed to break in case of tether snag. If the tether would snag just after ejection. The kinetic energy of the capsule $mv^2$ will be converted into potential energy of the strain in the tether: $ku^2$. The peak tension $F=ku$ will thus be:

$$F_{\text{peak,snag}} = \sqrt{mEAL},$$

With $k = EA/L$ and $L$ the current length of the tether. If $L$ is small, shortly after ejection, and in the neighbourhood of Foton, the tension will be very high and the tether will break, so there will not be a recoil.

In case of unforeseen jerk & slackness near the end of deployment, the capsule will bounce up, and will get into a free orbital trajectory that will tend to restore tension. The oscillation is dampened out without large effect on landing site (Fig. 5, [12]).

If the deployed length is intermediate (several hundreds of meters), the case is much less clear. The best solution is to provide a passive absorption mechanism near the end of the tether. This is called ripstitching (Fig. 6).

Furthermore there is always a chance that the tether is cut by micrometeoroids or debris.

If this would however happen, the YES2 tether will be (nearly) immediately removed from orbit by drag (low orbit) and momentum transfer effects.

Note: the relevant measure for meteorite risk is the integrated exposed time-length product (Annex 1.3). For YES2 we selected a singlestrand tether for simplicity. The part of the tether that is exposed to the space environment longest, should also be the thickest. With the first 3 km (first stage) of thickness 1 mm, the survivability probability amounts to 99.5% for the nominal mission, or 98.9% if the first stage phase is delayed to a full day for mission operation reasons.

Low impact on Foton

One often-expressed worry is the possible wrapping of the YES2 tether around Foton. YES2 intends to eject to nadir (downward), for simplicity of the attitude requirement of Foton. Now suppose the ejection will be in apogee. With the velocity vector pointing downward, it means that the instantaneous apogee of the capsule must be larger than the altitude at time of ejection. In case of a somehow friction-less deployment, eventually, the capsule could meet-up with Foton again and there is a potential danger of the tether wrapping around Foton.

In reality, a tether deploying from a spool will always dissipate some energy, even without friction, to account for:

- the increase in kinetic energy of the complete system as new parts of the tether gain speed,
- the shock energy (Carnot energy), required to bring into instantaneous motion the tether from the spool[12], in the same way as elements of a chain jump from tensionless to tensioned when pulled.

![Fig. 5: Tether deployment with and without feedback. The deployment without feedback deviates considerably. Because no tether length margin is included here, the capsule snags at the end of the tether. However the combined orbital/tether dynamics cause the tension to restore and the oscillation to dampen out.](image)

![Fig. 6: Ripstitching concept. The capsule moves with arrow. If the tether gets suddenly stuck, the ripping of the stitches will absorb some of the energy.](image)
From the law of momentum change, \( F = \frac{d(mv)}{dt} \), it can be directly derived that the minimum tension that accounts for this dissipation is equal to:

\[
T_{\text{min,deploy}} = \rho v^2,
\]

with \( \rho \) the linear density of the tether [kg/m], and \( \rho v \) the rate of increase of moving mass [kg/s]. This term is called the rocket term.

In addition, in reality, there will always be friction in the system. It will be part of the YES2 safety and contingency investigation what friction levels are required to dissipate enough energy to avoid risk of collision with Foton. It is proposed to put the brake in initial braking position, such that if the stepper motor fails, the system will decelerate gently. Depending on the results of the analysis, it may be required to eject more in backward direction, to decrease orbital energy of the capsule. This will lead to, firstly, a larger difference in orbital period, so to increase the distance between the two bodies in the subsequent apogee, and secondly, a lower apogee so that less time will be spent in the same altitude region. Note that the true anomaly of ejection does not need to be in apogee but can freely (and possibly more optimally) be chosen, because of the 2-stage deployment concept.

Moving into secondary level failures, if the tether would wrap, or the capsule should come back to Foton, one should consider that:

- The Foton weighs over 6000 kg vs. 0.2 kg/km tether (<7 kg total), so the impact of the tether will be low.
- The nominal tension in the tether is also low, less than 10 N throughout the mission, less than 0.1 N typically.
- The low ejection energy (20 kg at 2 m/s = 40 J, a walking child) limits the risk of damage to Foton subsystems by capsule impact.
- The tether design break strength is near that of typical handling loads (40 kg) so that the risk of deforming appendages of Foton is inherently low.

### 2.3 Capsule safety and landing

**Inherent safety**

As mentioned, the YES2 capsule is an Inherently-safe Re-entry vehicle (AIR). Rather than depending for a soft landing on a parachute system, the capsule will be its own parachute, by being light and large. The landing velocity relates to:

\[
v_{\text{landing}} = \sqrt{\frac{2g}{\rho_{\text{air}} V_{\text{AIR}}} \left( \frac{m_{\text{AIR}}}{\rho_{\text{air}} C_D S} \right)}
\]

with \( \rho_{\text{air}} V_{\text{AIR}} \) the buoyancy of the AIR capsule and \( m_{\text{AIR}}/C_D S \) the ballistic parameter.

A large volume (> 2 m3), a large surface and a low mass all reduce the landing velocity (YES2: 1<m/S<10).

**Inflatable capsule**

The main concept of interest to achieve such velocities is an inflatable capsule, because it is scalable to ISS applications.

The key to inherent safety with an inflatable (or unfoldable) capsule is to have a single stage inflatable (it either succeeds or it does not) and to inflate already in space.

The inflated capsule will decelerate at very high altitudes (>80 km), in the rarefied flow, with low density and therefore low heat fluxes. The capsule can be dimensioned such that, if for some reason the inflation fails, it will burn and be of no hazard (Fig. 7). In the contingency-case, the capsule with decreased surface will penetrate deeper into the atmosphere until it eventually decelerates as well. Interestingly, the peak of the total dissipated power \( F_{\text{drag}} v = 0.5 \rho_{\text{air}} v^3 C_D S \) remains nearly unaffected, and occurs at similar velocity (~5 km/s), but in a higher density region. The smaller surface area S causes increased heat load. The dissipated power expressed in [W/m2] in fact scales roughly with the ballistic coefficient. In reality heat flux and temperature are not directly proportional to dissipated power and will peak typically even before [Fig. 7].

![Fig. 7: Capsule wall temperature during re-entry, in case of successful inflation (lower curve), and failed inflation (upper). In case of failure, the capsule will burn.](image)

The inflation system and other mechanical hardware, and even the heavy instrumentation is jettisoned before entry, to reduce mass and hardness of the capsule even more.

If the capsule is spherical and the final velocity becomes supercritical (Reynolds number > ~300,000), the turbulent, viscous flow will stick to the wall on the back of the capsule, reducing the size of the capsule’s (pressure-less) wake, and therefore the pressure drag. The effect on landing velocity is roughly an increase by factor 2.

This is one of the reasons to consider a sphere-cone capsule. The steep gradients at the edge of the vehicle will ensure flow release and a large wake, so high drag. Also the sphere-cone allows for a relatively large nose radius (larger shock distance so lower heat flux) and reduces total surface area, both allowing for a potentially lighter capsule.
At a mass of 12 kg and diameter of 1.8 m, the Triple Tori expected landing velocity is less than 10 m/s, the equivalent impact energy (if relatively little ground winds) only about 500 J, equivalent to the energy of a handful of dropping soccer balls.

A good time for inflation seems to be the synchronization stage (Fig. 1-[6]). This is because then there is a stable situation with a well-known time since ejection. The inflation can thus be simply initiated by a timer connected to a microswitch. There will be no telecommand capability to the AIR capsule, so autonomous inflation is required. The inflation is also expected to reduce any remaining capsule librations when suspended from the tether, due to increasing moments of inertia as well as increasing arm and stabilizing torque of the tether tension.

However, the possibility of a long waiting phase of maybe a day could lead to excessive leakage of gas.

Later inflation (e.g. after cut of the tether) is possible as well, but it is more difficult to make a reliable, autonomous inflation system. Filtered measurements of tether tension and/or dynamic pressure are required then.

2.4 YESsim mission simulator

A complete mission simulation environment YESsim has been developed, connecting the following major functionalities:

- Tether deployment dynamics simulation
- Re-entry simulation
- Pressure-induced deformations on inflatable capsule
- Attitude propagation
- Heat transport throughout capsule
- Noise models & Monte Carlo
- Visualisations

This integrated 3D tool includes models for the different flow regimes, higher order gravity and solar pressure disturbances, as well as the latest versions of atmosphere and wind models (MSISE00, HWM93, G2S).

The heat transport through the capsule is based on models supported by test [17].

The validated tether simulator has been described in section 2.2 and includes tether deployer hardware models.

Tether & aerodynamic torques are calculated in real time.

The Re-Entry Simulation Tool (REST) includes engineering relationships for the different flow regimes.

YESsim will be used to make certain mission decisions, such as best time of inflation, optimal entry angle and time of tether cut at Foton, time of MASS/tether jettison from AIR. The attitude of the capsule when suspended from the tether will be evaluated. The capsule has no active attitude control, so pitch-off rate induced by the ejection must be dampened out or contained by the tether tension or initial spin.

With YESsim we can evaluate the required initial condition and acceptable angular rates for correct orientation at entry, as well as the possible use of the tether to support this [Fig. 9].

YESsim is used to study whether the inflatable capsule deformations cause attitude instabilities during the part of re-entry where heat flux and dynamic pressure are

![Fig. 8: Triple Tori mock-up](image)

![Fig. 9: Tether orienting capsule at entry. The capsule (circle) is at ~100 km altitude. The tether is 30 km long, so the upper part is outside the atmosphere. Tension near the capsule is now ~15 N but rising strongly.](image)
Landing area minimization

The Re-Entry Simulator Tool (REST) is the part of YESsim that is used for evaluating trajectory, heat fluxes and landing points.

Combined with the Monte Carlo tool, it is used for landing area determination. The Monte Carlo tool takes into account the errors of the density, the wind velocity, the drag coefficient and the lift coefficient (aerodynamic landing area). When coupled to the tether simulator, the total landing area can be simulated.

The collection of possible landing areas, due to orbital uncertainties in the planning phase, is called the landing zone. The landing zone is an important parameter for YES2. Although the nominal Foton landing zone in the Kazakhstan region remains a back-up for YES2, it will be attempted to meet the challenge of landing the first capsule ever on (Western-European) soil. Such a landing in inhabited could only be allowed for an inherently-safe vehicle. However, since the European countries in general are rather small, it may be necessary to obtain permission to land from more than one country. Not an easy task indeed.

This is where REST will help. It is used for minimization of the landing area in the following ways:
- recommendations for optimal initial conditions
- REST is coupled to an NRL-provided module, G2S, which allows for reading-in of actual weather predictions, to improve trajectory estimates at the last moment.
- The coupling of REST to the tether simulator will be used during the mission to automatically determine the optimal second-stage start and tether cut time for a landing near the nominal landing point & re-entry angle.
- REST will provide recommendations for optimal landing zone

How will the nominal landing point be achieved?

The orbit of Foton cannot be predicted exactly in advance, before launch. It will be more or less in a 304x264 km initial orbit, inclined at 62.8 degrees, degrading to about 290x250 after 15 days, near the end of the mission when YES2 will be initiated.

The argument of perigee is ~120 degrees, placing the perigee over Russia, and hardly changes during the mission.

A different orbit means different deployment dynamics and mostly, different entry angle. The tether deployment profile can in principle not be adjusted during the mission. There is no capability for telecommands to carry data, anyway it would be too stressful. So all control that can be executed is by precisely scheduling the start and cut events using time-tagged telecommands (required within about 10 s precision for accurate landing).

The time tags to the telecommands will be determined with YESsim/REST based on deployment simulations ran during the Foton mission, but some days before the YES2 experiment starts. It will use the actually achieved orbital parameters of Foton as measured with precision of some several kms at a daily interval.

So, in an iterative optimisation by YESsim/REST:
- First, the precise value of t2 (time interval between cut and star of second stage) will be determined, to obtain the correct entry angle.
- Next start of second stage will be adjusted to match the landing site.

What will be the best landing zone in Europe?

The combination of Earth rotation during the orbital period (1.5 hours) and precession of line of nodes creates a westward shift in ground track of nearly 23 degrees per orbit (Fig. 10b).

A possible Foton orbit-insertion error by Soyuz the launcher of 20 s per orbit was quoted, amounting to 5000 s after 15 days. This is equivalent to a possible a priori east- or westward unknown in groundtrack of about 20 degrees, or about plus or minus 1000 km at medium latitudes. In fact we can state, that we cannot make any pre-flight predictions on the longitude of the groundtrack during the YES2 mission. Before flight we may prepare to attempt to land in Spain, but the groundtrack may not pass over this country during the actual mission. Instead it may pass over France or Italy.

However, inspecting closely the groundtrack in Fig. 10b, we see that the consecutive groundtracks intersect near a latitude of 62.3 degrees. The highest latitude is 62.8 degrees (equal to that of launch site Plesetsk, as well as the orbit inclination). Every day, the groundtrack will pass through every longitude in this small latitude range (62.3-62.8). Moreover, each single ground track remains at this high latitude for 1000 km. This means, that every day we can land in this latitude range, and, even if the landing area is several hundreds of kilometers wide, the landing latitude remains well-defined. Rather than crossing most of the continent, the landing zone will be effectively as long as the landing area and as broad as the sum of the 0.5 degree latitude range and the cross-range of the landing area. Simulations show that the 3s landing area is about 400 x 100 km [Fig. 11].

Scandinavia seems therefore to be a good candidate. The 62.3-62.8 degree latitude region in Sweden is close to this width, it is populated, but not too crowded (~ population density 10 km^{-2}) and there are no major highways. Recovery is planned using the ARGOS system (an 80 gram satellite beacon for <350 m position accuracy). In this region, as a back-up system even a GPS-2-SMS (using GSM) could be considered, allowing to walk to the capsule only by the info you receive on your mobile phone.

In the context of the educational objectives of YES2, it is foreseen that school children will go out into the forests and retrieve the capsule!
Orbital-plane view of last phase of reference YES2 tether mission (taking nearly one orbit). The orbit (~288x247 km) starts more-or-less over Plesetsk in northern Russia (exact longitude cannot be predicted before launch). The YES2 capsule is suspended 3 km below Foton (1a-[6]), waiting for synchronization with the landing site (Sweden). About 15 minutes after passage of Plesetsk, the second stage of deployment starts (1c-[1]). The tether is cut a fixed time-interval later, near the equator over South America, in the ascending part of the orbit (1c-[2]). The capsule plus tether coast jointly towards the atmosphere. Entry at 120 km occurs at 1c-[3], landing in Sweden in the local afternoon (end of groundtrack, 1c-[4]), latitude 62-63 degrees.
10c. Reference operations and abort options of YES2 (here called STEP-1). Read from left-to-right, first top, then bottom. TTTC = time tagged telecommand. HK=Housekeeping, TsUP=Moscow control center. The full mission lasts only several orbits, with the flexibility to extend the 3 km vertical Synchronisation Phase (ground contact 4) indefinitely. The 3 telecommand during ground contact 5 have timetags that preferably have been created several days before.

Fig. 11: 3σ landing area/zone for tethered inflatable capsule re-entry (12 kg Triple Tori, S=3 m²) as calculated by REST. The 2σ zone (95% probability) would be entirely in Sweden.
Conclusions

Both the first and second Young Engineers Satellite have a similar approach to safety and contingency management, with this difference that YES2 has learned from the YES1 experience. There is more focus on system simplicity and more time is available for analysis and testing. The YES2 mission, tethered SpaceMail, a sample return by inflatable capsule, is a challenging one, especially since a landing site in Europe is one of the options considered. The concept of inherent safety is found indispensable and present throughout the project. A comprehensive summary and reference overview is given of all YES2 efforts concerning safety issues for tether, capsule landing and mission operations.

Acknowledgments

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Annex 1. Learning from YES1

The YES1 tether mission was rather complex in the sense that it included multiple stages, as described in Fig. A1 [4]. The mission was to start with ejection of YES from MAQSATH. The tether would deploy between YES and the subsatellite TORI. After full deployment, using MAQSATH as a major counterweight, the TORIYES system would be released. Orbital dynamics would start a rotation of the system. Eventual objective was to deorbit TORI from GTO by cut of the rotating tether in apogee.

A.1 Inherent safety on YES1

Inherent safety concepts were used already on YES1:

- During launch, the YES1 was contained in an oversized, octagonal box (Fig. A1), such that, even if it would rattle apart, it would still not endanger the launcher. Of course, in addition, the necessary shaker tests were performed.
- If something would go wrong during tether deployment, an Autonomous Tether Cutter (AUTEC) was programmed to go off after a few days, releasing the tether from its endmasses. Now the tether weighs only 5.5 kg at 30 m2 projected surface area, so has a very low ballistic coefficient. In fact, due to the particular GTO orbital dynamics in the nominal orbit, the solar pressure would blow the tether back to Earth in only two months.

A.2 Simplicity on YES1

As mentioned, YES1 carried a number of complex, newly developed systems. However simplicity was the key for the development of the critical tether deployer:

- Deployment from a fixed spool
  The SEDS barberpole brake was purchased, a friction brake that does not damage the tether and has a simple mechanism without pulleys. A similar device is developed for YES2 [Fig. 3a].
- Proven and commercially available technology:
  several successful missions included SEDS hardware (e.g. SEDS1, SEDS2, TIPS), Fig. A3.
- Collision risk in case of tether failure
  The late and radical change in Right Ascension of the Ascending node of the orbit, as measured with respect to the Sun, lead to a predicted contingency-case tether lifetime of up to 30 years and a collision probability with other satellites of up to 0.001. Both lifetime and collision risk calculations performed by the authors, were confirmed by independent calculations from consultants.
**Fig. A1:** YES ejection from MAQSATH in 1997. Tether deployment between YES (the octagonal satellite) and TORI (the small bright dish inside the octagonal box). Mission stages are shown below, leading after 18 hours to a re-entry and burn-up of TORI. YES was built and launched, with its tether payload, but not into nominal position. The tether was not deployed out of safety concern.

**Fig. A2:** Solar pressure direction during nominal GTO orbit for YES1. In a contingency case, the tether might end-up freely in orbit. In apogee, the solar pressure would decelerate the tether however and perigee would drop into the Earth atmosphere within 2 months, before the regression of line of nodes has turned the orbit around and with it the effect of solar pressure. A Kourou Local Time of launch was required between 13.00 and 2100 for this mechanism to work favourably. Ariane 502 launch time was shifted shortly before launch from the afternoon to the early morning.

**Fig. A3:** 4 km TiPS tether, 7 years in orbit
Fig. A4: YES1 Hyperlinked contingency tree, with decision events, contingency operations abort options. See text.
Potential collision candidates are concentrated in the Low Earth Orbit (LEO) region. The probability was derived as the product of the LEO satellite density with the LEO volume swapped over time by the passing freely rotating tether. Note that a satellite descending from GTO orbit spends only a few % of its time in the LEO region. Since the tether is very thin compared to the possible satellites it may hit, the average dimension of LEO satellites was used for the width of the swap volume, the length of the tether as conservative value of the height\[14\]. Although this risk is comparable to other proposed and executed space missions, we found that a first European tether mission should serve an exemplary function of prudence and responsibility, so together with ESA it was decided to leave the tether undeployed\[4\].

**Meteorite risk**

The YES1 tether was very long (35 km) and thin, about 0.25 mm in diameter, and could therefore quite easily be cut by micrometeoroids\[19\]:

\[
\text{Lifetime [years]} = \frac{(d \text{ [mm]} + 0.3)^3}{L \text{ [km]}}
\]

This conservative model for LEO (TIPS survives much longer than predicted), is certainly conservative model, for GTO. To reduce risk, a “Carroll caduceus” double strand design was implemented, stitched together at every 200 m \[4\]. The second strand is slightly longer than the first and therefore slack (supported by space charge forces), so strands will rarely be cut together. In this way, the cutting risk was reduced to 99.988 % \[18\].

**Contingency plan**

A hyperlinked contingency tree was developed \[Fig A4\], in which colors indicate risk levels, the highest risk in any branch level determines color. Branches go left and right from the base of the tree:

The base of the tree represents the chronological sequence of major decision events. Under the hyperlink, for each decision it is specified:

- what subsystems are required to perform well
- which measurements are required to make sure that operations are nominal
- under which conditions to go into contingency mode (right)
- under which conditions to go to a preventive, safe abort (left).

The contingency modes are specified in the rightward branches. The hyperlink specifies:

- The possible causes of the observed anomaly
- Actions to be taken
- Expected effects of action, possibility to return to nominal mission
- Secondary failures: effects and actions
- The safe abort options (leftward branches) specify:
  - Action required to abort mission
  - Effects expected
  - Secondary failures: effects and actions
  - The tree allows for a quick assessment or even quantification of mission risk.

**A.4 Inherently safe tether mission options**

After the cancellation of the tether deployment, Delta-Utec started investigations into an inherently safe tether, the DUTether: Tether Degradable by Ultra-Violet\[15\]. The idea being that after the short nominal operation of a momentum transfer tether, it will evaporate under the influence of ultra-violet, thus decreasing collision risks to zero and allowing for a much wider range of tether applications.

In addition, ref \[14\] reports of our study of safe orbital ranges for tether applications, basically concluding a perigee below 550-800 km (LEO/GTO), up to 1500 km for non-polar bare conductive tethers.