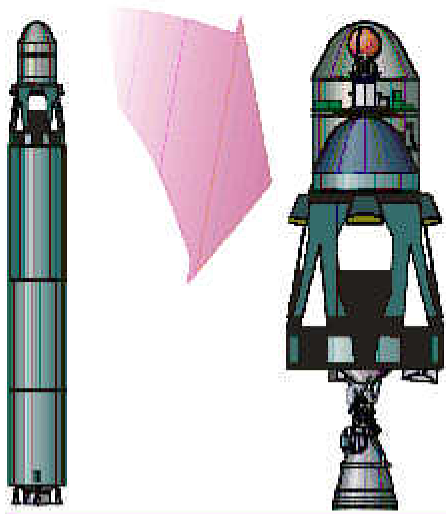
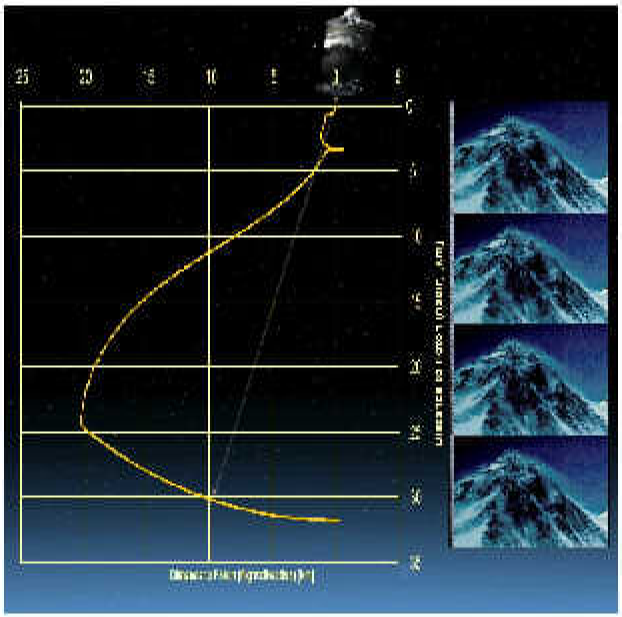
YES2 analysis & definition for reflight






M. Kruijff
E.J. van der Heide
2008-2009

YES2 as an umbrella project

- *Education*
  - 380 students
  - 180 designers
  - >100 interns
  - 90 papers
  - 50 theses
  - 25 countries
- *Technology development*
  - Tether experiment
  - Light re-entry capsule
  - Distributed/Model Based System Engineering
- *Satellite development*
  - Subsystems design
  - Analysis
  - Construction & test
  - ESA standards

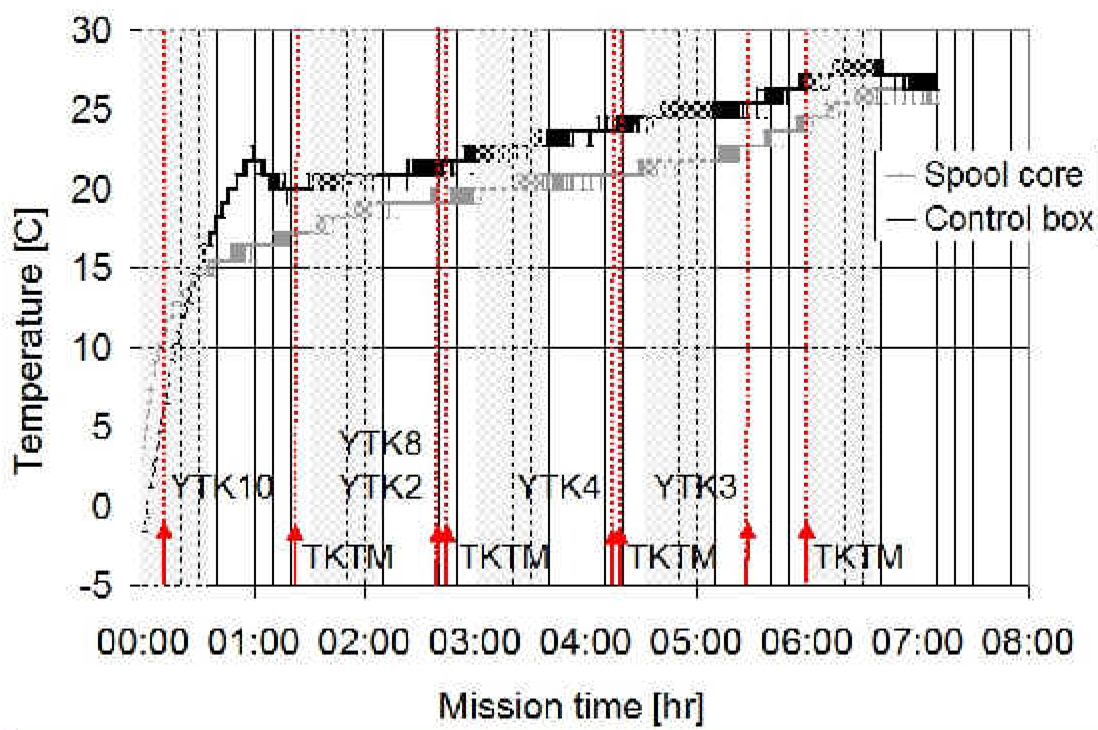
YES2 (2002-2007)

YES2 Mission

- Objectives
  - Two-stage tether deployment
  - Deorbit a re-entry capsule accurately using a release from a swinging tether rather than a retrorocket-based deorbit system

YES2 mission

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

YES2 Mission Data

NORAD (TLE)

- Release

DIMAC

accelerometers/magnetometers

- Tension (>0.01 Hz)
- Tether angle
- Loop rate
- Length

YES2 SSAU GPS/magnetometers

FLOYD (***OLD***)

- Optical Loop Detection: length/rate
- By reconstruction: tension, tether angle:

$$-\ddot{l} + l\left[(\dot{\theta}-\Omega)^2 - \Omega^2(1-3\cos^2\theta)\right] = \frac{T}{m} = \frac{F_B}{m}$$

- Brake turns, HK

Fotino

- 15+12 Aerothermodynamics sensors
- 3x3 Dynamic sensors
- Data not (yet...) available

MASS (0-100 m)

- Tension
- Angle

Science/data analysis objectives YES2

- Deployment reconstruction
- Determine landing site
- Assess SpaceMail potential
- Determine hardware performance
- Match simulation vs. mission data
- Study tether behavior
- Study controller performance

Deployment Reconstruction
First Stage

- The ejection system performed perfectly: 2.3 m/s (nominal) and 1.5 deg/s pitch off (better than nominal)
- YES2 featured the most complex tether deployment to date: a two stage deployment
  - It starts with a 3.4 km first stage controlled to the vertical, with the purpose to achieve beneficial initial conditions for an accurate and fast second stage
  - This 30 km second stage deploys the tether to a large angle (40 deg.) to obtain a backward swing for capsule release and re-entry
- The first stage of deployment is the most challenging stage for control due to low gravity gradient and the high impact of friction
  - Controlled deployment to such a short tether length has not been attempted before
  - It was fully successful, and the target length of 3400 m was achieved within 20 m
  - A swing angle of 10 degrees amplitude remained, within acceptable limits

Deployment Reconstruction
First Stage

- The observed oscillations in the first stage were analyzed:

1. A somewhat high stickiness of the tether made it difficult to recover from a heavy braking event in the first seconds of deployment. The controller succeeded, but only with significant overshoot and resulting in-plane libration angle of 10 degrees.
   – This heavy braking event was caused by an overestimation of deployment velocity due to an unfavorable software filter setting
      - The filter setting in question could not deal with what are thought to be subsatellite oscillation effects on the tether deployment that are only significant in the first 30 s and for which there was no ground testing or simulations done
      - A recommendation for simulator adjustment has been provided
      - The necessary adjustment for the software filter has been provided
   – The cause of stickiness was found to be likely due to thermomechanical settling of the spool (see later)

Deployment Reconstruction

First Stage

2. Also lateral tether oscillations were introduced due to the overshoot, reducing attainable re-entry accuracy. Simulations show that it is possible to dampen these oscillations.
   - A resonance between tether deployment velocity and brake controller occurred further exciting the lateral oscillations
     - This resonance is due to the 8 s delay of the software filter to estimate velocity, combined with the heavy initial disturbance
     - Apart from making the sofware filter slower, proper selection of brake pole roughness and pole rotation speed can avoid resonance
     - In general it is recommended to, before flight, closely study controller response for realistic but heavy overshoot cases and adjust parameters to avoid resonance

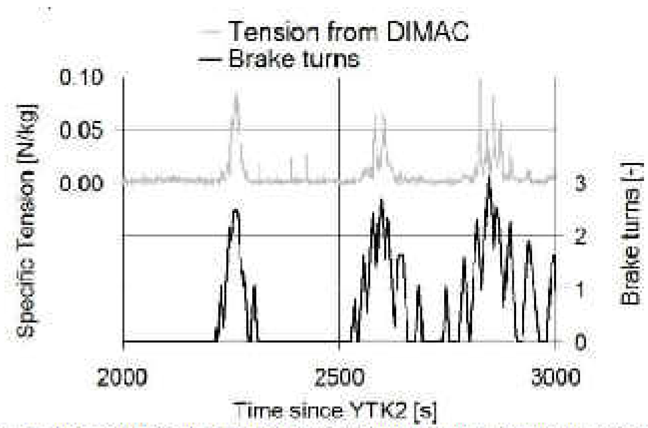
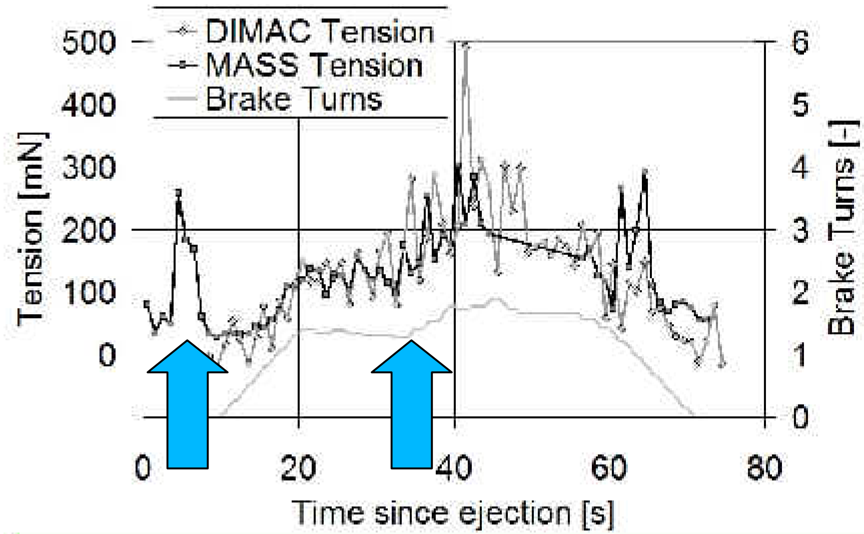


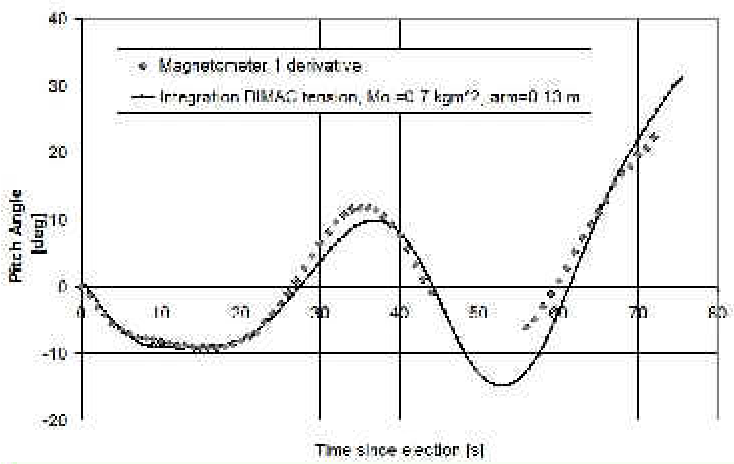
Figure 78. Brake controller causes tension pulses amplifying the transversal wave that arose from the first pulse.

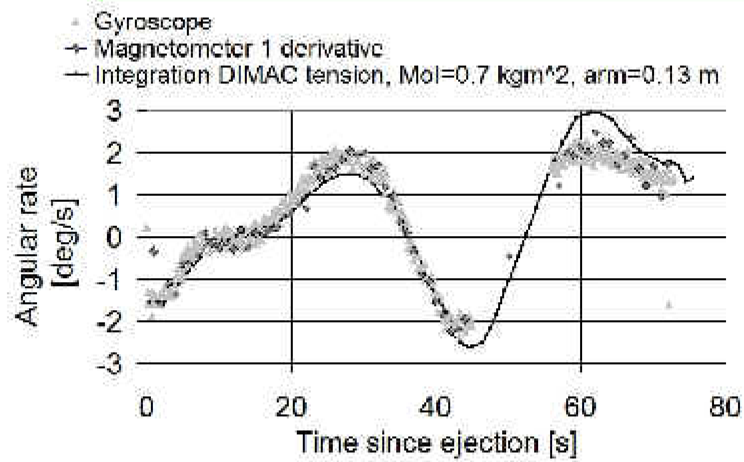
Deployment Reconstruction

Ejection (MASS data)

Left arrow: ripstitch deployment peak (nominal)
Right arrow: start of ~20 s increased braking event (not foreseen)

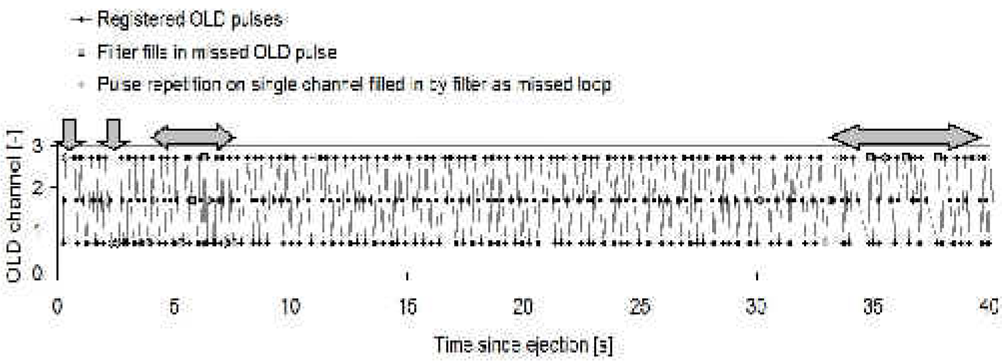




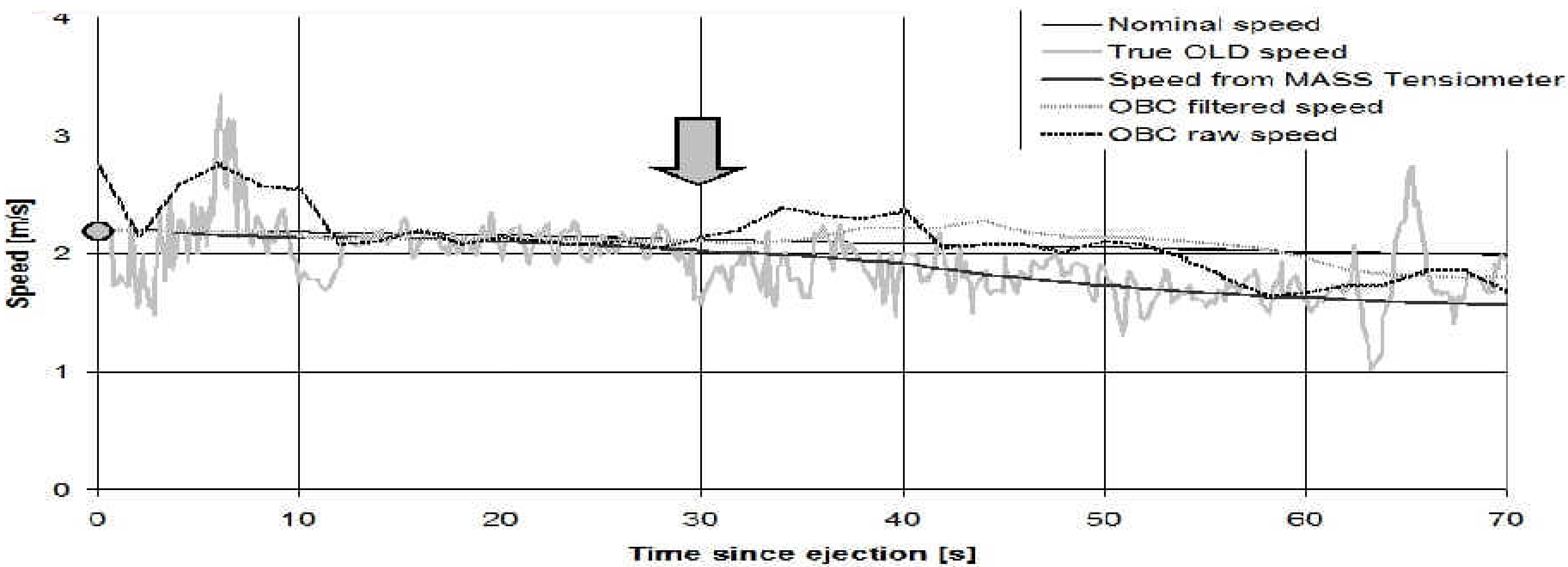


Deployment Reconstruction

Ejection (OLD data)

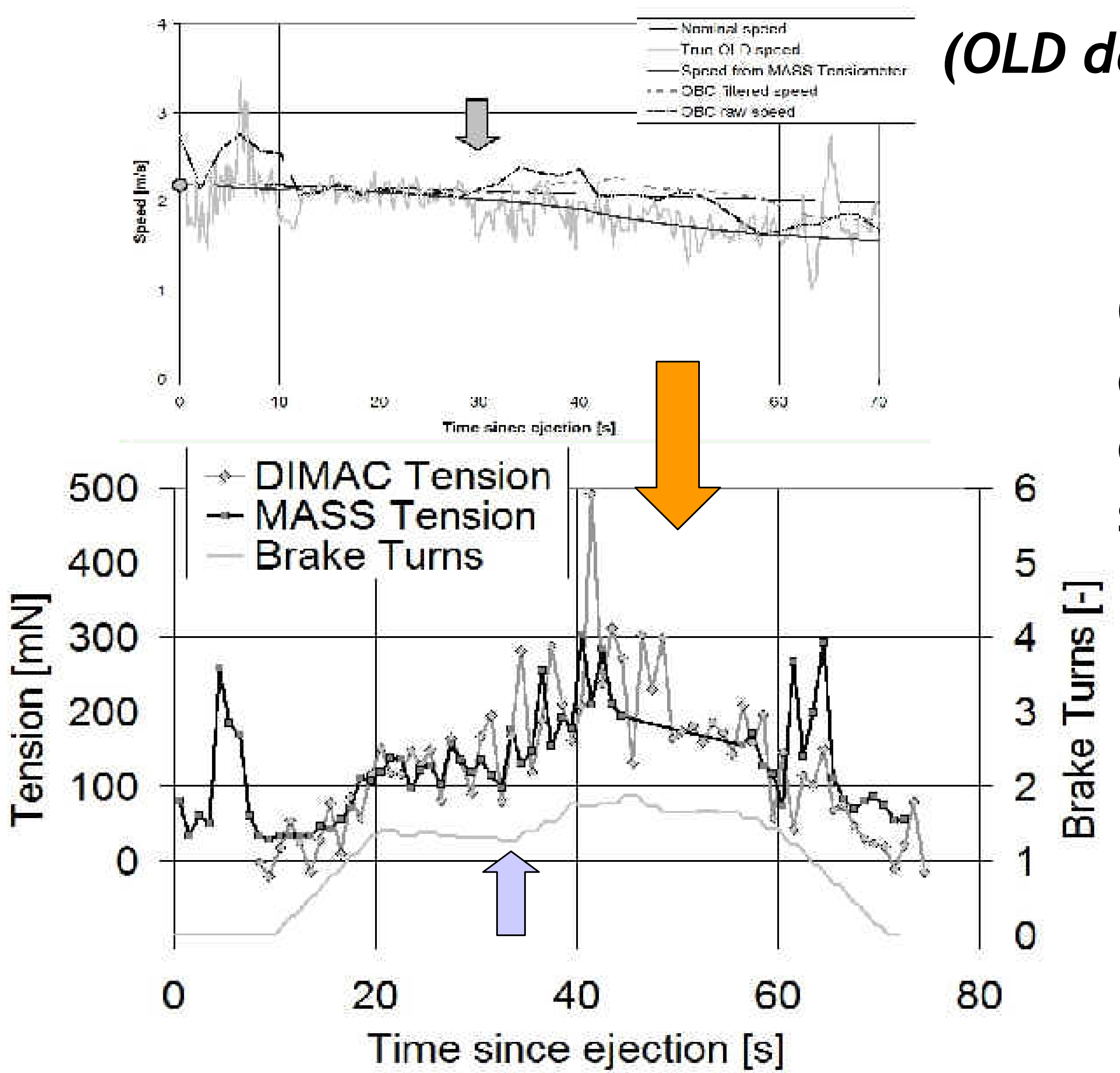


Unsuitable OLD filter setting causes brief overestimate of initial speed



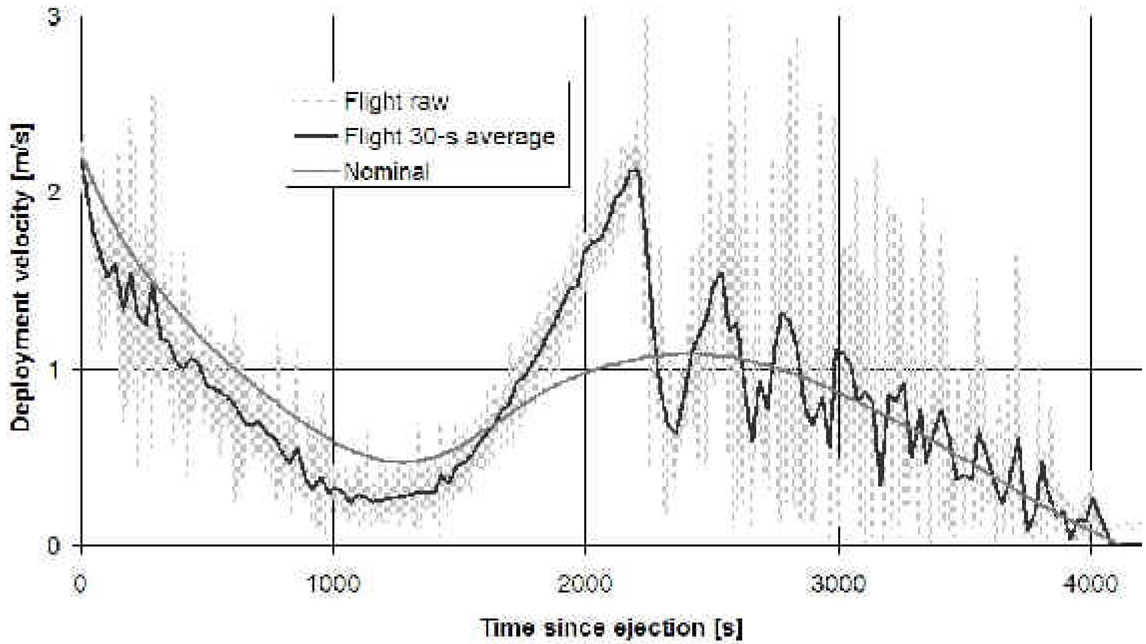
Deployment Reconstruction

(OLD data)

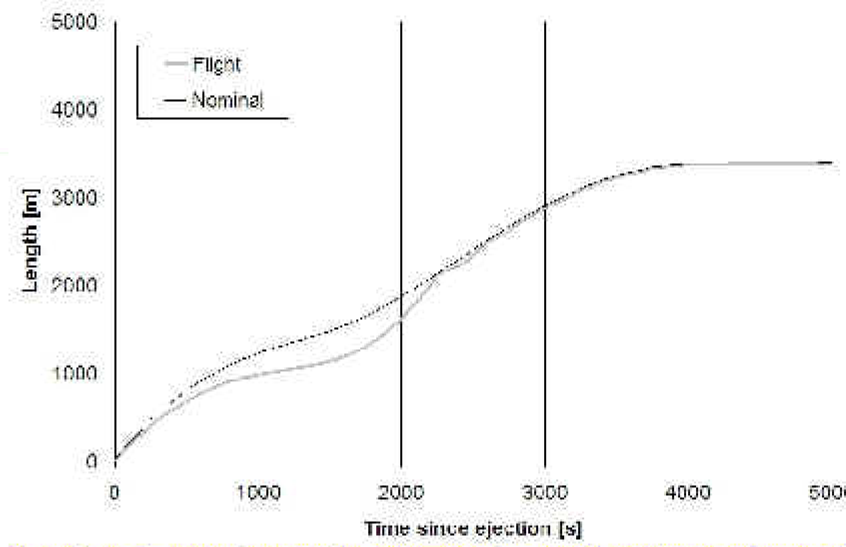


Overestimate of speed causes initial brake event, bringing early speed below nominal

Deployment reconstruction



Stage 1 close to nominal but with oscillations



Deployment Reconstruction

Second Stage

- The hold phase (no deployment) and restart of the second stage (brake release) started off nominally, demonstrating the feasibility of the most complex and critical phase of the deployment
- The remainder of the second stage is a relatively straightforward acceleration with a moderate brake levels and smooth but heavier braking near the end

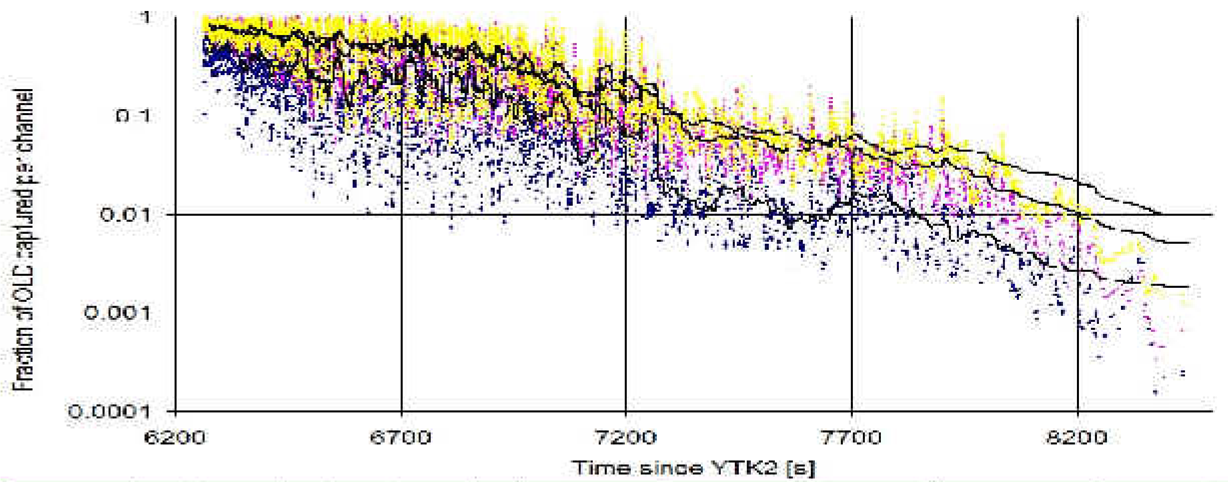
Deployment Reconstruction
Second Stage

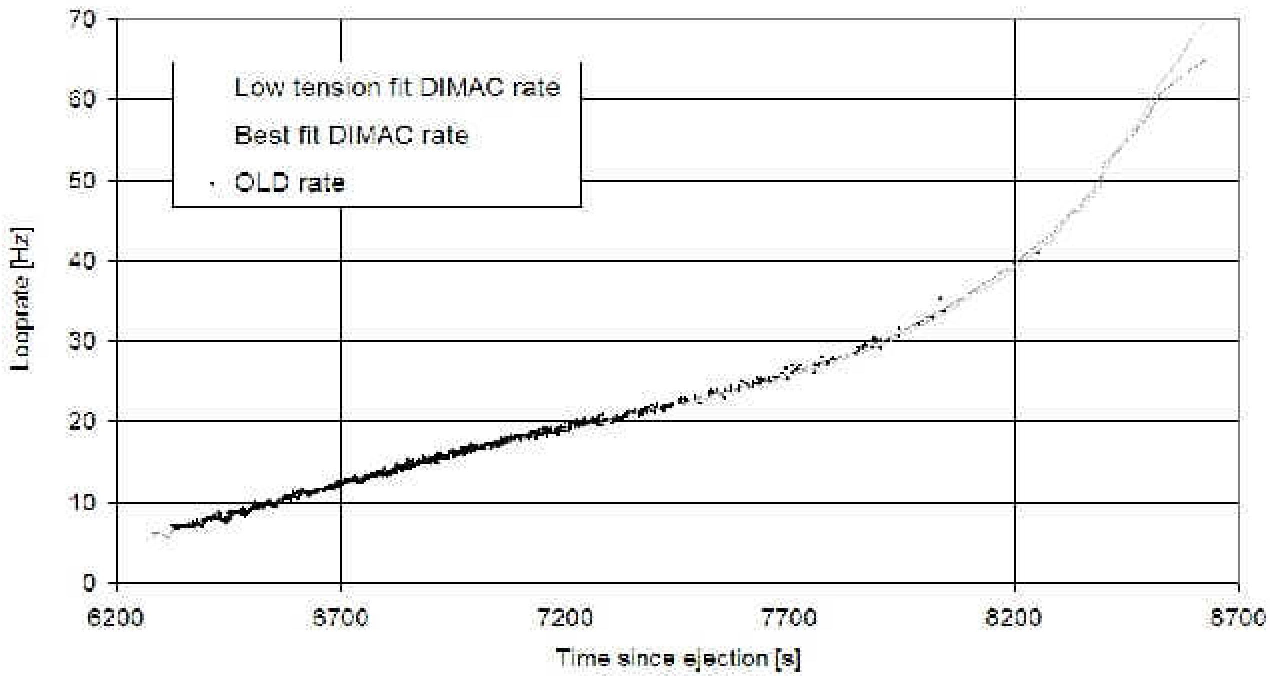
- However, near t=6200 s the controller set the brake to zero, resulting in a lack of endbraking and thus a significant endshock.
  - An ever decreasing fraction of OLD interrupts was actually registered by the OBC, caused underestimate of length and speed and the appropriate controller response was to set brake to zero
    - The cause of the poor signal registration is probably due to increasing EMC noise on the OBC's input channels swamping the actual (correct) OLD signals
      - The EMC sensitivity was increased due to off-nominal operating voltage for the signal receivers and slowly rising OBC temperatures
    - The off-nominal operating voltage was due to a tested but insufficiently analyzed hi-power-consuming patch, for which several better alternatives were readily available in construction/test phase
      - The lack of analysis of alternatives and sufficiently close analysis of test data related to the patch was due to severe time pressure in the construction phase
    - The patch was necessary in the first place due to known signal failures on both the engineering model and flight OBC boards in the construction phase
      - The OBC boards signal failure history should have been more adequately prevented and/or identified by better inspection, acceptance and verification procedures

Deployment Reconstruction
Second Stage

- The 1.7 km tether margin were all deployed making the final length 31.7 km rather than 30 km
- Nevertheless a near nominal swing angle was achieved and the tether was released at nominal time close to the vertical as planned
- The overdeployment led to a steeper re-entry and the capsule was targeted ~1200 km upstream of the nominal landing point outside the reach of a student-initiated ground station near the nominal landing point.
- The capsule re-entry conditions were probably within the nominal envelope
- No beacon signal from the capsule was received, possibly because of:
  - Disintegration of capsule possibly due to fast spinning after tether shock
  - Failure of parachute and subsequent crash
  - Failed/insufficient power supply to beacon
  - Water landing

Deployment reconstruction





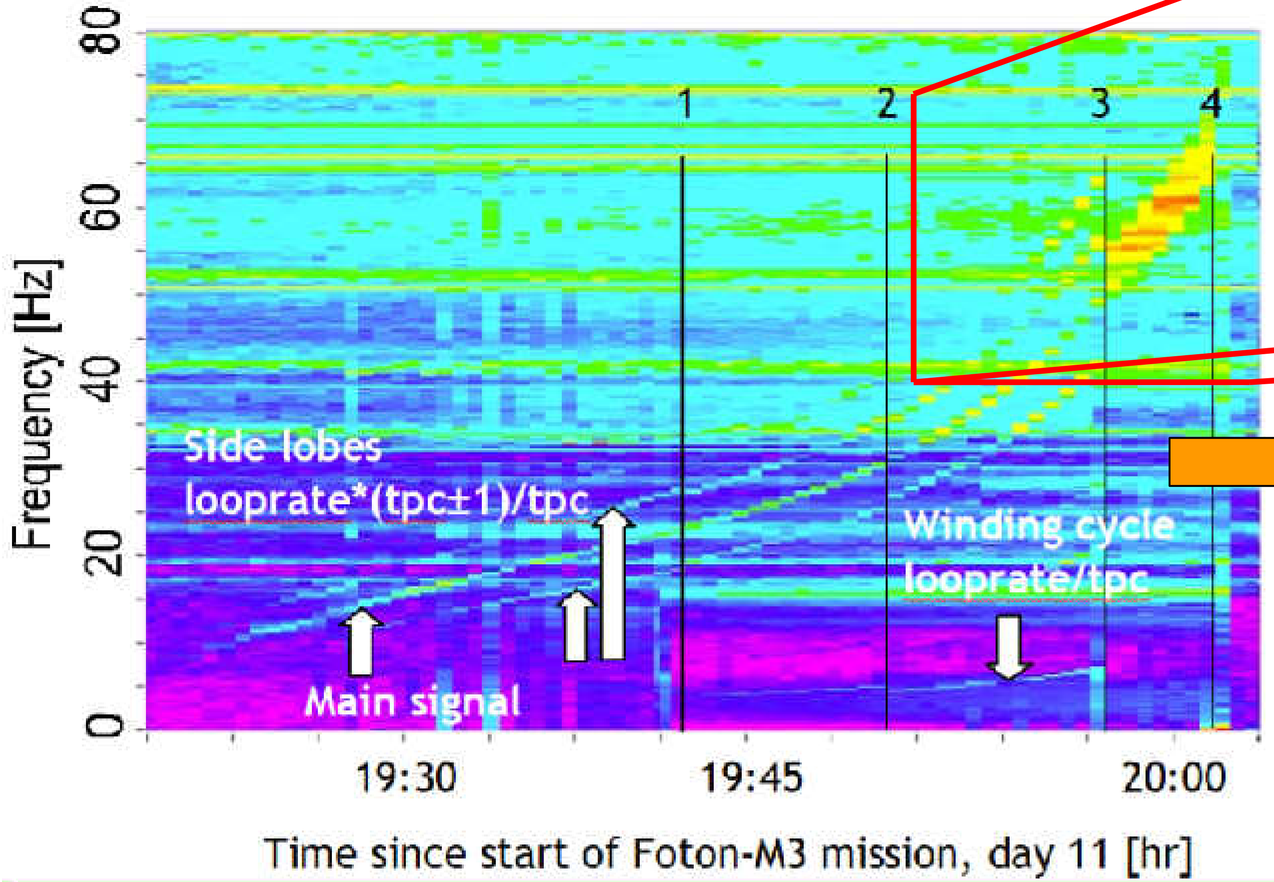
Stage 2

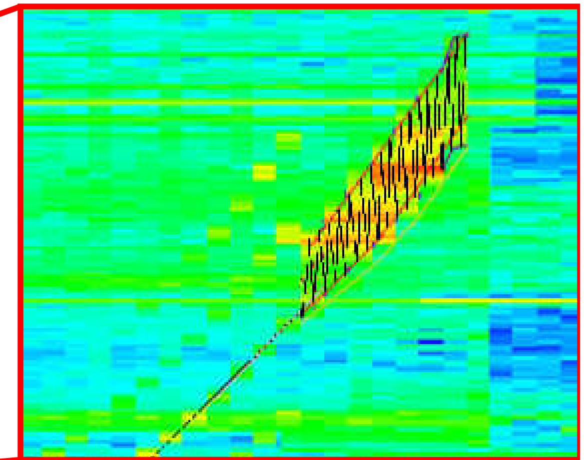
Despite decreasing registration of the OLD signals on all 3 channels, looprate vs. time could be accurately determined from 2 independent sources and therewith the full deployment could be reconstructed within 150 m accuracy

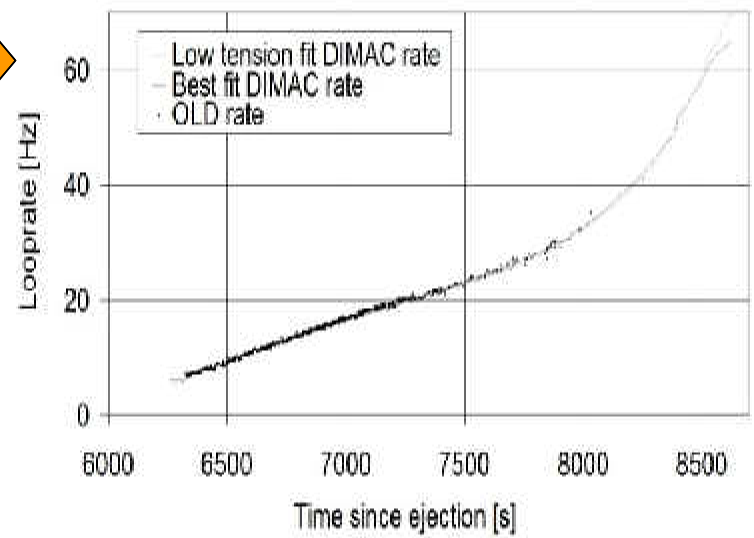
Second Stage OLD rate

spool's fingerprint visible in 4 transitions in spectrograph

	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

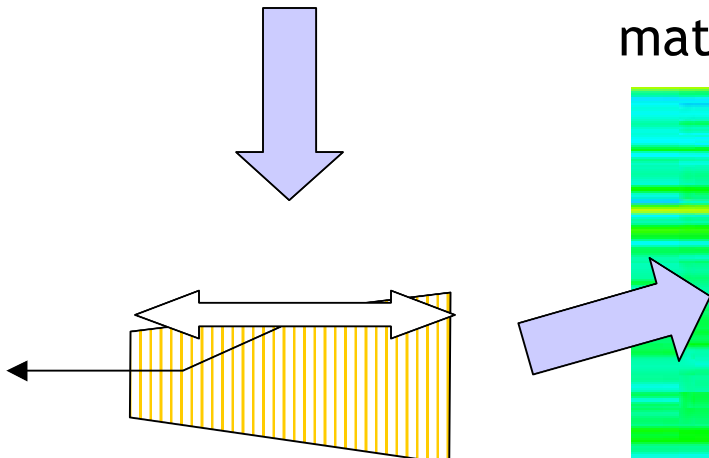


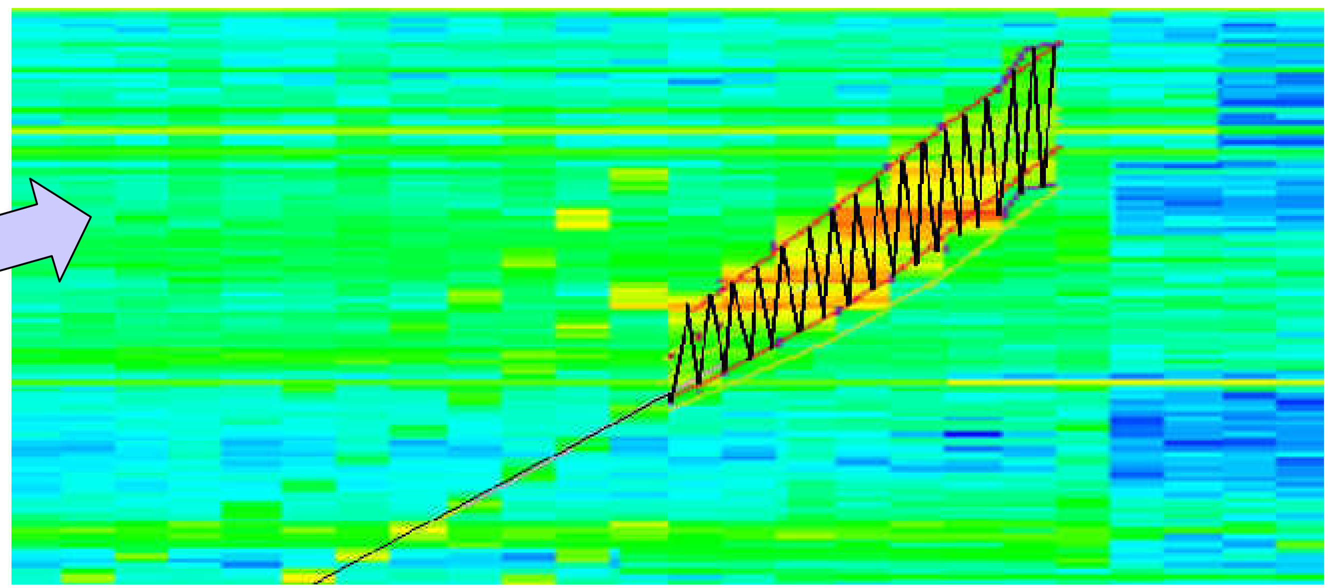




End of unwinding

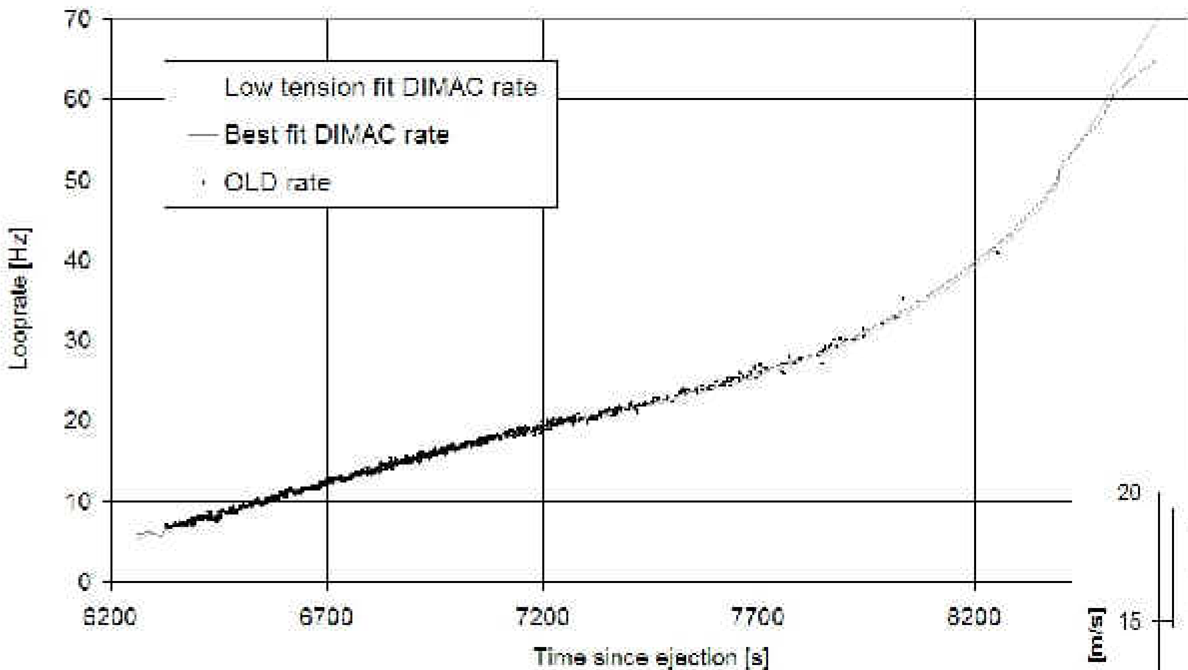
- Criss-cross part of deployment delivers smooth looprate (with side-lobes)
- As soon as parallel-wound bit of deployment starts however (within flanges of core) the rapid back-and-forth travel of the unwinding tether over the width of the core due to core cone angle causes zigzag pattern superimposed on looprate
- The predicted pattern based on core dimensions matches the observation accurately

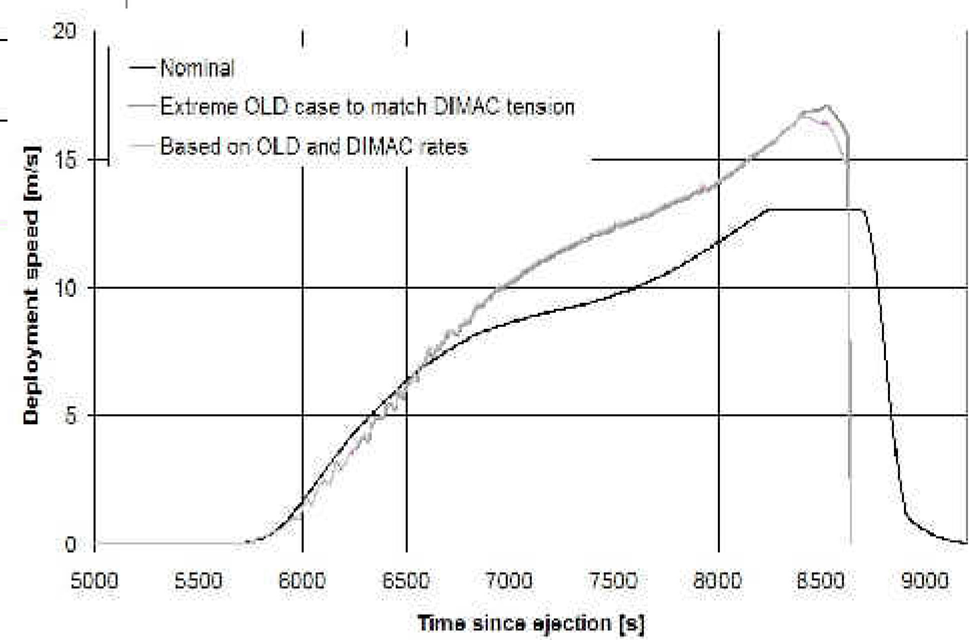




Deployment reconstruction

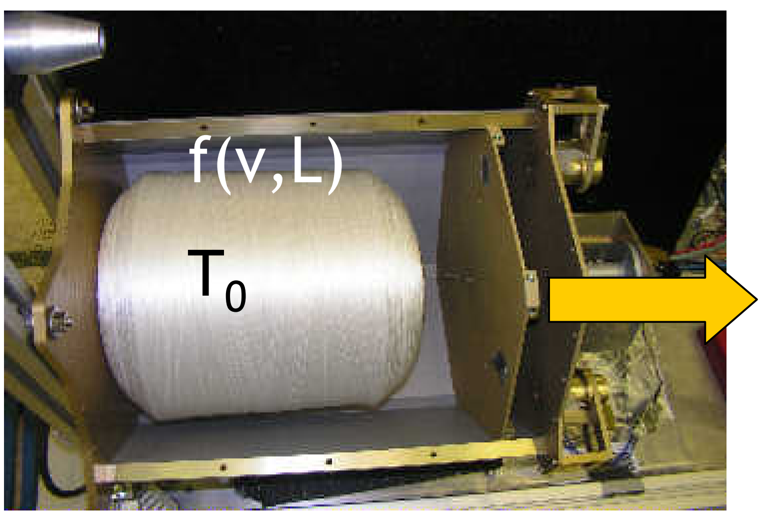
Stage 2



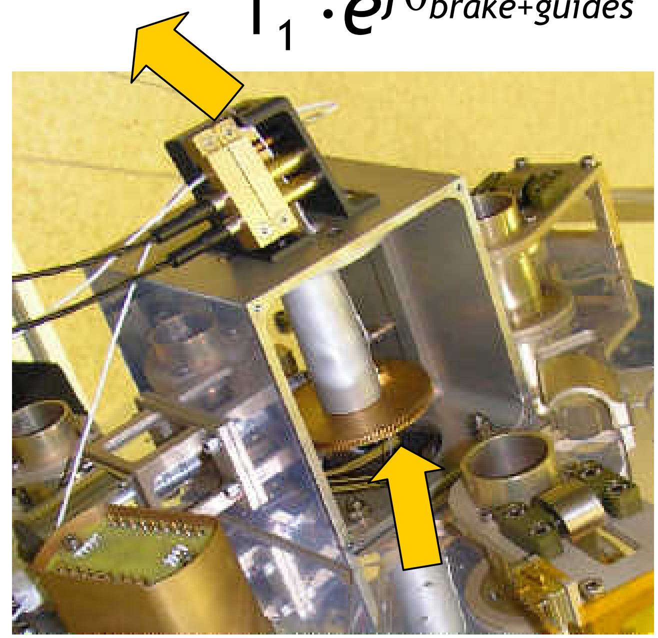


Hardware performance in flight

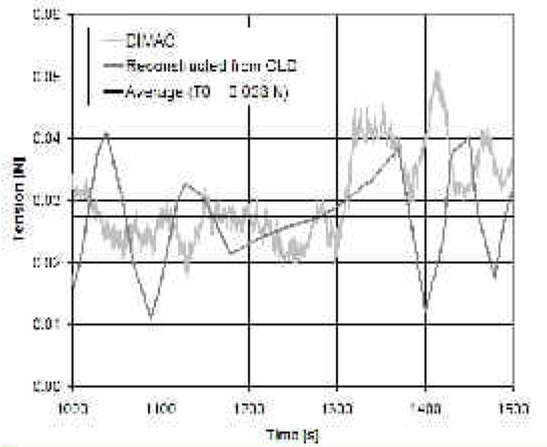
- Control depends on accuracy of tension model
- Three components:
  - Minimal Deployment tension T_0 (low speed, no brake)
  - Velocity/length dependency $f(v,L)$
  - Brake friction f
- *Tension* $= [\, T_0 + f(v,L)\,]\, e^{f\theta_{brake+guides}}$



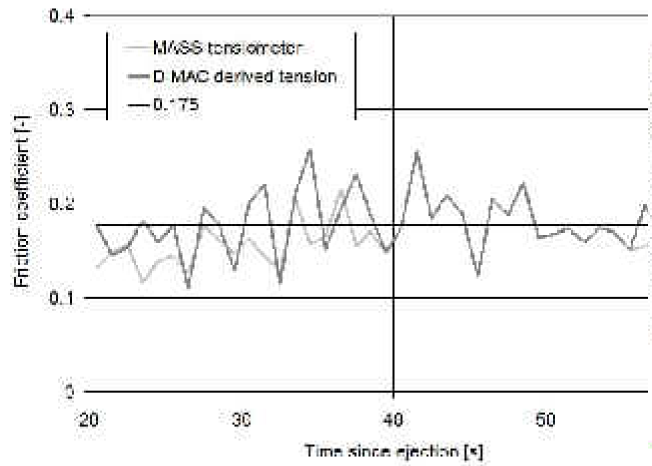
$T_1 = T_0 + f(v,L)$



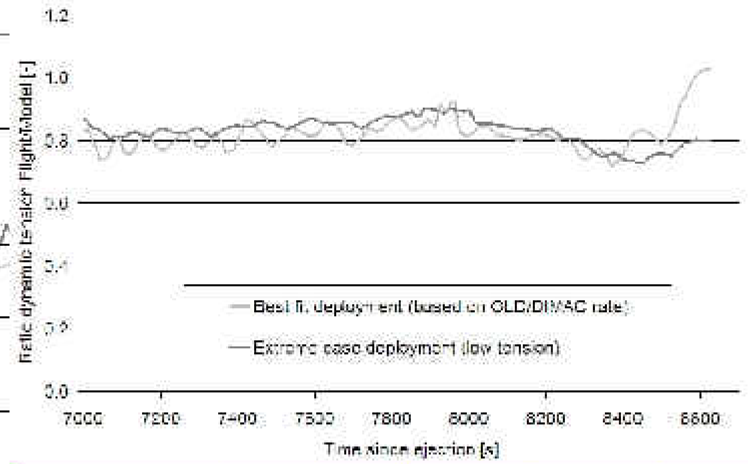
Hardware performance in flight



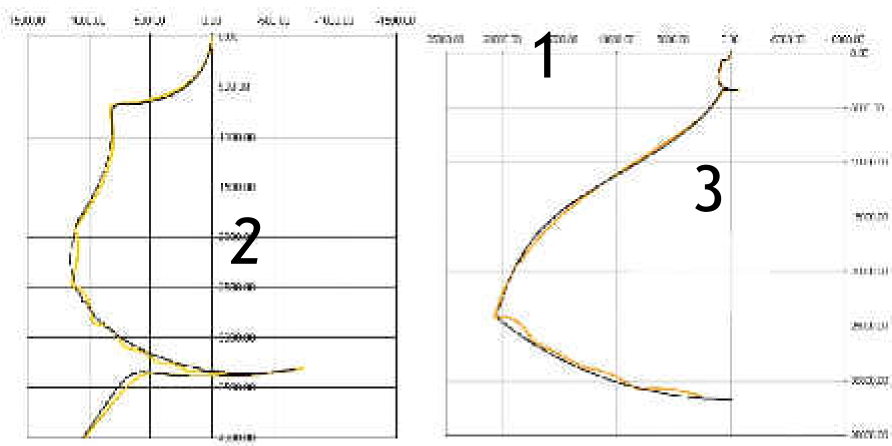
1 – T_0



2 – *f*



3 – *f(v,l) or I*



Hardware performance in flight

$$T = \left(T_0 + I \frac{\rho \dot{l}^2}{\left(1 - A_{sol} \frac{l}{l_{tot}}\right)^E} \right) e^{2\pi f(\dot{l}) n + f_{guides}\left(\theta_{guides} + \theta_{ref} - \theta_{Foton}\right)}$$

Property	Nominal	Acceptable	Flight
Friction f	0.2	0.12-0.3	0.175-0.25
Stickiness T_0	0.01 N	0.005-0.03 N	0.023-0.045 N
Dynamic dependency I	8	2-20	7-8

Hardware performance in flight

- The tether deployer system functioned nominally with no visible failures throughout the mission:
- The system can be considered ready for future missions:
  - Barberpole + Stepper driver & motor
  - Canister + OLD system
  - Core
  - Attachment and damping systems (ripstitching, Prusik knot)
  - Tether release system (relay box & cutters)
  - Controller and software

Hardware performance in flight

- Although tether release from Foton could be confirmed with full certainty, the 20 s of available post-release data was found to be insufficient to conclude on Fotino release from MASS.
- Some minor software issues were observed (timetagging with various time references, filter settings) and recommendations were provided
- The tether spool itself behaved nominally especially at high speed and in parallel, but at low speed the unexpected amount of stickiness was barely acceptable
  - The stickiness due to thermal settling should be determined before flight and details of tether/controller design need to be tuned according to test results

Simulation Matching

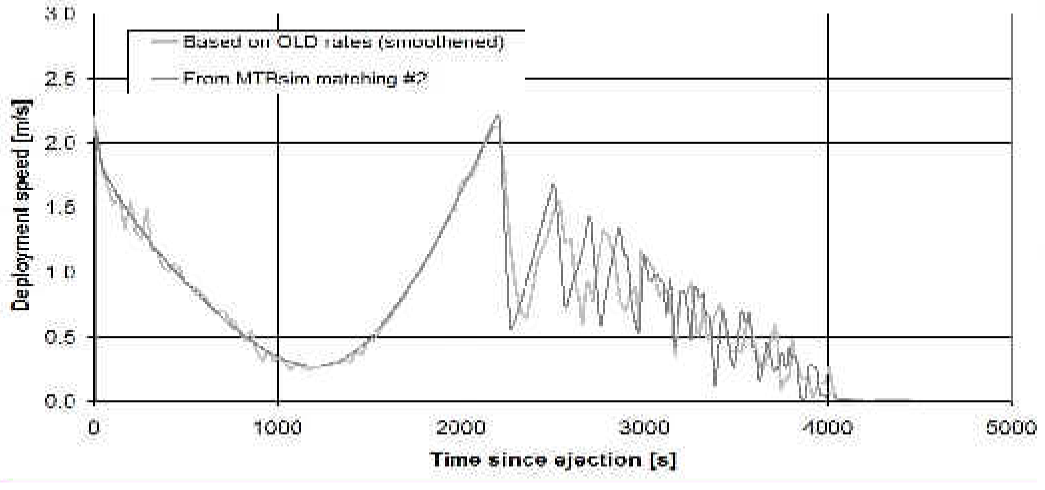
- By plugging the measured hardware parameters into a numerical model of the system, the history of deployment speed and closed-loop control performance could be reproduced accurately, confirming predictability and consistency of hardware performance
  - Only minor adaptations to the measured parameters (order of 10%) were sufficient to obtain a near perfect match to the measured deployment profile
  - Also tension measurements during deployment and in the swing were sufficiently convincingly reproduced
- The simulation match allowed to study the effect of tether damping and stiffness on control (match #1, match #2).
  - More damping was observed in the YES2 tether than predicted in advance, due to not sufficiently representative measurement method. The tether stiffness matched the predictions closely.

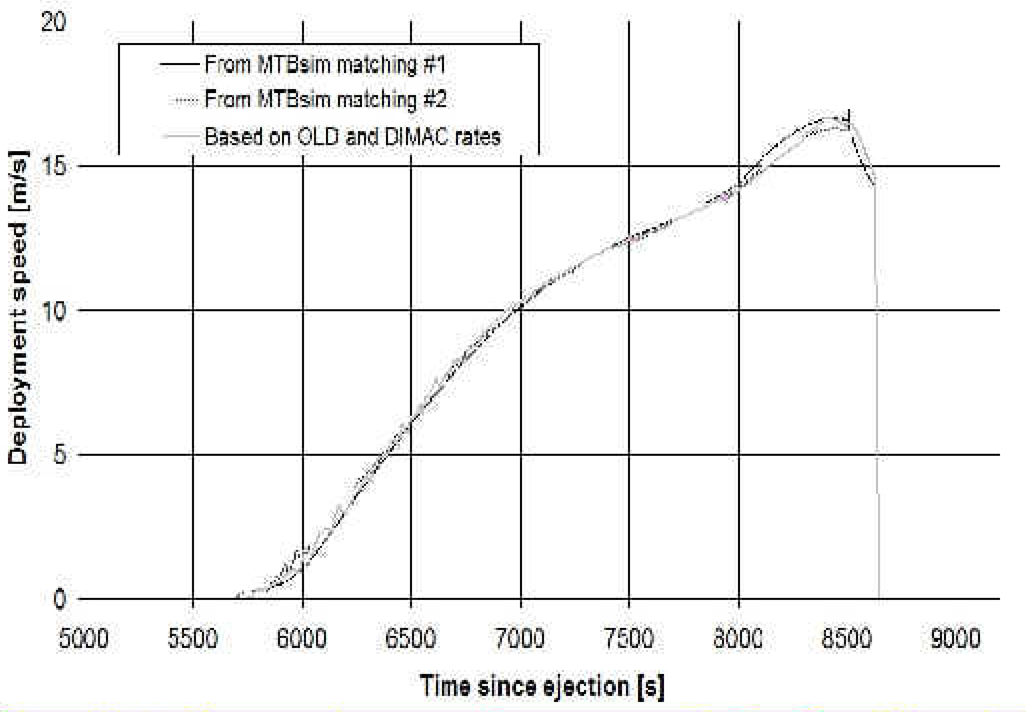
Simulation Matching

- DIMAC data on tether exit angle (3-axis accelerometers) and Foton attitude (magnetometers) produce a picture of tether in-plane deployment angle
- The simulation match provides an independent estimate of the in-plane dynamics of the tether
  - In-plane dynamics from the simulation match are in close agreement with DIMAC measurements, strenghtening confidence in both the measured deployment profile and in the simulator applicability
  - The oscillations superimposed on the main tether swing evidence persistent lateral oscillations in the tether
- All results are in agreement with a third data source, the observed cold-gas attitude control effort of the Foton vehicle (tracking tether to a maximum of 30 degrees from nadir)

Simulation matching

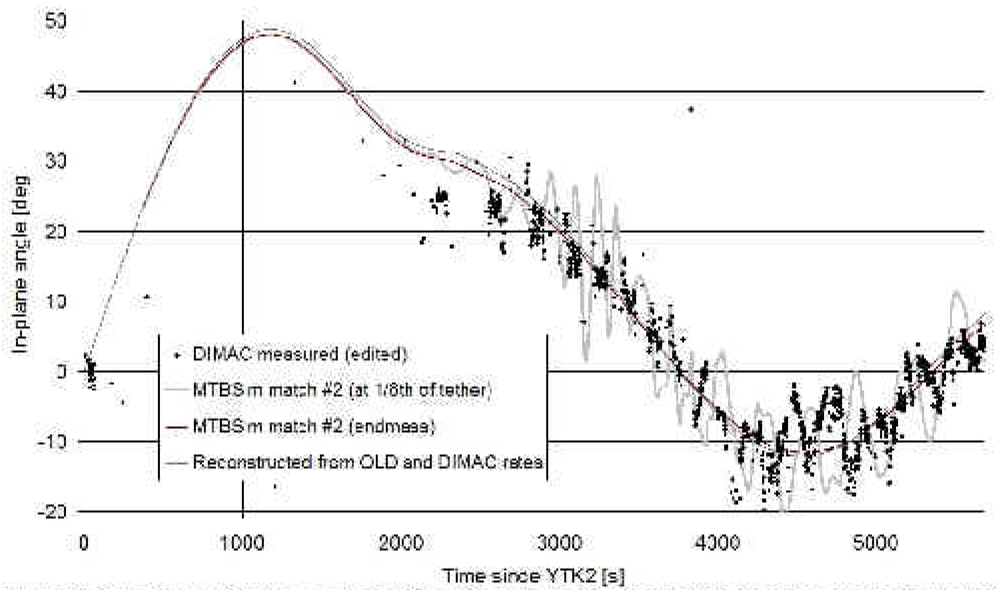
Stage 1+2

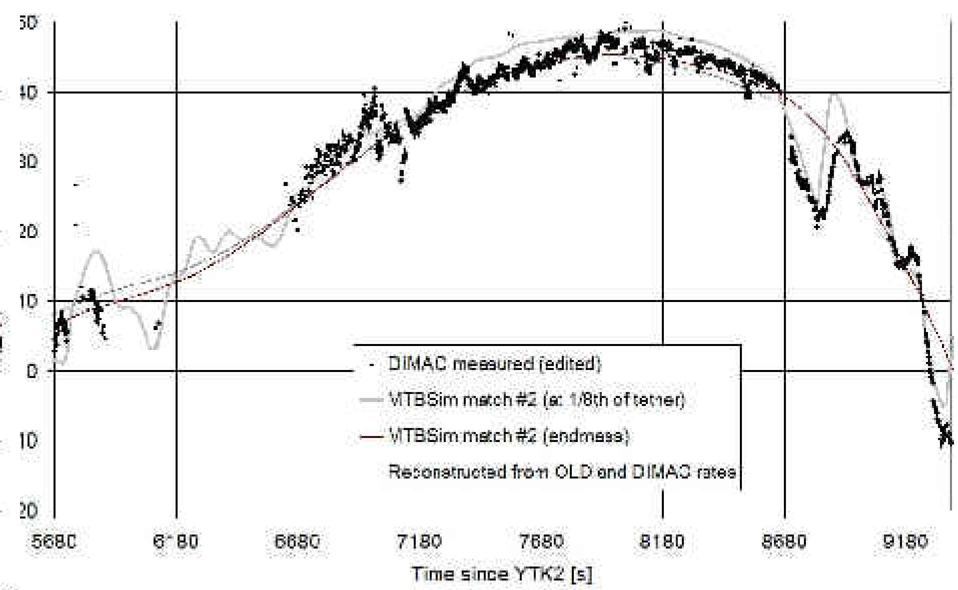




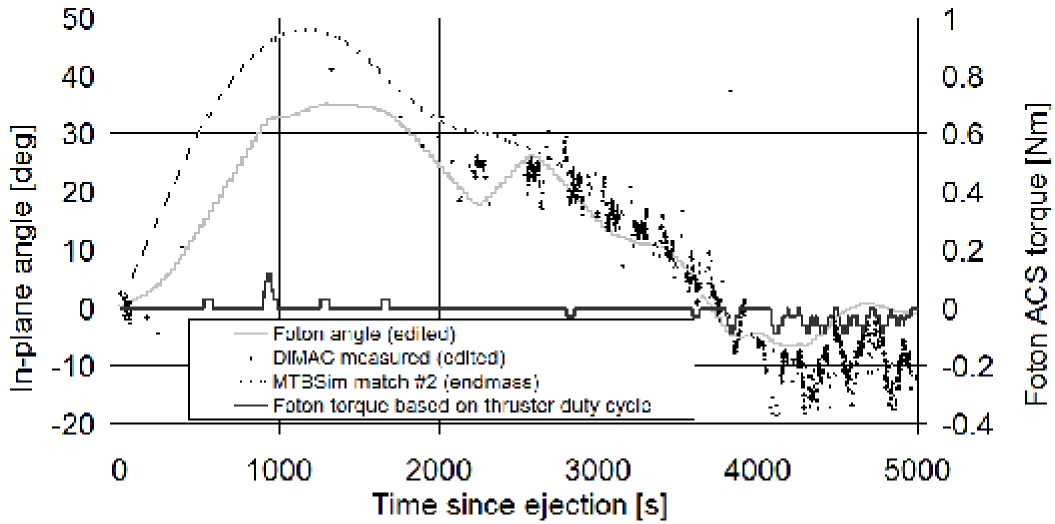
Simulation matching

In-plane angle from simulation matching vs. measured by DIMAC
Direct evidence of lateral waves dynamics

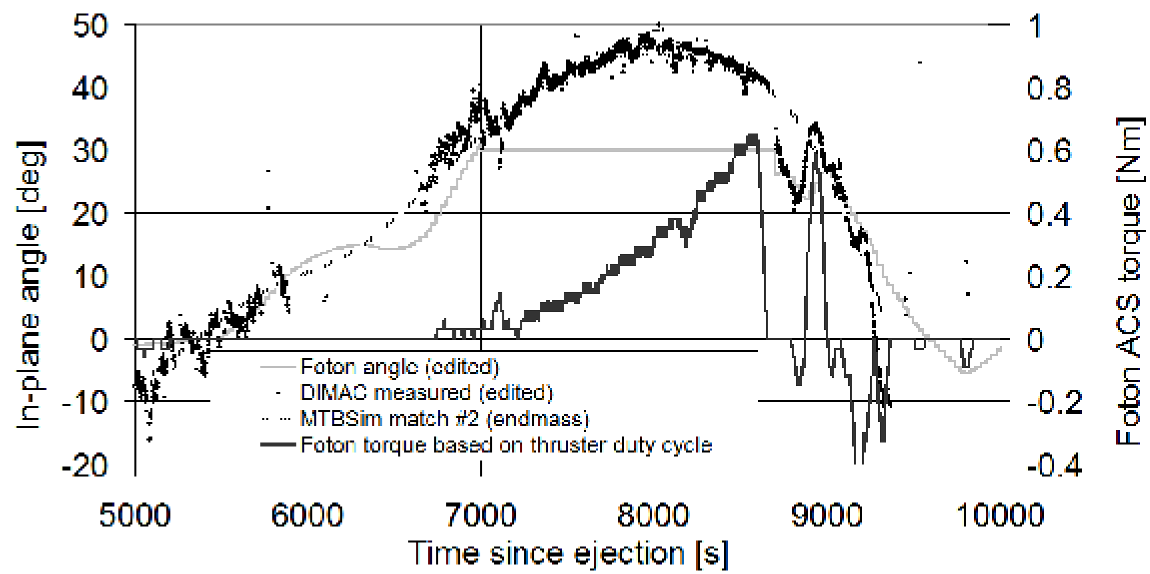




Simulation Matching

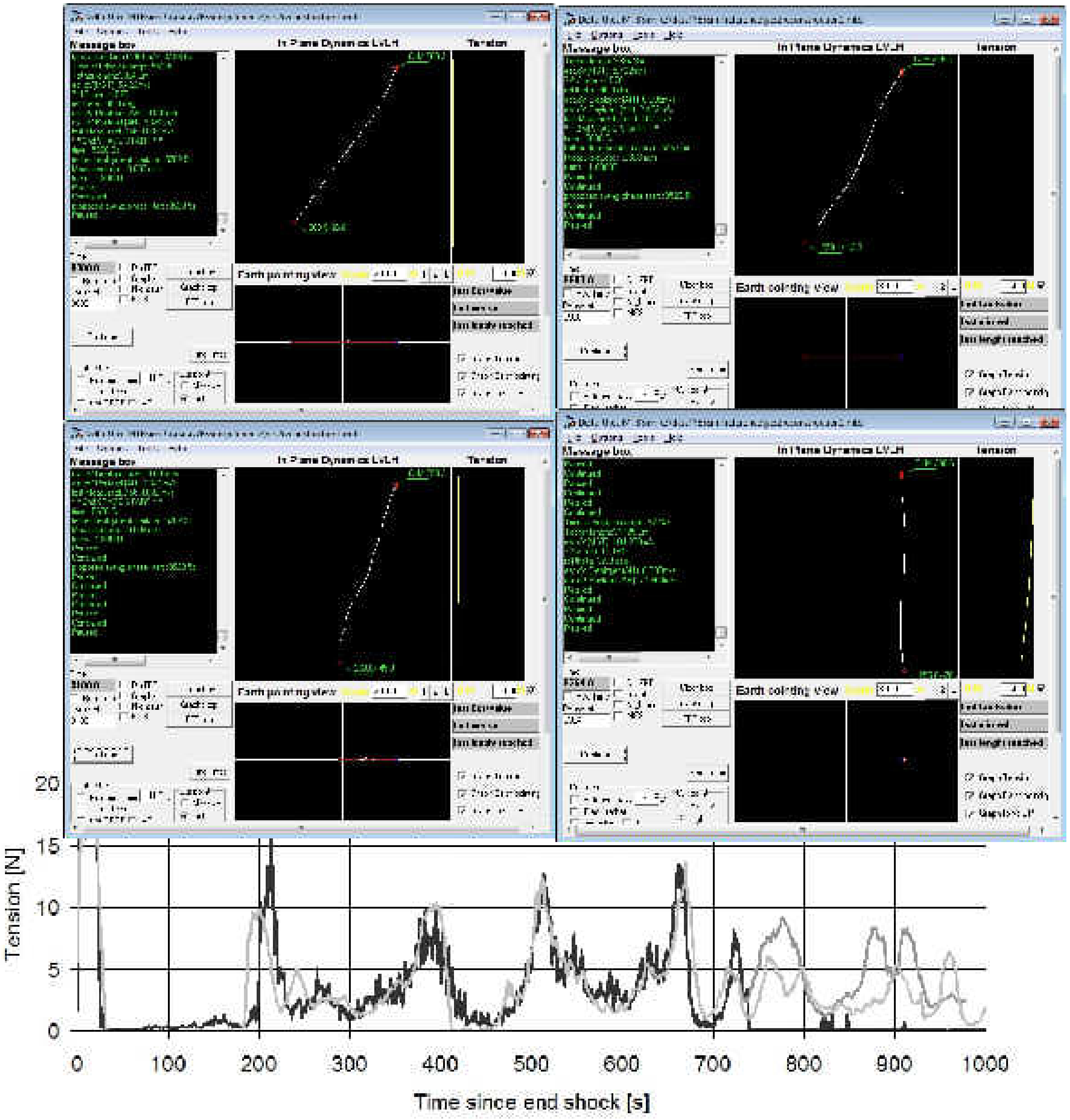


Estimated in-plane angle vs. Foton control effort (tracking tether to max. 30 deg)



Simulation matching

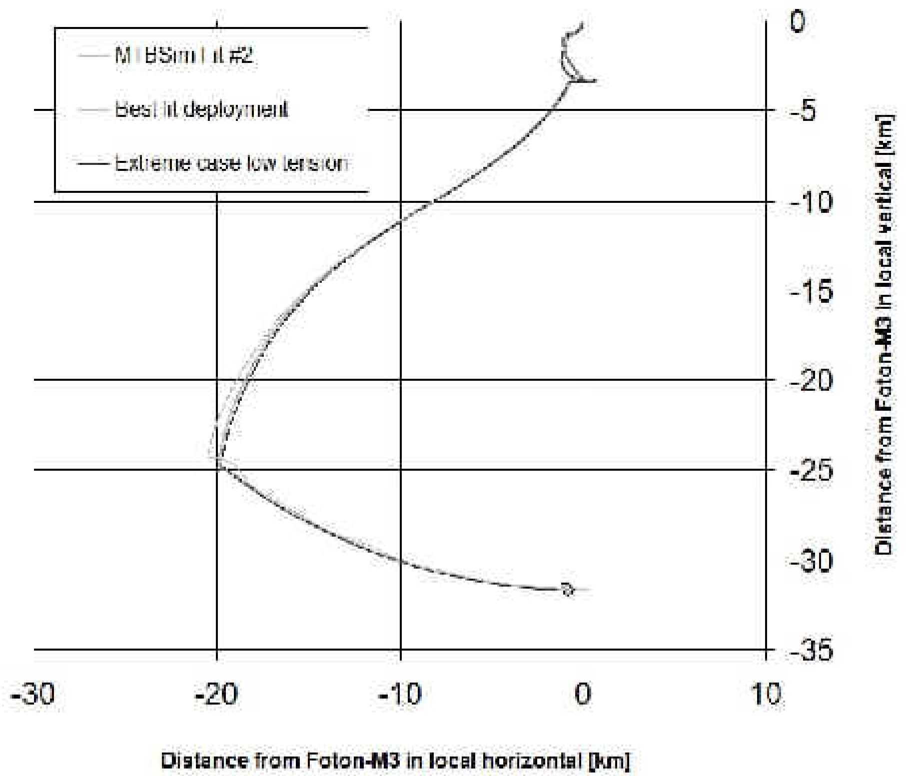
Swing shows similar longitudinal and lateral waves in simulator and in data

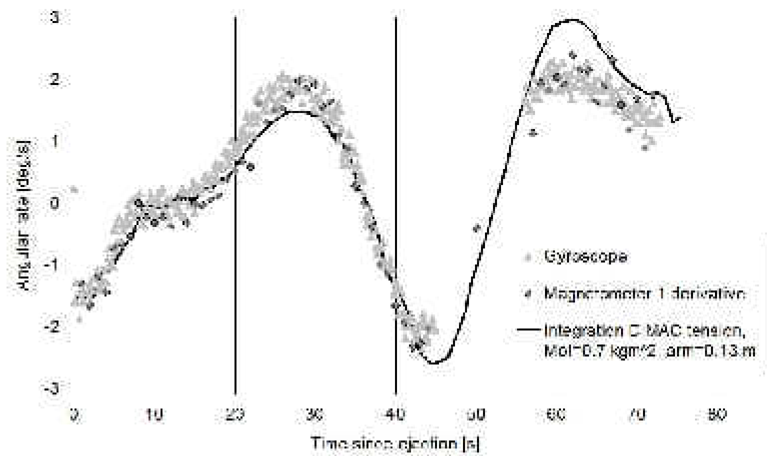


Determine Fotino landing site

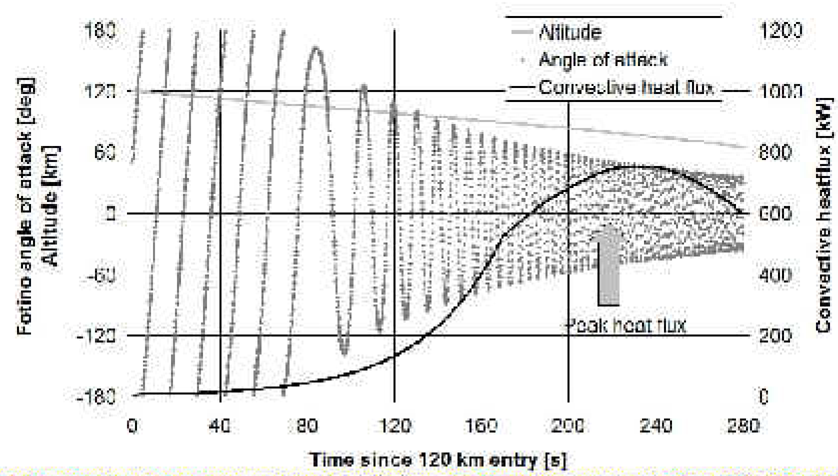
- With the in-plane angle known the deployment, swing and capsule release can be plotted in local horizontal-local vertical
- The simulator match provides the initial conditions for the capsule re-entry so its likely landing position can be determined (with ~250x30 km accuracy)
- The simulator match, as it is based on hardware and control models and includes a manually inserted control failure from t=6200 s onwards to simulate the OLD registration failure, also provides the possibility to view the hypothetical YES2 deployment and re-entry *without* that failure.
  - The resulting simulation shows a near-complete recovery of the first stage oscillation and landing in the nominal landing area
  - If the controller resonance at the end of the first stage is also removed, the landing is almost perfectly on the target

Determine Fotino landing site

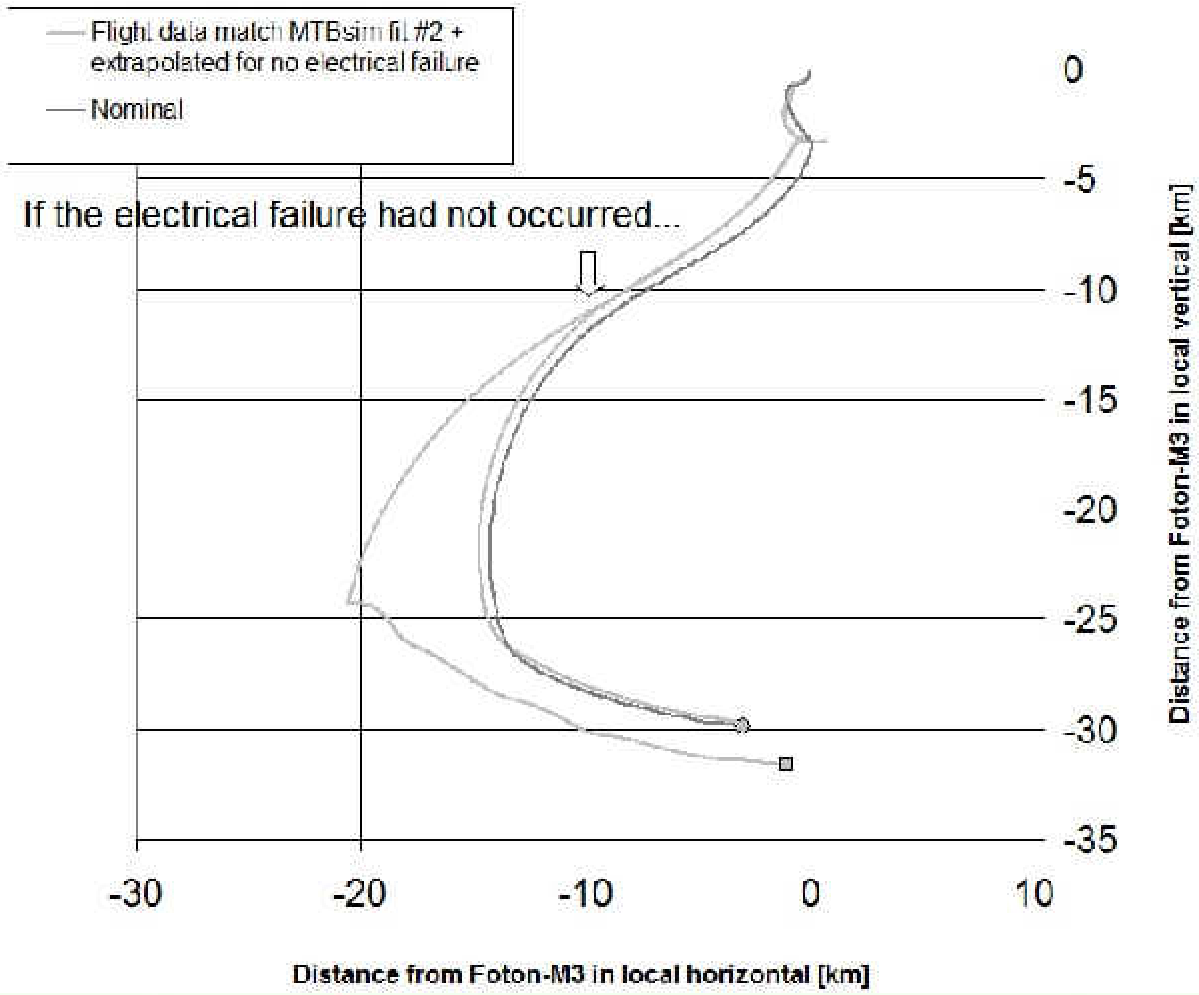




Worst-case Fotino angle during entry



Determine Fotino landing site



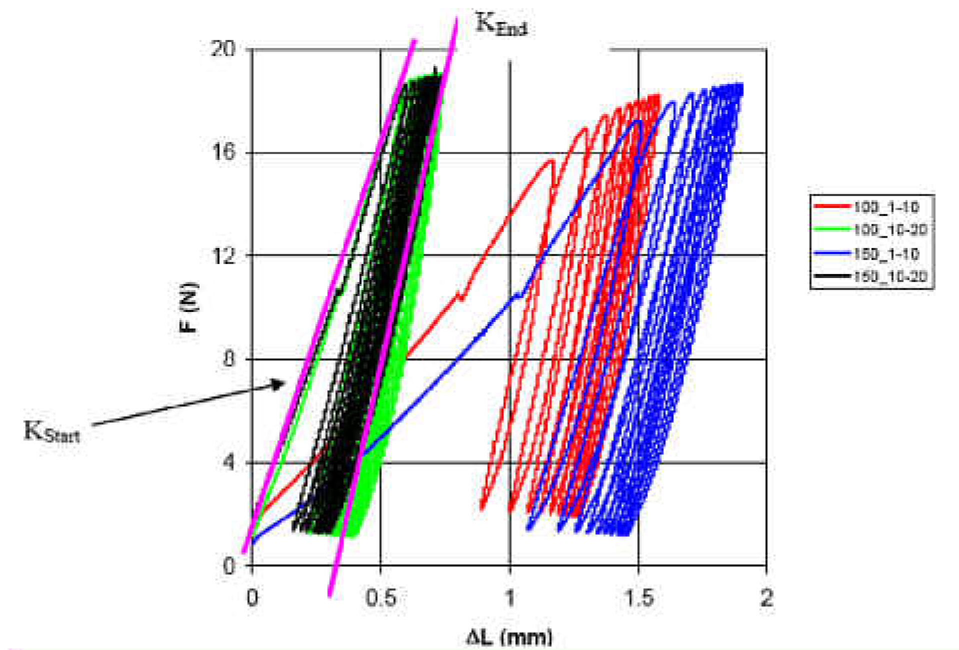
Determine Fotino landing site

Wave and tether properties

- The simulation matching provides *lateral and spring-mass* oscillation related tension profiles, depending on tether properties that can be compared to the DIMAC measured tension
  - Overall, these complex dynamics were well represented both in behavior and amplitude
  - Actual tether stiffness and damping could be inferred
  - Simulations were performed of the swing with and without Fotino release to compare to DIMAC data and understand whether release occurred, but no unambiguous conclusion could be drawn.
- DIMAC also measured soundwaves due to the endshock which match in appearance the result of our mathematical modeling
  - The measured data confirms the speed of sound in Dyneema tether of ~10 km/s

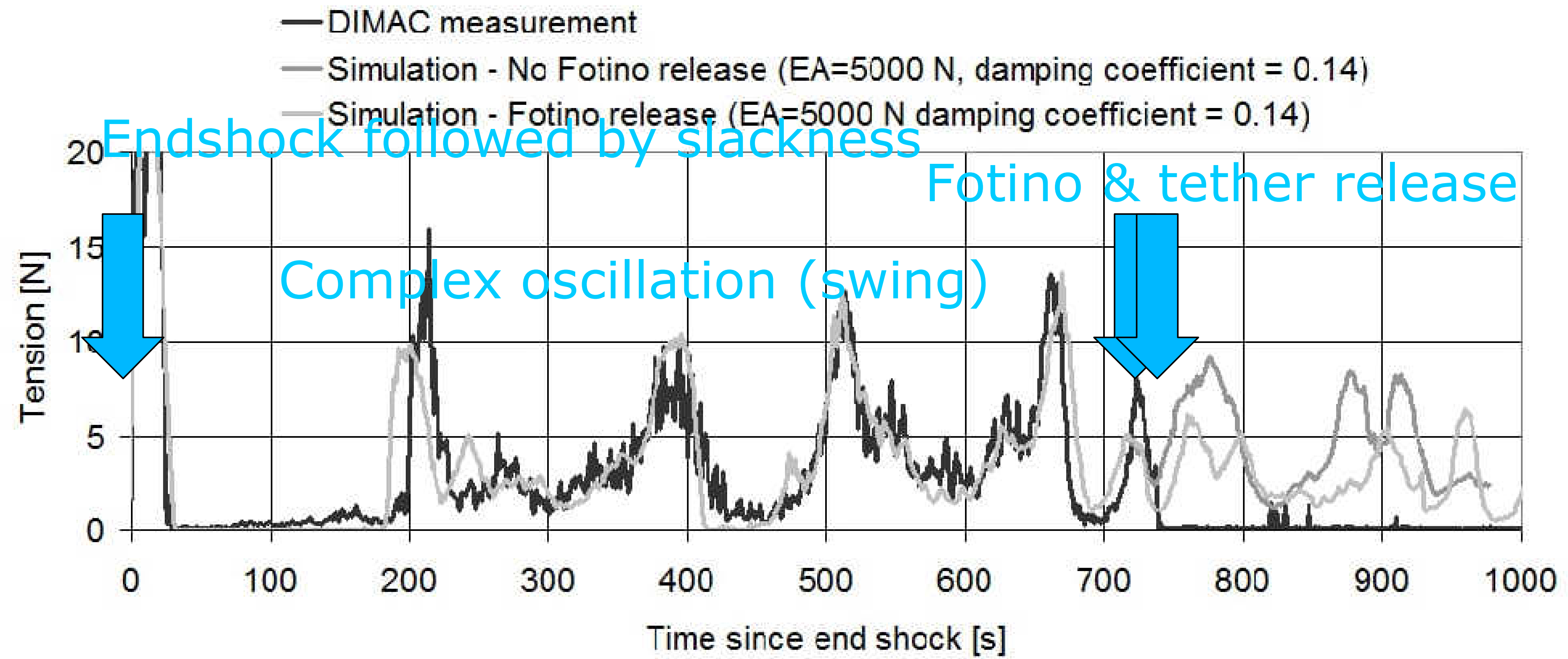
Waves and tether properties

Flight tether stiffness matched pre- and postflight ground test results (Krefeld, Reggio Emilia)



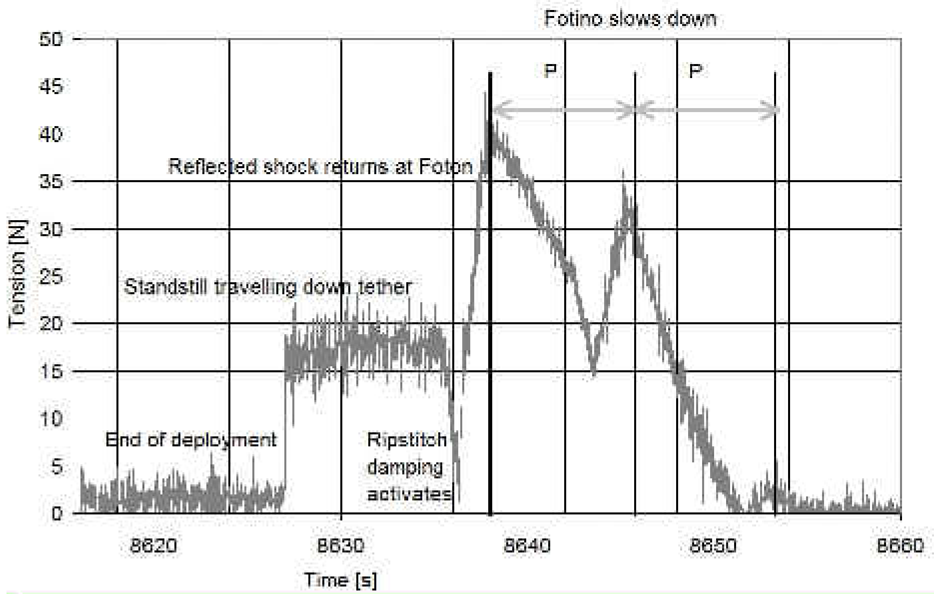
Waves and tether properties

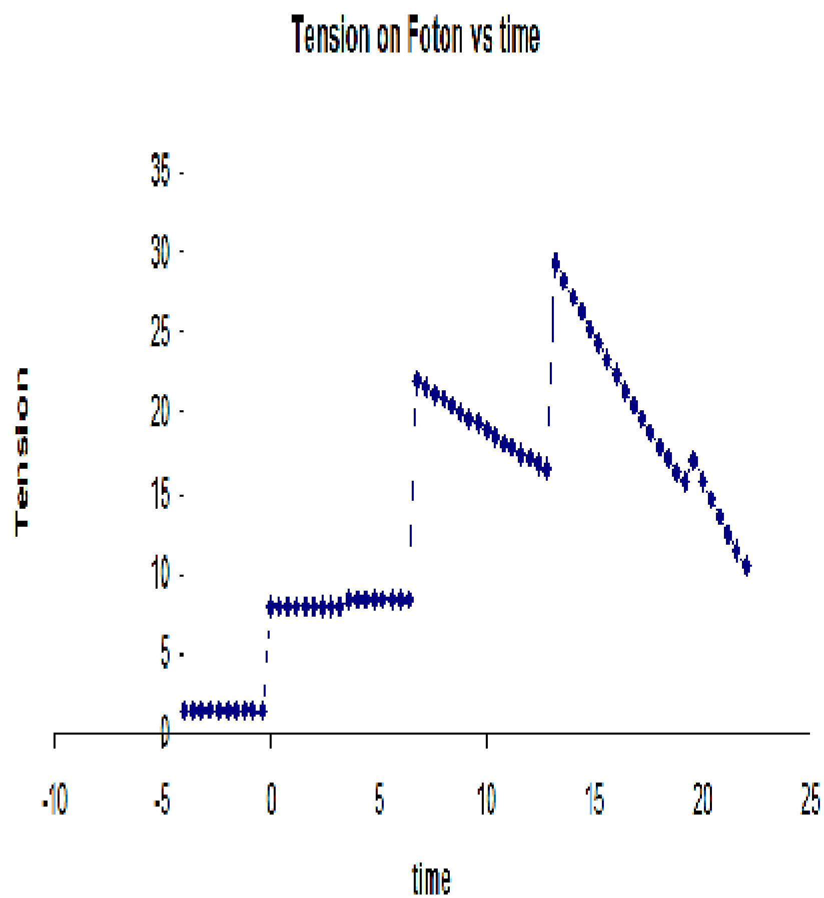
Spring-mass dynamics
Flight data vs. simulation



Waves and tether properties

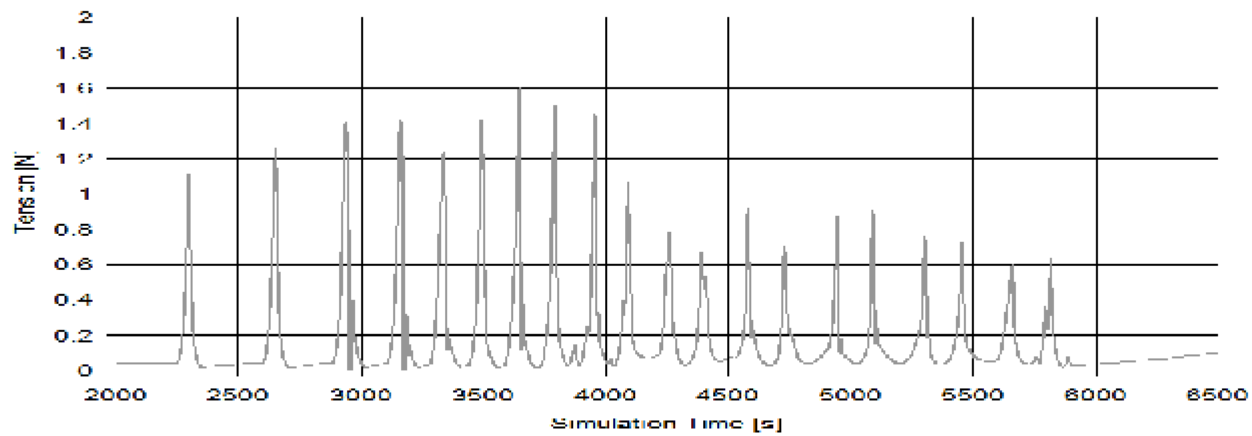
Longitudinal wave
Flight data vs. simulation

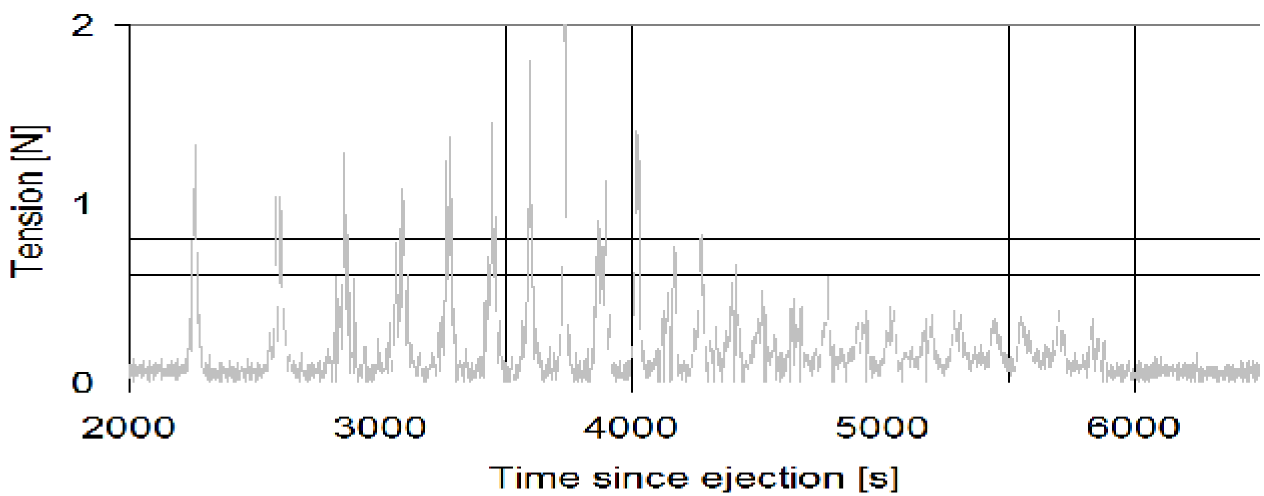




Waves and tether properties

Lateral waves (1st stage & hold phase)
Simulation vs. Flight data





Deployment analysis summary

Ejection

Mission parameter	Data sources	Description	Attainable accuracy	Nominal value	Acceptable range	Result
Ejection speed	OLD	Initial OLD rate	0.1 m/s	2.2 m/s after tie-downs	1.2-3 m/s	*Nominal*. 2.2 m/s after tie-downs
	MASS tensiometer + OLD	Integration of acceleration derived from MASS tensiometer, fit to OLD rate development	0.1 m/s			
	DIMAC + OLD	Integration DIMAC accelerations, fit to OLD rate development	0.1 m/s			
Subsatellite initial dynamics around center of mass	MASS gyroscope	Direct measurement (1 axis)	0.2°/s	10°/s initially		*Nominal*. 1.55°/s initially
	MASS magnetometers	3-axis derivatives	1°/s			
Subsatellite continued dynamics around center of mass	MTBsim Simulator + DIMAC	Simulation using tension data fit to initial MASS data	-	Max 90º amplitude oscillation	Max 90º amplitude oscillation	*Off nominal*. Subsatellite appears to be tumblingas a result of slackness.

Deployment analysis summary

Deployment

Mission parameter	Data sources	Description	Attainable accuracy	Nominal value	Acceptable range	Result
Deployment speed t<6260 s	OLD	Rate data	~0.05 cm/s	0-6 m/s	-	*Acceptable*. Initially too much braking due to temporary bad filtering
	DIMAC (+ OLD)	Confirmation by comparison of DIMAC derived tension to OLD reconstructed tension (Eq. 1)	1%			
First stage length profile	OLD	Loop count	20 m	-	-	*Nominal*.
First stage length	OLD (+ statistical analysis)	Loop count, time interval/statistical analysis to estimate error	20 m	3390 m	3100-3700 m	*Nominal*. 3380 m
	DIMAC	Gravity gradient tension from DIMAC for hanging tether	~100 m			
Deployment speed 6260-8626 s	DIMAC	Spectrograph rate profile	0.2-0.7 m/s	5-13 m/s	-	*Off-nominal*. 5-16 m/s, due to OLD registration failure
	OLD	Rate data (interpolated over last 400 s)	1 m/s			
Second stage length profile	DIMAC	Integration of spectrograph rate profile	100 m	30000 m	29000-31000 m	*Off-nominal*. 31700 m, due to OLD registration failure
	DIMAC	3 Transition points in winding turns per cycle setting from spectrograph, end of deployment from tension spike	100 m			
	OLD	Reconstruction using rate data	~200 m			

Deployment analysis summary

Trajectory

Mission parameter	Data sources	Description	Attainable accuracy	Nominal value	Acceptable range	Result
In-plane angle	OLD (+ DIMAC, MTBSim)	Reconstruction using rate data, with Eq 2. or MTBSim. Better if amended with DIMAC spectrograph rate data	2º	0-50º	-	*Acceptable*.
	DIMAC	From ratio of x-axis and y-axis measurements combined with Foton orientation from magnetometer and horizon sensor	5º			
	GPS	Determine vector to system center of mass. Not performed yet	~1-5º (estimate)			
Out-of-plane angle	DIMAC	z-axis acceleration	~1º	0º	5º	*Nominal*. 0º
Fotino release Tether release and entry angle Fotino, stability and heat flux	OLD+DIMAC+ MTBSim Simulator	Continuation of dynamics after deployment completion by simulation. Measured tension drop at tether cut.	1%	Release at t=9364 s, 6º before vertical. Entry angle 1.4º	20 s release error 0.2º entry angle error	*Acceptable*. Release t=9364 s. Entry angle 1.5º
	NORAD ground based radar	NORAD measurement of Foton orbit after release evidencing momentum transfer	6%			
Fotino landing site	Fotino Beacon	ARGOS signal (failed)	350 m	Near Tasty Taldy, 66.3E 50.6N Kazakhstan	200 km error	*Off-nominal*. ~1250 km upstream, approx. 55.7E 41.6N
	OLD+DIMAC+ MTBSim Simulator	Simulation based on match of DIMAC tension profile during swing	125 km			

Deployment analysis summary
Hardware

Mission parameter	Data sources	Description	Attainable accuracy	Nominal value	Acceptable range	Result
Deployer performance Tether stickiness, dynamic tension effect, brake friction coefficient	DIMAC	Derived tension	10-25%	See Eq. 1	About a factor 3, 50% on friction	*Nominal*. Friction (10-15%) Dynamic effect (15%) *Acceptable*. Stickiness (factor 2.7-4)
	OLD/DIMAC	Deployment reconstruction	10-25%			
	OLD+DIMAC + MTBsim Simulator	Deployment matching	10-25%			
	MASS tensiometer	Brake friction coefficient	~15%			
Tether properties Stiffness *EA*, damping ζ, speed of sound *a*	DIMAC	Derived tension	-	*EA*=5000 *a*=10 km/s ζ=0.08	About a factor 3	*Nominal*. *EA* = 5000-10000 *a* = 8.8 km/s. ζ= 0.14-0.16

YES2 vs. SEDS

	SEDS-1	SEDS-2	YES2 stage 1	YES2 stage 2
Year	1993	1994	**2007**	
Tether diameter [mm]	0.75	0.75	0.5	
Tether linear density [kg/m]	0.33	0.33	0.18	
Endmass [kg]	26	**26**	14	
Ejection velocity [m/s]	1.64	**1.6**	2.2	
Control	open loop	**closed loop**	closed loop	closed(/open) loop
Control input	-	**2 optical loop sensors**	3 optical loop sensors	
Control output	wraps around capstan	**wraps around capstan**	wraps around capstan	
Control interval [s]	-	**8**	2	
Length target/obtained [km]	20/20	19.75/19.78	3.38/3.39	30.1/31.7
Final velocity target/obtained [m/s]	0/7	0/0.02	0/0.00	0/15
Angle target/obtained [º]	-/53	0/4	0/10	40/45
Minimum tension expected/observed [N]	0.01/0.035	0.03/0.015	0.008/0.03	
Maximum tension [N]	7	2.5	~1	40
Maximum speed [m/s]	10.6/12.8	5.6/5.9	2.2/2.2	13/16
Length/velocity data	YES	YES	YES	YES
In-plane angle data	NO	Ground radar	YES	YES
Tension data	Tether exit, endmass	Tether exit, endmass	At endmass, deployer acceleration	Deployer acceleration
Endmass dynamics data	YES	YES	Partial	NO

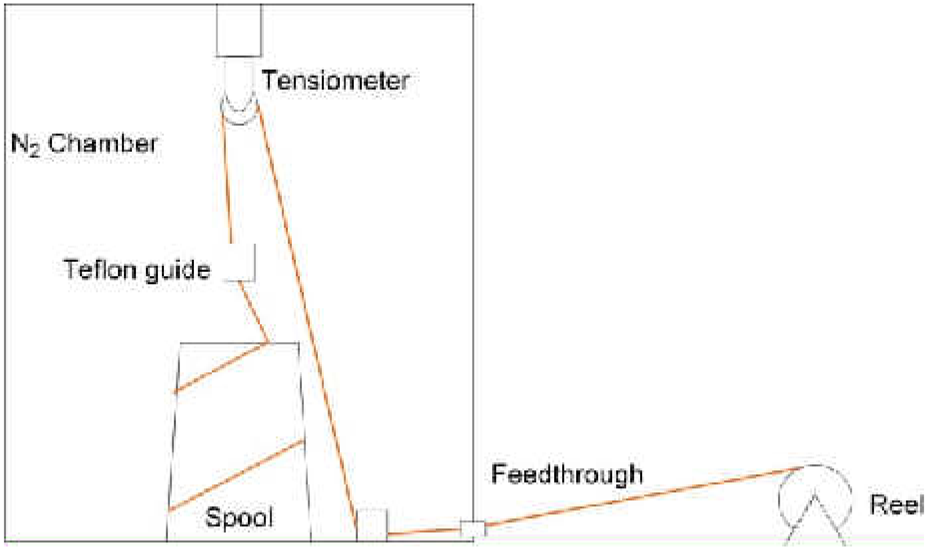
Tether Stickiness

- A test campaign was performed to determine the cause of the observed Tether Stickiness at low deployment speeds
- Deployment tension on a back-up sample of flight tether was measured at 0.25 and 0.5 m/s under a variety of environments
  - Ambient
  - Vacuum
  - Low humidity (N_2)
  - Low temperature
- Tether samples were taken and chemically analyzed at various test stages, and from rejected and test tethers
  - antistatic coating and tether thermal treatment explain differences between tethers but not between flight and ground tests

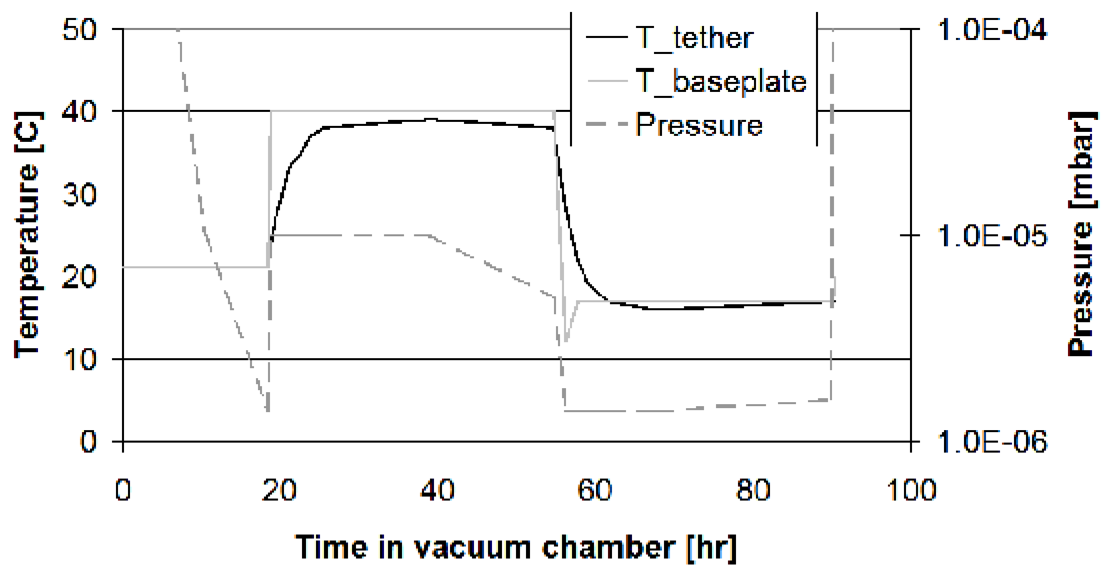
Tether Stickiness

- Various hypotheses were tested, only one explanation was consistent with all measurements
  - Thermomechanical settling increases the peaks of the deployment tension (‘hooking effect’) and therewith the average
  - Storage releases tension on the outer layers of the spool
  - Vacuum exposure effect (offgassing) penetrates only millimeters into the spool and has a light reducing effect on deployment tension

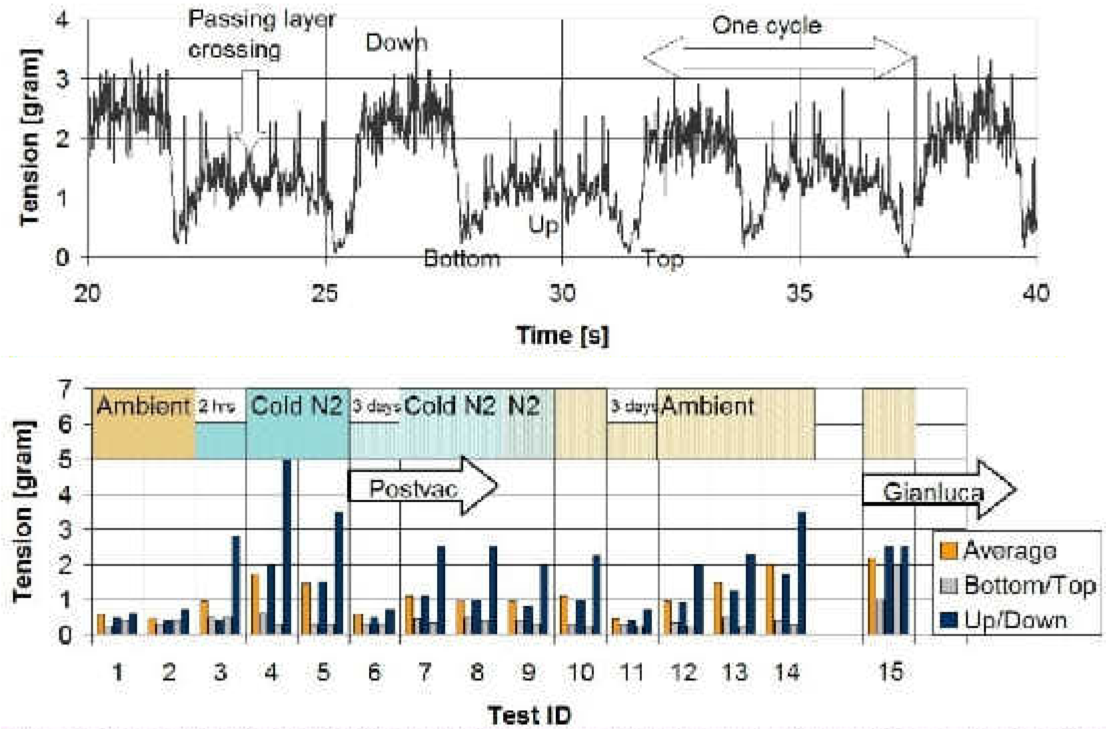
Tether Stickiness

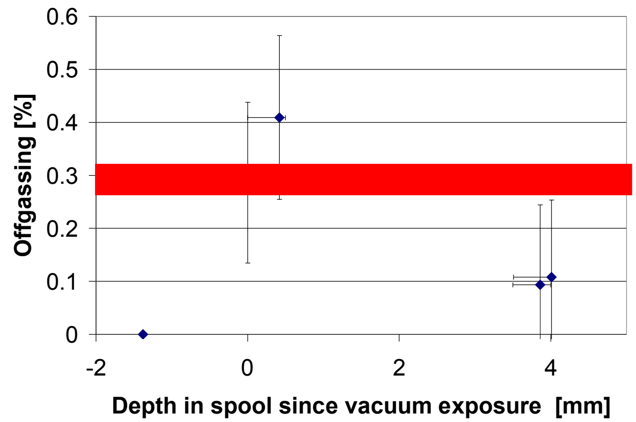


Tether Stickiness



Tether Stickiness





OLD registration issue

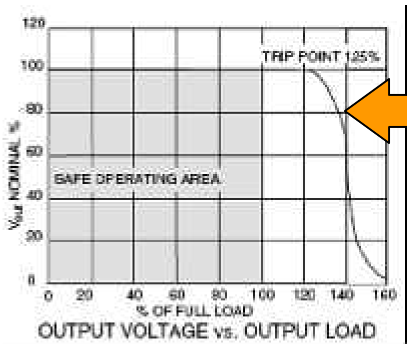
OLD test overview

Purpose	YES2 system	OBC	SW	OLD	Deployment
SW requirement verification, signal robustness	None	EM (full)	EM	None	Simulated
OLD system qualification & deployer characterization	FM	None	None	FM	Open loop full deployment, full velocity range
System test	FM	FM	EM	FM	Open loop max. 4 m/s
Flight tether and friction characterization	EM	EM (partial)	Near-FM	-	Full open loop deployment, full velocity range
Closed loop deployment test	EM	EM (partial)	Near-FM	EM	Full closed loop deployment
Critical functionality, contingencies, interfaces	FM+Foton	FM	FM	FM	None
FM SW deployment performance	Emulated by PC	EM (partial)	FM	Emulated by PC	Full closed loop deployment
MISSION	**FM**	**FM**	**FM**	**FM**	**Full closed-loop deployment**
Software testing	EM	EM (full)	FM	EM	High speed deployment
Software testing	Emulated by PC	EM (full)	FM	Emulated by PC	High speed deployment
OLD failure test	EM + DC/DC converter	EM (full)	FM	EM	High speed deployment

OLD registration issue

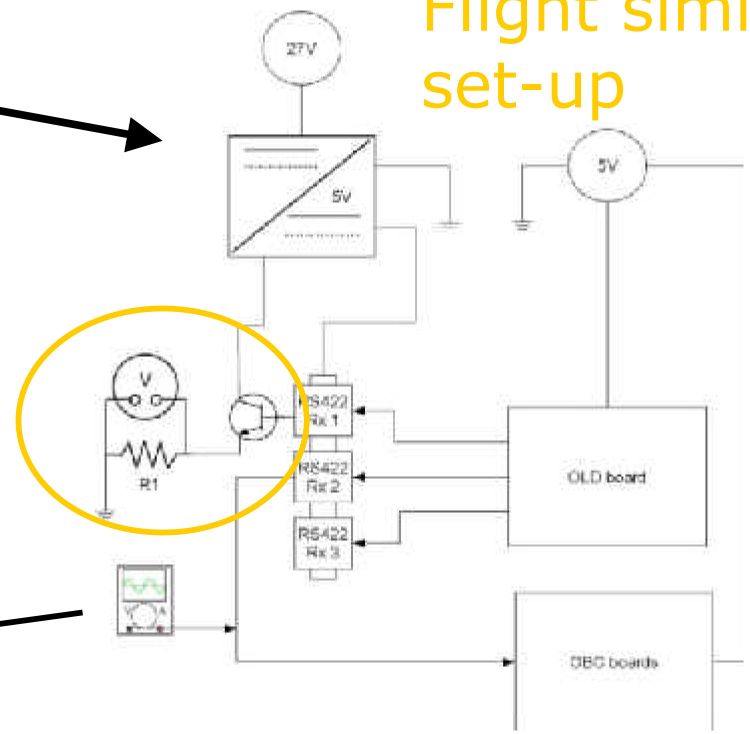
Registration failure reproduction

Flight converter response



Operation level decreased due to patch

Flight similar set-up



patch

EMC noise swamps OBC input, critically dependent on R1 (and thus temperature), at room temperature limit is within 0.1 V from flight system value (explains transients)

YES2 issues and solutions overview

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	Follow a somewhat more industrial approach. 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.
Technical		
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, which lead to a decrease of velocity	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-channel OLD failure case), or - 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.	- 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 - perform a sensitivity analysis to demonstrate controller robustness
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 Central Processing Unit (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 integration/testing 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: telemetry, 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

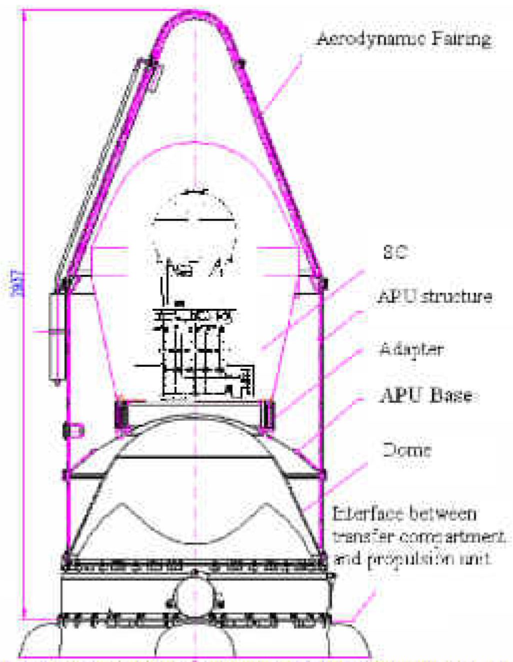
Conclusions

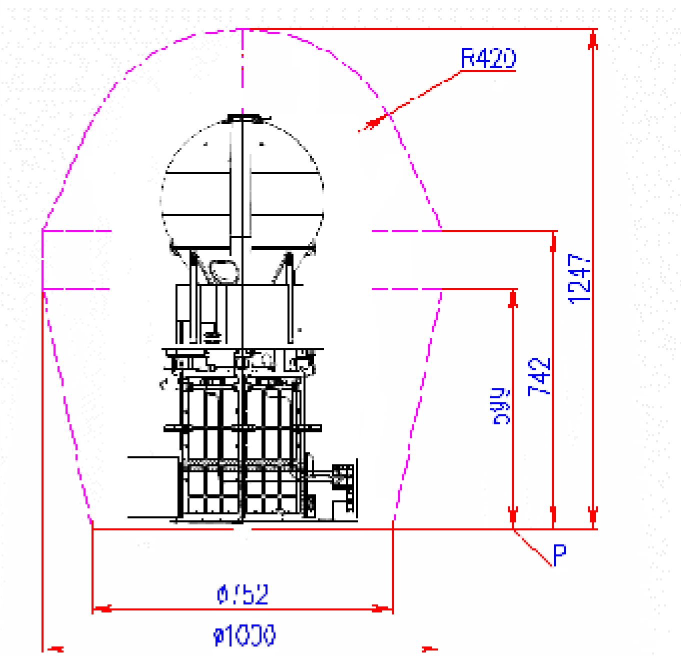
Despite lack of capsule location and electrical failure late in deployment, the YES2 science objectives were achieved

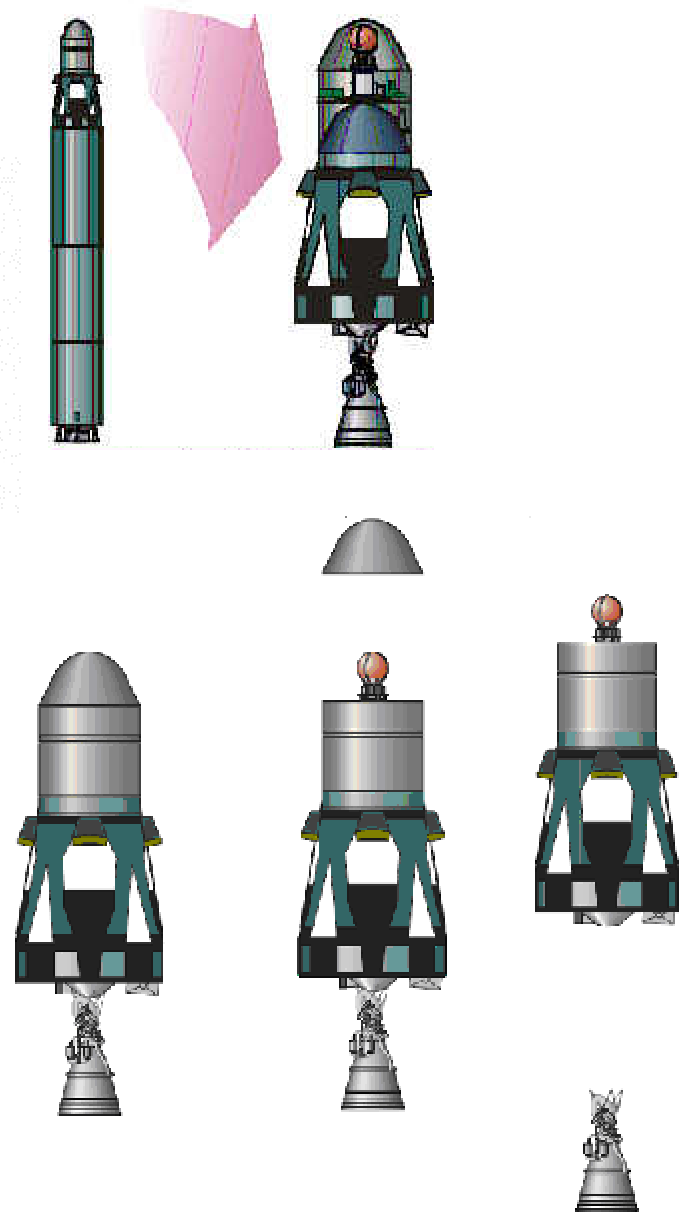
- Hardware and controller performed well, w. lessons learned.
- Tether dynamics simulation fidelity convincingly demonstrated

- Two stage controlled deployment with intermediate hold phase
- Deployment reconstructed within 2 deg, 150 m
- Smooth endbrake not demonstrated but...
- Endshock allowed for better understanding of tether properties and dynamics
- Fotino position could (only) be estimated
- SpaceMail potential was assessed, within envelope

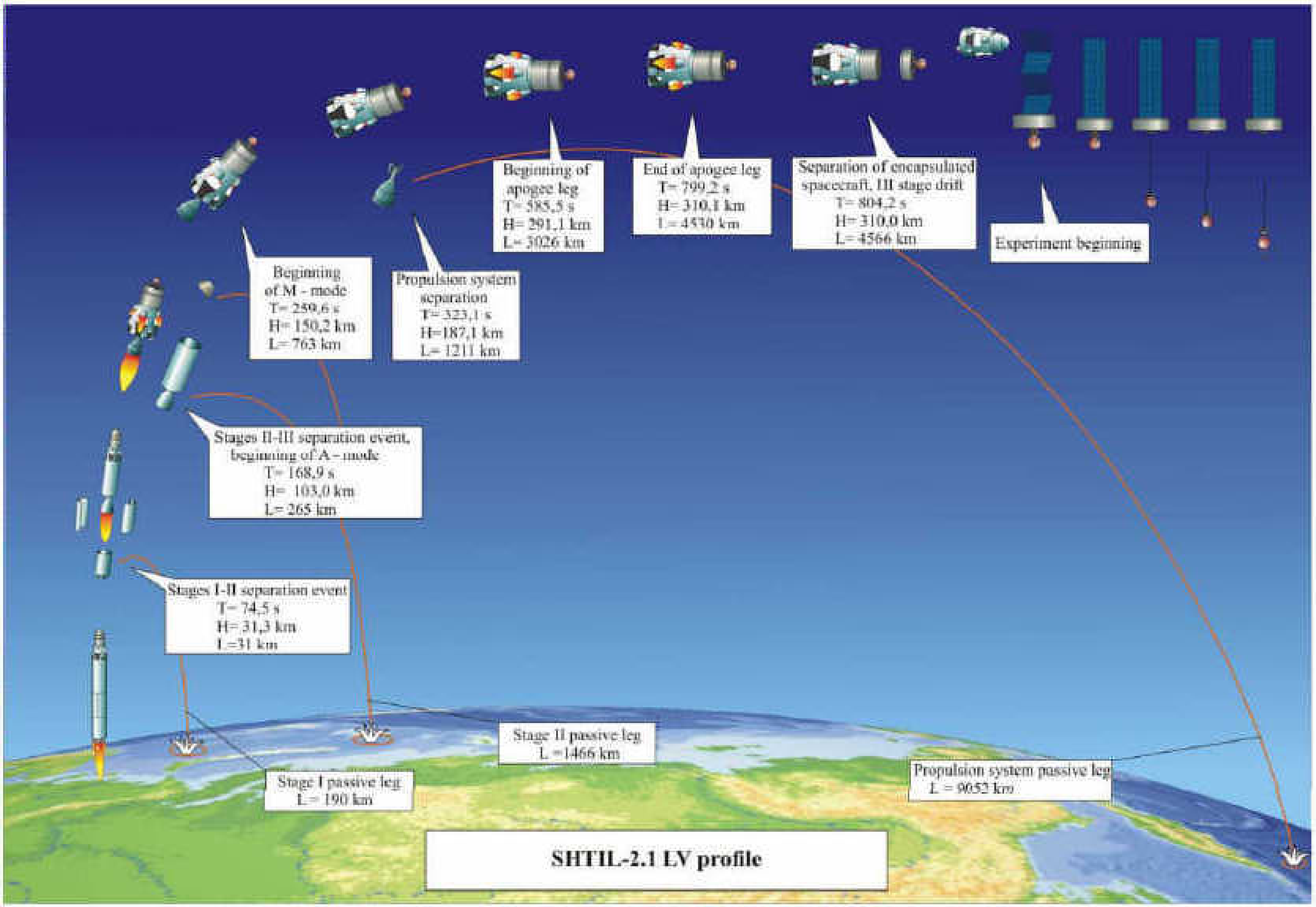
YES2R mission scenario on Shtil 2.1







YES2R mission scenario on Shtil 2.1



YES2R mission scenario on Shtil 2.1

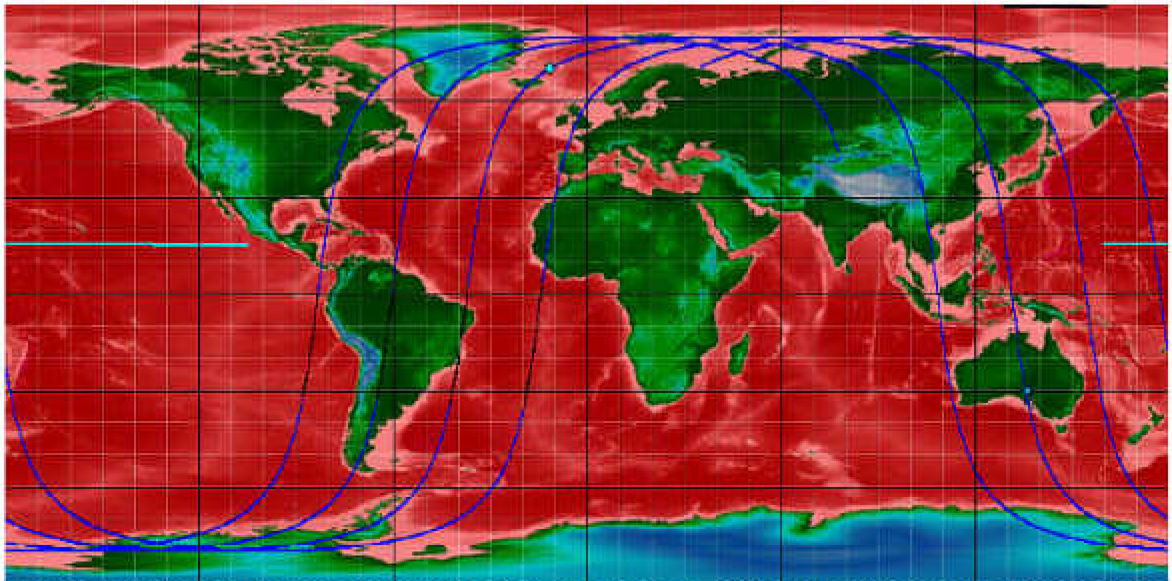


Figure 2. Landing in Woomera (yellow circle), shortest mission, 4800 s 1st stage complete, 7100 s second stage, 10950 s release Fotino. The first yellow circle indicates Fotino release point. Two orbits later California will have tether visibility, where MASS+tether re-entry can be timed

Time	Event	Remark
T0	Shmel orbit insertion	Orbit 325x325 km, i=79 deg
T0 + −10 min	Shmel NADIR attitude orientation	
T0 + −15 min	YTK1 power ON YES2 YTK8 Switch on MASS/YTK10 ARM Pyros	These commands are all pyro-safety related and are sent by the launcher system
T0 + 20 min 19:12 UTC	YTK2 eject MASS/Fotino	Ejection time over Kamchatka ground station
T0 + 110 min	First stage visible over Canary Islands, Western Europe	Observatories record tether dynamics on video
T0 + 100 min	Hold phase starts (autonomous)	Tether length reaches 3.4km
T0 + 127 min	Start 2nd phase (autonomous)	Tether deploys from 3.4 to 30 km.
T0 + 191 min	Release Fotino	Near vertical in swing. No cut of tether at FLOYD. Timing of release set pre-launch on MASS w.r.t. ejection.
T0 + 226 min	Fotino landing near Woomera, Australia	Coming in from the North over Australian desert, landing around 7:45 AM SLT
T0 + 360 min	Viewing opportunity of full tether from East Coast USA	
T0 + 380 min	Main Telemetry Session #1	Miass
T0 + 450 min	Viewing opportunity of full tether from mid USA	
T0 + 470 min	Telemetry Session #2, (Optional) Tether cut command YTK3 with delay	Telemetry and Telecommand opportunity from Miass
T0 + 510 min	(Optional) YTK3 execution or autonomous: Cut of tether	
T0 + 540 min	(Optional) Entry of Tether/MASS system in front of Californian coast	In visibility, so recorded by observatory video
T0 + 560 min	Telemetry Session #3	Minsk (mobile station)
T0 + 600 min	End of experiment	

YES2R mission scenario on Shtil 2.1

Long duration version

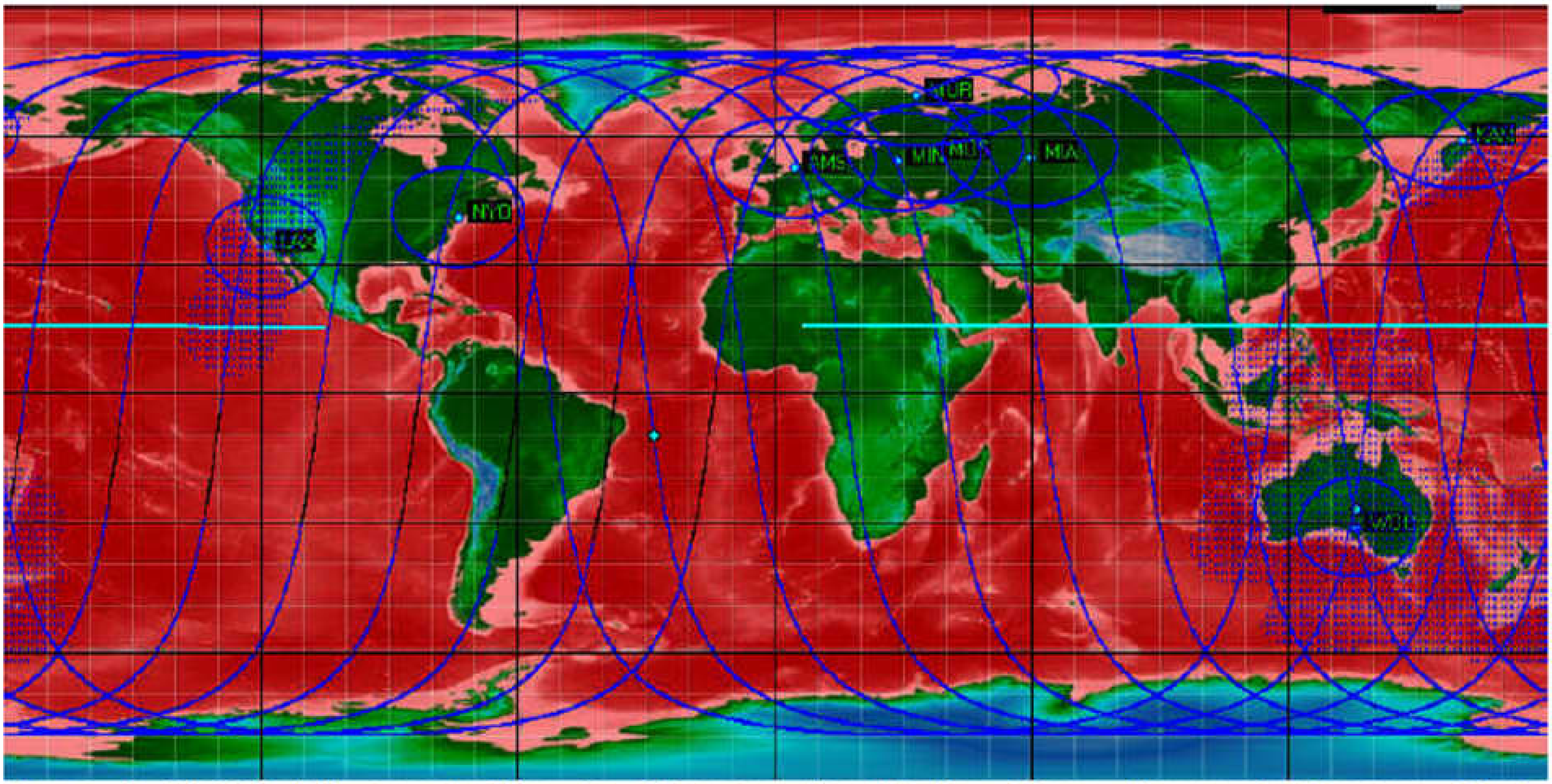
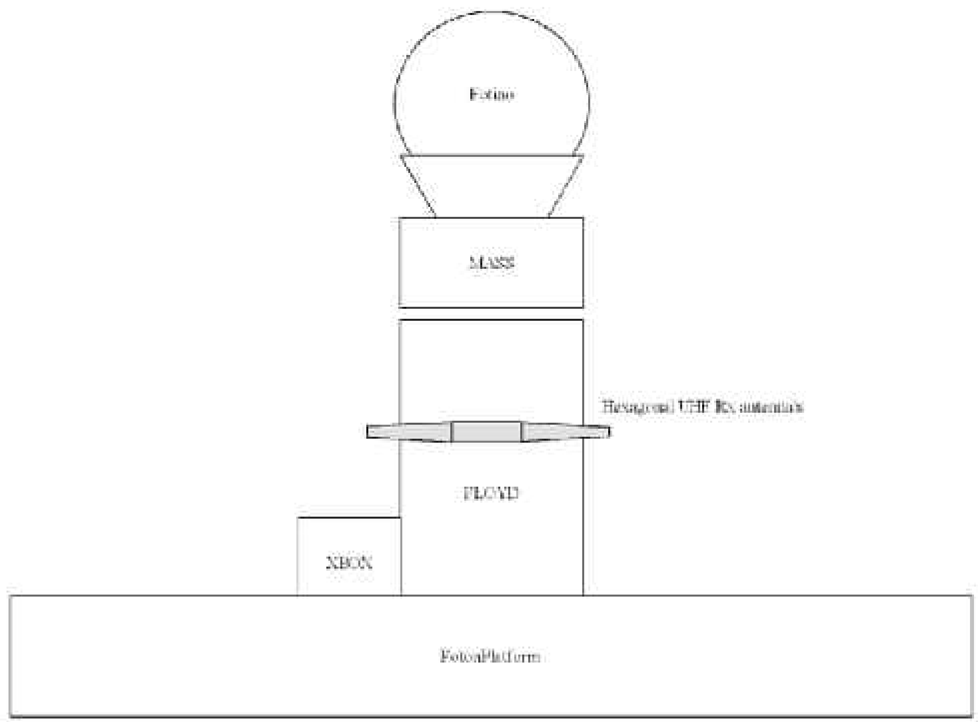
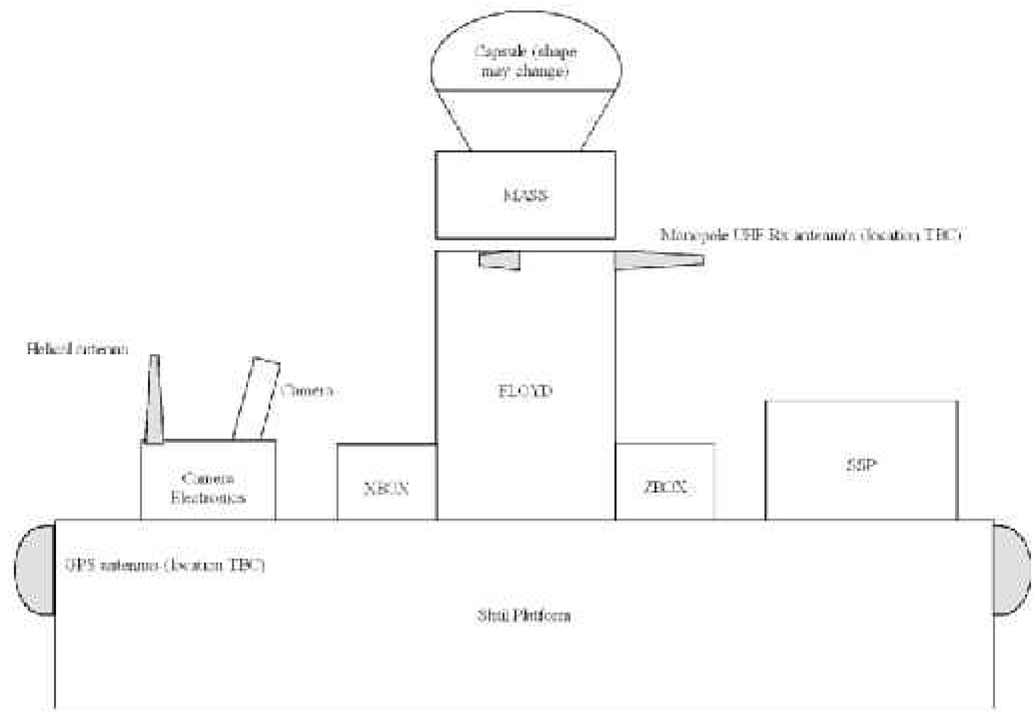


Figure 5. Visibility/TM opportunities for Woomera, Kamtchatka, Miass, Murmansk, Moscow, Minsk, Amsterdam, New York and Los Angeles. Good tether visibility regions are indicated with red dots (for capsule landing, followed by Kamchatka passage and Western Australia passage). The first stage can be observed from Los Angeles, the start of the second stage from Sydney (looking eastward).

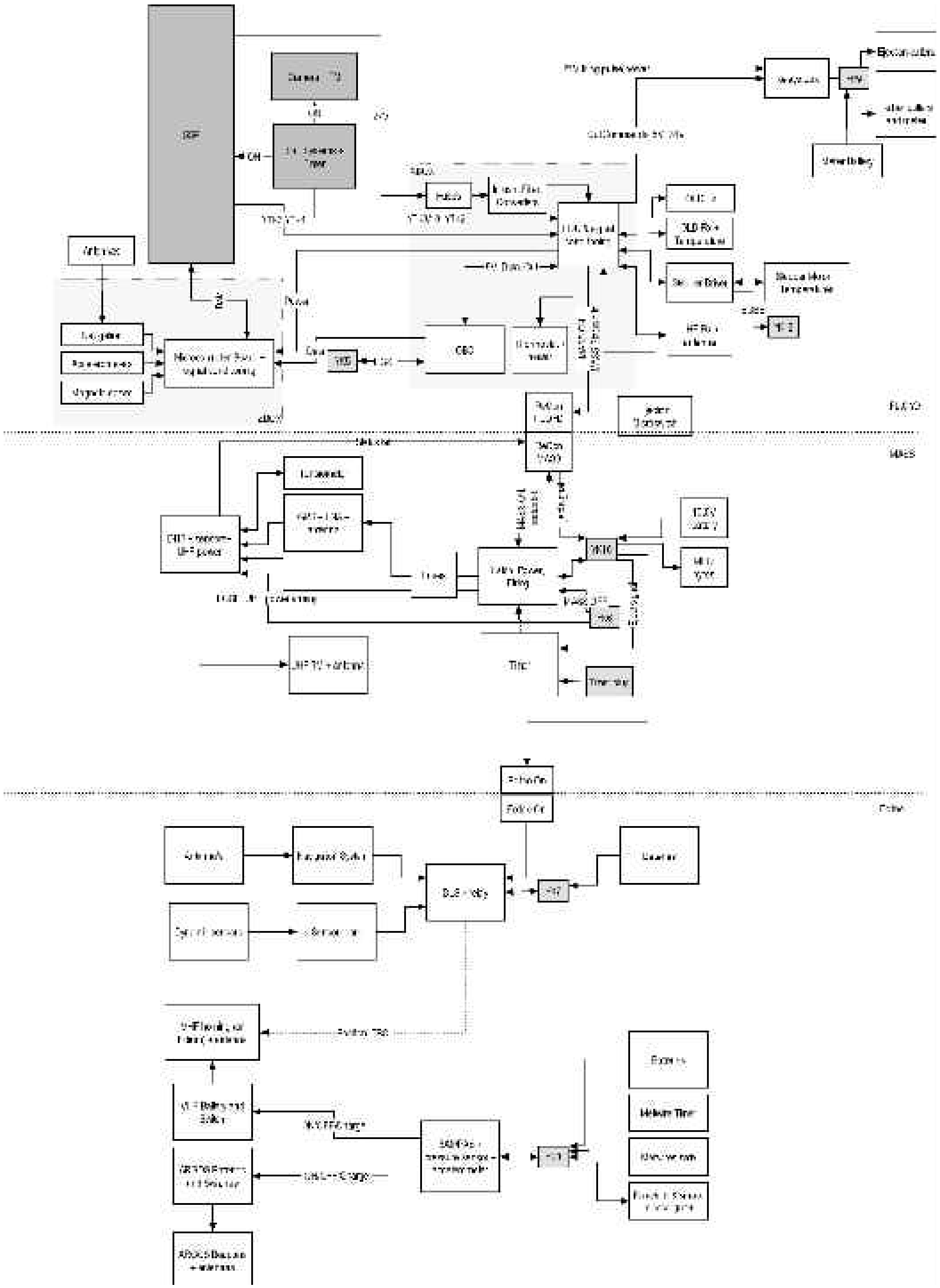
YES2R mission scenario on Shtil 2.1

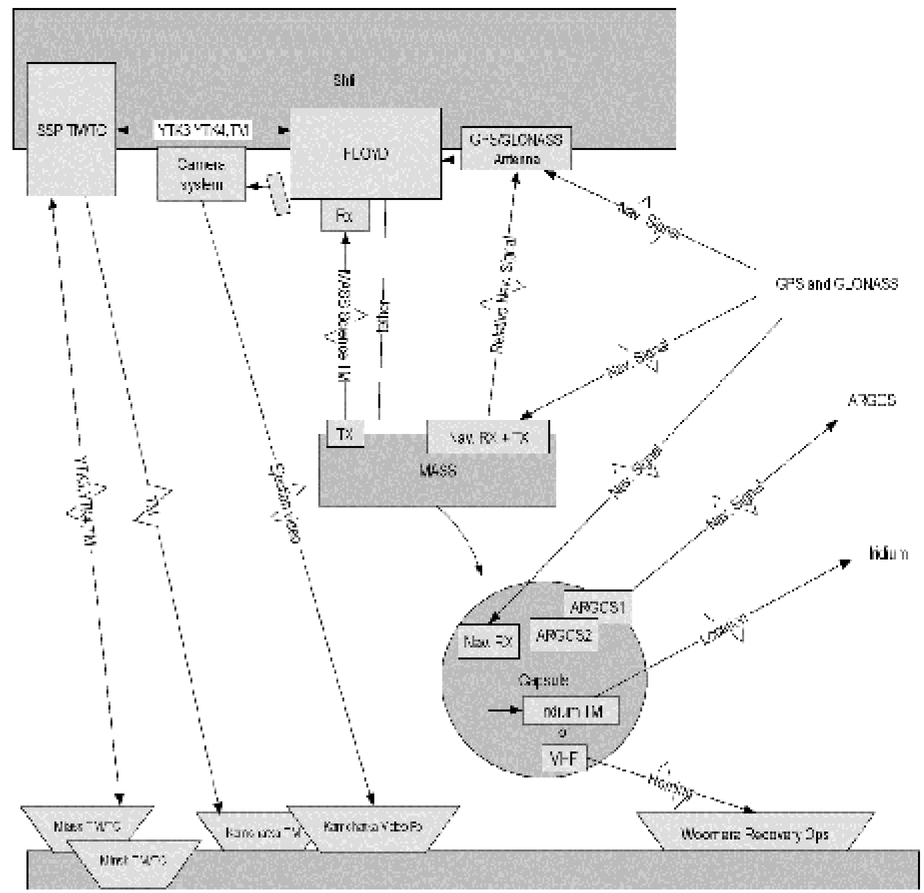
- YES2 vs. YES2R





YES2R mission scenario on Shtil 2.1





YES2R mission scenario on Shtil 2.1

YES2R mission scenario on Shtil 2.1

Possible funding scheme & consortium

- 1.5-2.0 MEuro manpower + 0.5 Euro Hardware + launch
- Based on YES2 design and existing system engineering database with technical lessons learned
- Semi-educational project
- Extensions for autonomy, additional data, video, new re-entry capsule (possibly RBB/REBR-type)
- 40-45 kg (depending on extensions)
- Lead : RMIT (AU Space Science & Education Grant)
  - Subcontractor: Bradford Engineering (manufacturing)
- ESA participation:
  - Re-entry capsule (Von Karman Institute via Prodex)
  - Co-launch on QB50
- Other parties from Spain, Greece, Switzerland, Belgium and Russia foreseen for smaller roles