Electric solar wind sail

ESAIL D32.4
Main tether reel test results

Work Package: **WP 32**

Version: **Version 1.0**

Prepared by:	University of Helsinki, Timo Rauhala, Göran Maconi
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Approved by:	University of Helsinki, Edward Hæggström

(List of participants:)

Participant no.	Participant organisation	Abbrev.	Country
2	University of Helsinki	UH	Finland

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1. Purpose

The purpose of this document is to present the results of tether deployment system tests for the Aalto-1 satellite.

The described tether reel is the actual reel that the tether was manufactured on. In addition the deployment system consists of isolation for the tether, two launch locks, an unreeling motor, and an end mass to extract the tether in space.

While the unreeling procedure described here closely resembles the one conducted at DLR in task D31.3, there are notable differences; (1) the tether type (4-wire vs. 2-wire Heytether), (2) the tether length (100 m vs. 11m), and (3) the layered structure of the tether on this reel. In addition, one tether reel underwent a vibration simulation before the unreeling. The bond quality on this tether was investigated after unreeling.

2. Introduction

The Electric Solar Wind Sail (E-sail) is a proposed propellantless propulsion method for interplanetary missions.

It uses centrifugally stretched positively charged tethers to create thrust from the momentum flux of the solar wind. The magnitude of the theoretically estimated E-sail effect should be experimentally verified in space.

The tether is stored on a reel [1] [2] during the spacecraft launch. It is manufactured by the Tether Factory [3] (D21.3) directly onto the reel that is used on the mission. Once in orbit, the tether is unreeled. Reliable tether deployment is a requirement for successful E-sail missions.

3. Test overview

The aim of the tests is to investigate the tether unreeling, to verify the reliability of the unreeling procedure and to ensure that the bonds do not suffer from stacking many layers of tether or by the unreeling procedure. All tethers are used only once (reel out only), and samples are extracted from the unreeled tether. The tests are videoed to allow close *post hoc* visual inspection. A vibration simulation was done in a LDS v650 vibration bench at the University of Tartu. The vibration simulates the launch vibrations of a European Space Agency Vega booster rocket [4]. Two unreeling tests are done: before and after the vibration. Both test sequences are performed in the same manner.

Altogether three 4-wire Heytethers were manufactured, two 100 m tethers and a 40 m long tether. On the 40 m long tether the base wire of the tether was cut at 40 m due to a mechanical fault. Based on the tether’s quality (count of failed bonds), the tethers were designated as follows: 1) Flight reel (100 m, least number of failed bonds), 2) Test reel #1 (40 m) and 3) Test reel #2 (100 m). Test reel #1 was unreeled without undergoing a vibration simulation whereas the Test reel #2 underwent the simulation at the University of Tartu, Estonia.

3.1 Tether description

The tether is a 4-wire Heytether comprising dia=50 µm base wire and three dia=25 µm loop wires. The loops are 3.5 mm tall. One of the three loop wires is bonded twice as often as the other two. This results in loop lengths of 20 mm on one loop wire and 40 mm on the other two.
The tethers are manufactured onto their mission reels to minimize the risk of breaking the tether integrity during reel to reel transfer. In addition, during manufacture, the tethers are reeled so that the tether build-up on the reel is even, Fig 1.

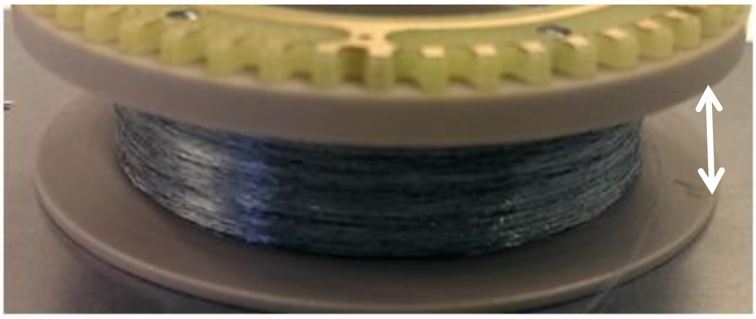

Fig 1. 100 m of 4-wire Heytether on an Aalto-1 flight reel. There are 15 layers of tether on the reel. The tether is uniformly distributed over the available space (1 cm, indicated by the white arrow).

3.2 Deployability

The deployability of tether was be tested by gravity-assisted unreeling. The tethers were unreeled in the HU Physicum building in a 15 m high stair hall. Different end masses were used to find the minimum mass for successful unreeling (the end mass of the flight model will be 1 – 1.2 g). The end mass was reattached near the spool at every 15 m. The tests were done using comparable unreeling speeds to those used when unreeling in space (1–3 mm/s) [5]. A Maxon 24V DC 2332.968-21.216-200 motor was used for the unreeling.

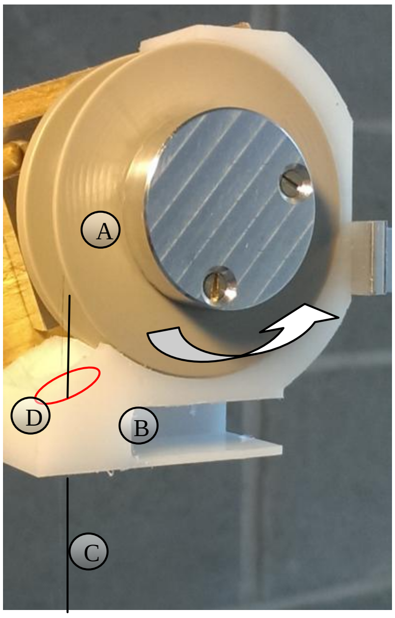

Fig 2. A) Tether reel, B) Tether isolation (cut open to enable visual inspection of tether behavior during unreeling), C) Tether (enhanced for visibility), D) Opening in the isolation for an end mass and tether outlet.
To unreel the tether, the reel is turned in the direction indicated by the arrow. If the tether gets stuck on the reel, it is pressed against the inner wall of the tether outlet (indicated by a red circle).

3.2.1 Results of unreeling Test reel #1

A 40 m long 4-wire Heytether was unreeled in the first unreeling test. During the production there were 10 failed bonds on this tether. The unreeling video showed no additional broken bonds. There were 9 layers of tether on this reel. The tether was unreeled at 1,5 mm/s.

Various end masses were tested during the unreeling of this tether. Also, the tether isolation was attached onto the reel assembly to determine whether the isolation has affects the deployability of the tether, Fig 2. Results of the unreeling are presented in Table 1.

Table 1. Tether unreeling results for Test reel #1.

	End mass (g)	Result
40 m reel, no isolation	0,014	Fail
40 m reel, no isolation	0,12	Fail
40 m reel, no isolation	0,25	OK
40 m reel, no isolation	0,4	OK
40 m reel, with isolation	0,016	OK
40 m reel, with isolation	0,12	OK
40 m reel, with isolation	0,25	OK

Fail = While unreeling, tether is stuck on the underlying tether structure.
OK = Tether unreels without problems.

3.2.2 Results of unreeling Test reel #2

A 100 m long tether (10.000 bonds) was unreeled after being subjected to a vibration simulation in a LDS v650 vibration bench at the University of Tartu. The vibration simulates the launch vibrations of a European Space Agency Vega booster rocket [4]. There were 51 bonding failures (0.51%) on this reel out of which 41 were cases where the bond did not attach and ten were cases where the loop wire being bonded was cut during bonding, Fig 3. A *post-hoc* video analysis showed 8 additional broken loops on the second layer of the spool. All together there were 15 layers of tether on this spool.

A 0,05g end mass was selected taking into account previous experience with Test reel #1. The tether unreeling was started with the tether isolation in place. The unreeling was halted altogether 17 times because of a broken loop wire still on the reel becoming entangled with tether in the tether outlet, Fig 4. It is important to note that many of these problems were due to *one single* broken loop wire, not different broken loops for each problem. To discard broken loops at the tether end, Fig 3, we unreeled a few meters of tether without having the isolation in place.

The unreeling commenced without having the isolation in place. There were 12 jams during a 10 m of reel-out. Each was resolved manually before continuing the test. These jams were expected since, in the light of our experience in Test reel #1, Table 1, the end mass was too light (0,05g) to be unreeled without the tether isolation.

Next the isolation was reinstalled. Apart from the problems caused by the broken loops, the unreeling was successful.

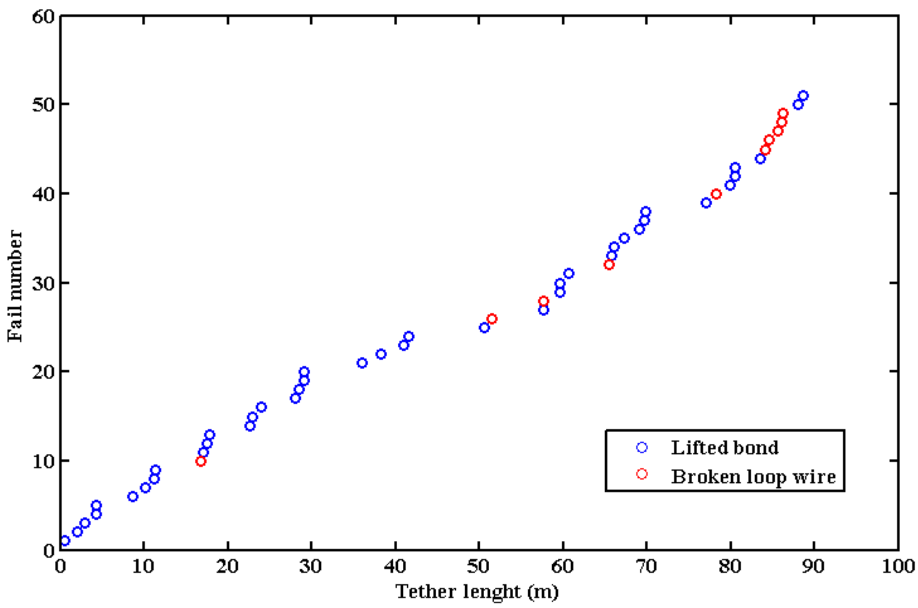

Fig 3. Bond failure analysis for the manufactured tether. The failure rate is reasonably constant during the production. However, the ‘Broken loop wire’ failure mode is more prevalent in the later stages of production.

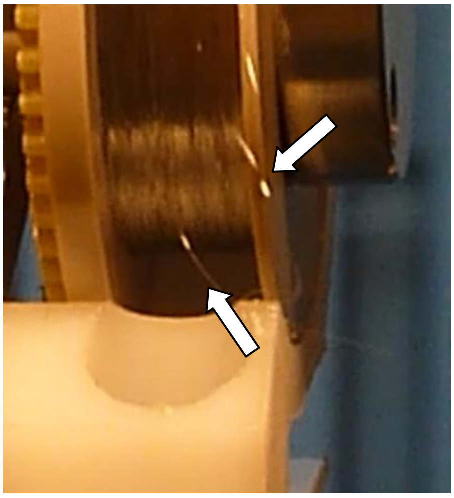

Fig 4. A broken loop wire on the reel (lower arrow) causes the tether (upper arrow) to jam on the tether outlet.

3.3 Effect of unreeling/vibration on bond quality

As a standard procedure, the quality of the bonds on the tether is verified before and after production by destructive pull testing [3]. This assures that there is no significant drop in the maximum sustainable pull force of the bonds during production.

Similar pull tests were done on the bonds of unreeled tethers. This was done to investigate whether the bonds suffer from stacking many layers of tether or by the unreeling procedure.

3.3.1 Results of pull tests on Test reel #1

There were four 1 m long samples extracted from the 40 m long tether. The results of the tests are presented in Table 2.

Table 2. Post-unreeling pull test data. The length denotes the length of tether from the start of production. Ten measurements were done on each 1 m sample and an arithmetic mean was calculated from the measurements. The uncertainty is calculated as one standard deviation of ten measurements. Values are measured in grams (g).

0 m	10 m	25 m	40 m
10,82	10,51	9,27	11,39
10,69	10,87	10,45	10,45
11,03	11,21	10,15	11,24
10,36	11,69	10,16	9,86
9,14	11,25	10,22	10,35
11,21	11,03	10,69	11,08
12,39	10,84	9,78	10,68
11,57	11,37	10,27	11,52
10,63	11,05	9,73	11,22
10,37	13,47*	10,53	11,66
10,82	11,09	10,13	10,95
±	±	±	±
0,85	0,34	0,43	0,58

*Measurement failed and is ignored in the result.

3.3.2 Results of pull tests on Test reel #2

Thirty 1 m long samples were extracted from the vibrated 100 m reel. In addition, pull-tests were performed before and after production of the tether. For this report 14 of the samples were analyzed. The results are presented in Fig 5.

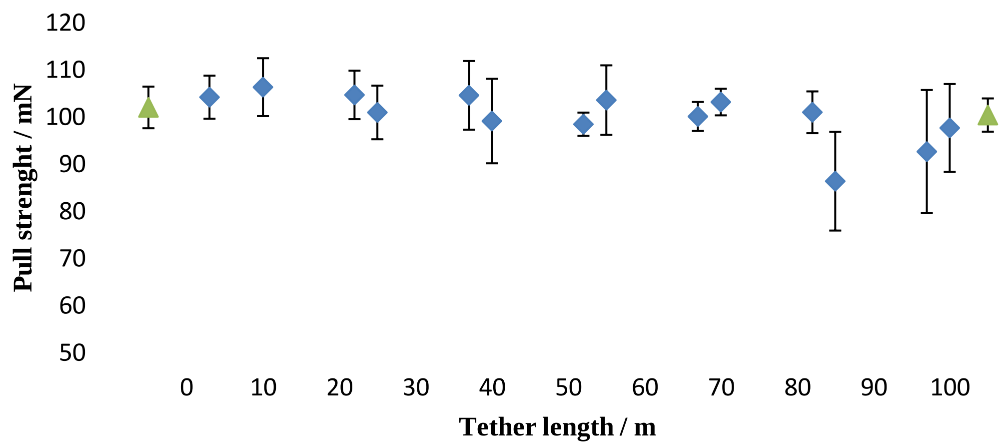

*Fig 5. **Post-unreeling pull test data of the vibrated tether.** Length denotes the length of tether from bond #1. Ten measurements were done on each 1 m sample and the arithmetic mean was calculated from the measurements. The uncertainty is calculated as one standard deviation of ten measurements. ‘Before’ and ‘after’ production data are marked with green triangles. A weaker part in the tether is evident between 85-100 m. This correlates with a part of the tether with an increased rate of broken loops during production, Fig 3.*

4 Discussion and conclusions

The pull tests results for both reels show no significant drop in pull strength of the bonds on the inner tether layers on the reel. On Test reel #1, at 40 m, the pull strength still exceeds 10 g. However, on Test reel #2, the pull strength of the bonds drops slightly after 80 m. This is in accordance with previous experience of long-tether manufacturing [6]. Thus, there is ***no evidence that shaking the tether affected the bond strength***.

A *post-hoc* video analysis revealed no additional broken loops or lifted bonds on Test reel #1. On Test reel #2 eight additional broken loops were detected on the second layer of the spool (at 10 m tether length coordinate). The pull strength of the non-failed bonds in this area is nevertheless good, Fig 5. The manually kept production log does not reveal presence of broken loops (however, since only our later factory employs an automatic image-based log, we cannot rule out the possibility that the loops were broken prior to reel-in and shaking).

This issue will be addressed by manufacturing flight-model tethers using the new automatic tether factory before space missions are undertaken. In addition, it could be possible to modify the mechanical design of the tether isolation and reel in such a way that even broken loops can be tolerated during the unreeling process.

The results show that the bonds do not suffer when stacking many tether layers on the reel. However, it is clear that effort has to be put into ensuring that the loop wires do not break during production and that the unreeling process is more tolerant towards unlikely events like this. The ***unreeling process itself appears to be safe for the tether and the bonds.*** The 40 m tether was unreeled successfully with an end mass as low as 0.016 g (with the tether isolation in place). Apart from the broken loop wires, the result was duplicated with the shaken 100 m tether and a 0.05g end mass. There were no bond or loop breakages during the unreeling of either the 40 m or the 100 m tether.

References

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