Electric solar wind sail

ESAIL D52.1
Conceptual E-sail designs and specifications for component development

Work Package: **WP 52**

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1. Introduction

The purpose of this WP (WP52, “Design concepts”) is to analyse, trade and down-select different top-level E-sail design concepts and to arrive at one concept that will be used for subsequent WPs. The goal was reached in consensus between the partners in the Tartu February 2011 project meeting.

Many E-sail top-level designs have been considered. They are all potentially viable, but some look clearly more promising than the others. We used ten criteria for informally ranking the designs. These ten criteria are reliability, performance, flight dynamical stability, permitted solar distance range, high-energy radiation tolerance, scalability, modularity, payload requirements, suitability for on-line health monitoring and cost. In this WP we have explicitly looked at reliability, performance and flight dynamical stability. In other criteria there are usually no large differences between different top-level designs. The main reliability question at the top level is whether or not the design can be made to survive a maintether breakage event. The main performance question is how much extra mass the design contains (in Remote Units, auxtethers, etc.) and how large transient mechanical loadings occur on the maintethers in case of maintether breakage.

The main tool used in the analysis is the dynamical simulator programme developed at FMI. During this WP, a new Lua interface based dynamical simulator was written which allowed us to study a wide plethora of different geometries in a short time. This dynamical simulator allows one to build a model in Lua language composed of an arbitrary collection of rigid bodies, point mass bodies, interaction force fields between bodies and external force laws on them. For nearly all geometries, stability in flight was evaluated when the system was left in a naturally varying solar wind (historical data were used) with no active tether potential control (all tether potentials constant) and with 30 degree angle with respect to the solar wind. This test mimics a worst-case scenario where the E-sailer is left without navigation in the solar wind with voltages on. The rotation rate was set such that the average maintether tension was 5 grams, and if needed, runs with different numbers of maintethers were made to find out the maximal stable number for the quoted parameters. This test was designed to bring up stability differences between the different top-level designs. For the best design considered, stable flight was possible for as many as 100 tethers at 4 gram average tether tension and 1 N total thrust.

maintether breakage events and subsequent tether jettisoning were also modelled with the simulator and the transient tether loads were monitored. For the best candidates, deployment was also modelled with the simulator. There were no large differences in this regard.

The selected design is the stretched auxtether concept. It was mentioned as a “bonus” option in the DoW and is rather closely related to the baseline concept. The stretched auxtether option is actually much better in performance than the baseline at least if high reliability (survivability of a maintether breakage event) is required. We ran the stretched auxtether model successfully in the solar wind test at 96 tethers, 4 gram average maintether tension and 1 N average thrust. In the maintether breaking test, the same model achieved nearly no increase in maintether tension due to outward swinging of the Remote Units. Taken together, these results indicate that it is possible to build a 1 N thrust E-sail by the stretched auxtether approach whose mass could be as small as 100 kg (or a little larger) even when the extra reliability requirement is imposed that the model must be able to survive a maintether breakage event. The average tension of 4 grams leaves a reasonably large safety margin of 2.5-3 since our already achieved aluminium tether wire bond strengths are 10-11 grams at 25 μm diameter.

We also preliminarily simulated a simple deployment scheme with the model. Due to the large number of possible deployment procedures, an exhaustive modelling was not attempted and would be outside the scope of this WP.

2. Down-selection of E-sail concepts

We will now discuss each considered E-sail design concept in turn, listing also its main weaknesses and strengths.

2.1 “Naive” E-sail

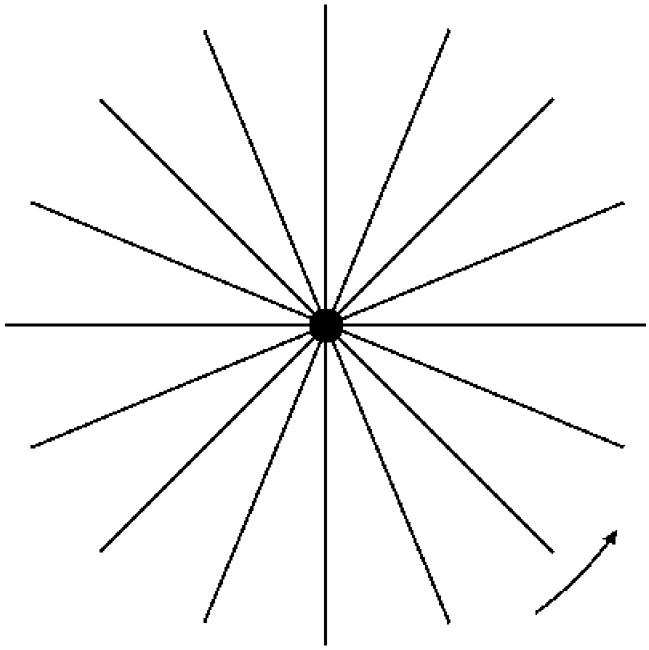

Fig. 1 “Naive” E-sail (spinning tethers attached to a spacecraft)

The basic engineering problem that all E-sail designs must resolve is that the maintethers must now collide with each other even though the temporally varying solar wind modifies their rotational state in a quasi-random way. Therefore it has been clear all the way from the birth of the E-sail in 2006 that a “naive” E-sail (Fig. 1) consisting only of spinning maintethers most likely wouldn't work because variations of the solar wind and other reasons would cause the angular speeds of the tethers to be slightly unequal so that sooner or later a faster rotating tether would reach and collide with its slower moving peers. There still remains a small chance that the mutual Coulomb repulsion of the charged tethers would be enough to prevent the tethers from physically colliding even in the naïve concept. However, even if this would be true in some or even most solar wind conditions, it is difficult to see how it could guarantee the absence of collisions in all operating regimes and E-sail usage patterns. Therefore, it is assumed that the naïve model is unworkable and it is presented here solely for pedagogical reasons. By and large, the other E-sail concepts to follow here are different ways to guarantee that the tethers will not collide with each other in irregular solar wind conditions.

2.2 Continuous fine-tuning of maintether lengths

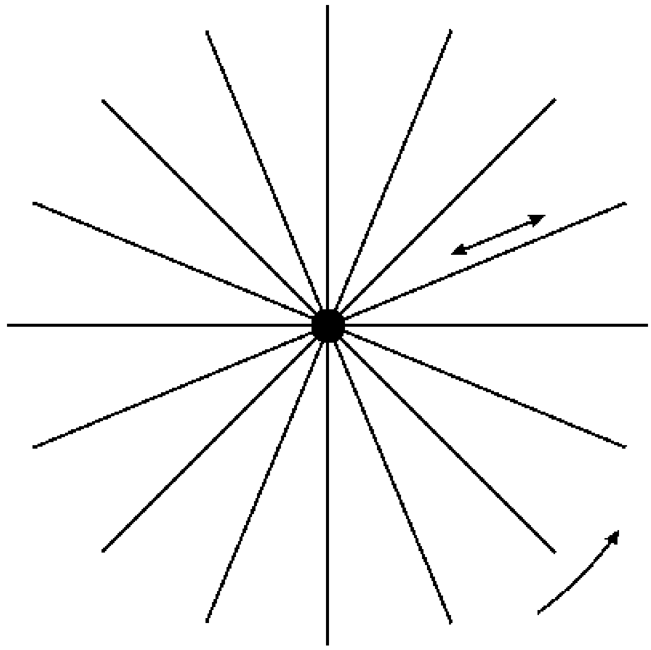

Fig. 2 Continuous tether length fine-tuning to keep tethers apart

One can prevent the tethers from colliding if one slightly reels in a too slowly rotating tether and correspondingly reels out a tether that rotates too fast (Fig. 2). The conservation of angular momentum causes the angular speed of the tether to be tunable by tuning its length.

The problem with this approach is that it needs many moving parts (all maintether reels must remain mobile throughout the mission) and that the multi line tethers probably cannot be reliably reeled in and out a large number of times, because once the tethers are exposed to space, micrometeoroid collisions may produce stray wires in them which might mechanically harm the subsequent reelings. It would be possible to correct this problem by making the root part of the maintether from a thicker monofilament wire or tape, but it is difficult to estimate beforehand how long stretch of such root tether is needed. This relates to another issue which is algorithm development. The algorithm should be able to keep the maintethers from colliding while reeling each maintether in or out as little as possible. A concrete algorithm with proven reel limits has not been developed.

Initiating the spin of the E-sail in the naïve and fine-tuning concepts is a separate problem. The angular momentum needed is so large (tens of million Nms) that it would be expensive to produce it by thrusters on the main spacecraft placed on tips of fixed booms. One trick is to use a certain “pumping procedure” in which the lengths of the maintethers are modulated in sync with the rotation while the spin plane is simultaneously turned with respect to the solar wind by modulating the tether potentials. In this way it is possible to reduce or increase the spin at will, by exchanging angular momentum with the solar wind. One only needs a seed amount of angular momentum to get the tethers sufficiently deployed so that the process can be initiated.

Another way to spin up is the so-called "Siamese Twins" concept which is applicable to any type of E-sail. In the Siamese Twins, two E-sails are initially mounted together on a common axis. The axis is rotated by a small electrical motor such that the two E-sails are spun in opposite directions. The result is a pair of oppositely rotating E-sails which after separation can start to fly independently. The Siamese Twins requires almost no mass overhead due to spinup, but has the requirement that two E-sails are deployed at once. It also has the reliability issue that the two tethers planes spin relatively speaking very close together (e.g., tether length 20 km versus spacecraft separation of a few metres) so that the mechanics should be very symmetrical to avoid collisions of the counter-rotating tether rigs during spinup.

In Earth's magnetosphere, magnetic torque produced by currents flowing radially in the tethers could be used for spinup. However, then the spacecraft should be carried away from the magnetosphere by some other form of propulsion, because the E-sail does not work inside the magnetosphere where there is no solar wind.

2.3 Centrifugally stabilising auxiliary tethers

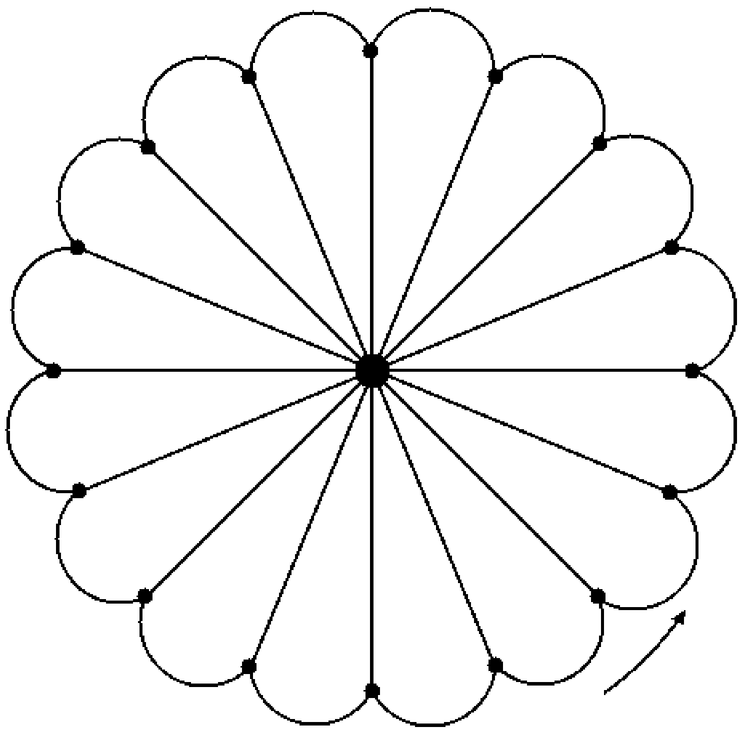

Fig. 3 Centrifugally stabilising auxiliary tethers (old baseline and present fall-back solution)

If one connects the tips of the maintethers together with non-conducting auxiliary tethers whose length is ~1.5 times larger than the corresponding circle arc length (Fig. 3), the centrifugal force acting on the auxtethers tends to equalise the maintether spacings. This concept was invented in the summer 2009 and was taken as the baseline for this project in the proposal and the DoW. The auxtethers are reeled out from Remote Units located at the tip of each maintether. Once the Remote Units are there, it makes sense to also install small thrusters in them to solve the spinup problem at the same time. Compared to earlier ideas, this is a very attractive model because it solves the tether collision and spinup problems without uncertainties and without moving parts during flight.

Closer analysis of the dynamical properties reveals, however, one deficiency in the centrifugally stabilised auxtether model which reduces the performance or alternatively decreases the reliability. This deficiency is related to what happens if a maintether gets broken. According to micrometeoroid flux model based lifetime predictions, such an event should be very unlikely if a four-line, and about 2.5 cm wide Hoytether or equivalent construction is used: in a full-scale 1 N E-sail with 2000 km total tether length, the probability of tether breakage is only 1% over the first 5 years in space, using the Grun et al. 1985 model applicable to 1 AU for modelling the micrometeoroid flux. Nevertheless, to increase the robustness of the E-sail, we would like to develop a design which survives a maintether breakage event. The problem with the centrifugally stabilised design is that if a maintether breaks, the corresponding Remote Unit and its associated auxtether swings outward by the centrifugal force. The broken maintether pieces can be jettisoned from the Remote Unit and spacecraft ends, but the problem is that the neighbouring maintether experiences a relatively strong (factor ~3-6 times larger than nominal) transient mechanical loading when the outward moving masses suddenly tighten the auxtethers. The implication is that a corresponding overdesign of the maintether must be done which decreases the overall performance by increasing the mass of the maintethers and also increases their surface area, which then increases the electron gun power consumption. Thus if one wants the rig to withstand a maintether breakage event, its performance is lowered. For this reason, a better model was sought for.

2.4 "Edgy" model

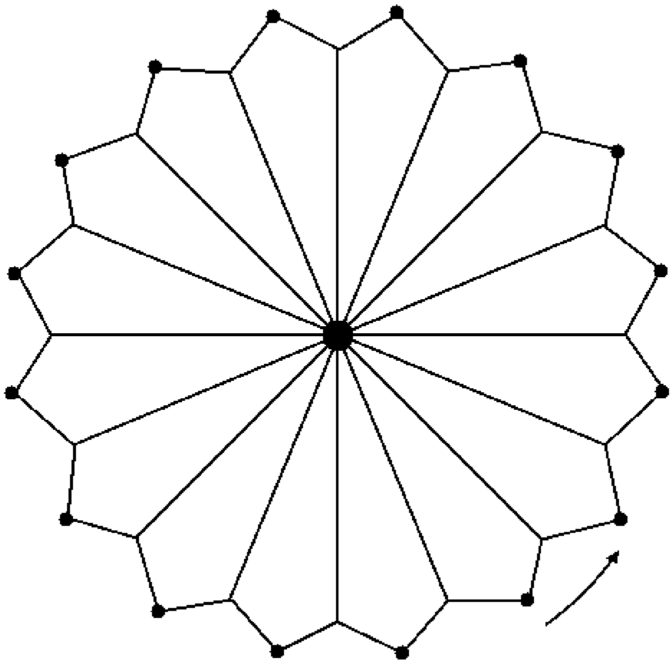

Fig. 4 "Edgy" model, with Remote Units at the middle of each auxtether

In the centrifugally stabilised auxtether design, the auxtethers form the ballast mass that keeps the maintethers apart. The system is dynamically stable only when the auxtether mass is larger than the Remote Unit dry mass. While this works, it provokes the question whether one could save mass by using the Remote Units themselves as ballast, instead of the auxtethers. To address this, Fig. 4 shows an alternative design where the Remote Units are placed at the middle of the auxtethers and the maintether/auxtether junctions do not contain any massive items. However, this "edgy" variant does not perform very well in dynamical simulations; it seems to be more vulnerable than the other designs to some harmful modes of oscillation. It also has the problem that if a maintether breaks, it cannot be jettisoned from the outer end: from the Remote Unit one cannot jettison it because that would break the auxtether ring and cause a fatal collapse and at the maintether/auxtether junction there is nothing where a jettisoning device could be installed. In order to enable jettisoning and thereby to make the system survive a maintether breakage event, an additional unit should exist at the maintether/auxtether junction that would only contain the remote-triggered jettisoning device. While possible, that would largely nullify the mass benefit and increase complexity.

2.5 Emil's model

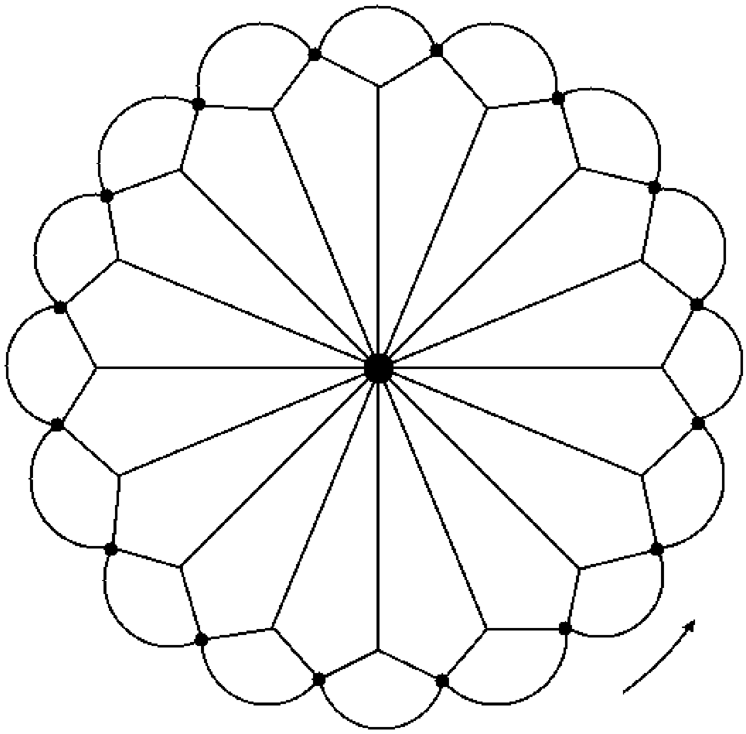

Fig. 5 Emil Vinterhav's model with redundant auxtethers

We also considered a variant, proposed by Emil Vinterhav (Fig. 5), which is like Fig. 4 except that the Remote Units at the edges are also connected to each other by an extra layer of centrifugally stabilising auxtethers. Emil's model would allow for jettisoning of a Y-shaped maintether+auxtether piece in case of maintether breakage and - as a unique feature among auxtether-based models - it would also survive an auxtether breakage event without fatally collapsing. Unfortunately, it turned out in dynamical simulations that the flight dynamics properties of Emil's model are not very good. Because the system is also rather complex and massive, we did not consider it further.

2.6 Stretched auxiliary tethers

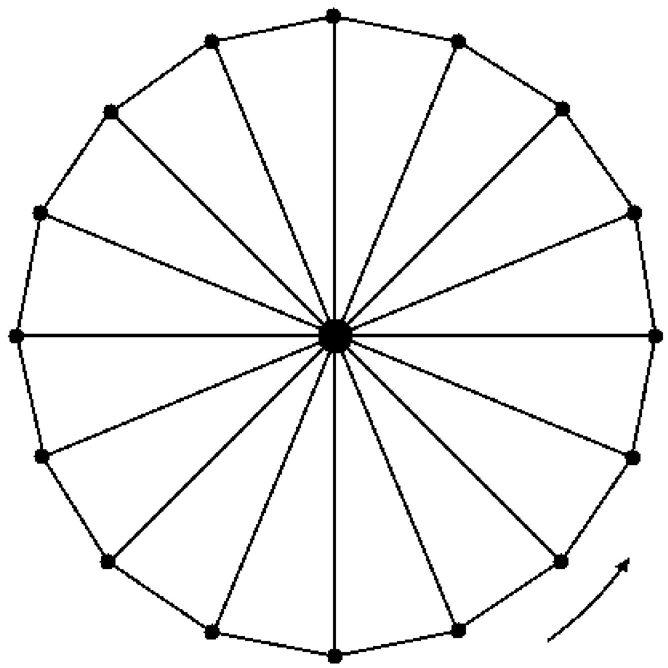

Fig. 6 Stretched auxiliary tethers: the new baseline model

The transient loading on the neighbouring maintether in case of maintether breakage event can be mitigated by increasing the elasticity of the auxtethers. It turns out that this does not harm the dynamical flight properties. However, one can do even better: once the auxtethers are made elastic, one can decrease their length so that they are stretched all the time (Fig. 6). At the same time, they can be lightened because the dynamical stability no longer hinges on the mass of the auxtethers, but rather on the elastic connecting force that they provide. They can be made as lightweight as the mechanical connection allows. When we tested this stretched auxtether model in the dynamical simulator, we found that its flight dynamical properties are even better (about two times better) than in the centrifugally stabilised auxtether design. (The figure of merit we used here was the maximum thrust that one can stably obtain from the E-sail with fixed maintether tension and fixed number of tethers.) The flight dynamical properties of the stretched auxtether model are *remarkably* good when compared to a number of other models that we have simulated.

The stretched auxtether variant also solves the outward swinging and subsequent transient loading problem in case of a maintether breakage. If a maintether gets broken, the corresponding Remote Unit moves outward only slightly, because it is held in place by the tight auxtethers. Since the Remote Unit does not “fall” outward and the tethers remain tightened (not slack) at all times, there is no transient loading shock problem. Thus the stretched auxtether model provides two times higher performance in ordinary flight and is also able to withstand maintether breakage events with no loss in performance. The situation is helped if the auxtethers, besides being elastic, contain as much material damping (loss modulus versus storage modulus, also called damping tangent) as possible. Dynamical simulations show that damping helps to reduce potentially harmful vibrations in all E-sail models. A benefit of the stretched model is that there is a natural place where this damping may be installed, i.e. the auxtethers themselves.

To implement the stretched auxtether design, one needs to be able to produce auxtethers with a certain engineered amount of elasticity. The elasticity must not change too much as a function of temperature or with aging. We are confident that these conditions can be met. This is the subject of WP2.4, the work of which is ongoing.

2.5 Solar blade design

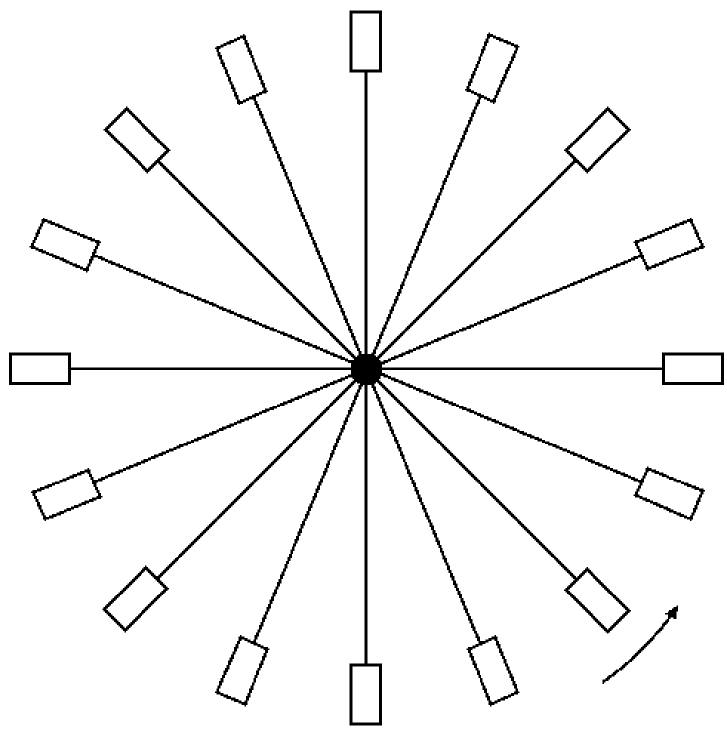

Fig. 7 Active flying of each tether by small solar sail blades at the tips

Other models are possible. Fig. 7 shows an elegant model with a small solar sail blade at the tip of each tether. The rotational state (angular speed) of each tether is controlled independently by turning the solar sail. Because the E-sail thrust is always along the tether-perpendicular component of the solar wind, one cannot control the 2-D motion of the tether by adjusting only one parameter which is the tether's potential. Tether control is enabled by the solar sail because it can produce thrust also in other directions. In place of a solar sail one might be able to use some very high Isp ion engine (FEEP thruster), but then the lifetime of the system would at least in principle be limited by the amount of ion engine propellant. The weak point of the solar sail equipped E-sail is that all the solar blades must be adjusted continuously. If the mechanism which is responsible for the adjustment fails for one of the blades, the corresponding tether must be jettisoned. The benefits of the solar sail option would be good modularity and scalability (any number of tethers could be used without changing the control algorithm) which includes the possibility to validate and flight-test the system at low cost by using a small number of tethers, maybe only one.

2.6 Near-ring models

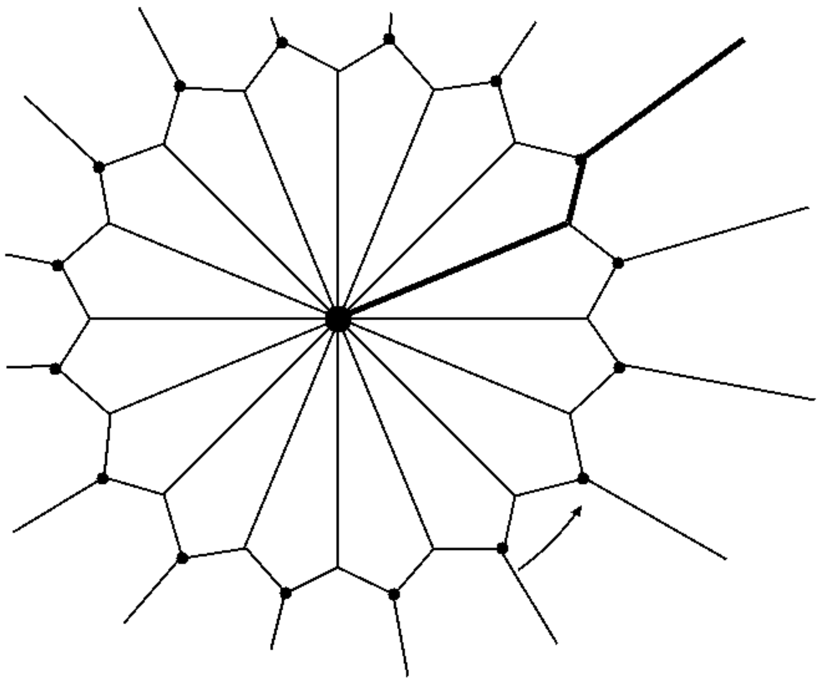

Fig. 8 Central part of one the near-ring models One of the conducting paths is shown by thicker line.

We have also considered various designs where a stabilising auxtether ring exists not at the maintether tips, but at some intermediate distance, e.g. at 500-1000 m from the spacecraft (a “near-ring”, Fig. 8). The maintethers would then consist of a shorter piece which is deployed from the main spacecraft and a longer piece which is deployed form the Remote Units on the near-ring. These models would be robust against maintether deployment failures and deployment speed differences. After many promising trials with the dynamical simulator, we finally were not able to find a model that would be fully robust in terms of flight dynamical stability without a possible need for active control at some point of flight. Another issue with these models is that as the Remote Units are located at a much closer distance to the central spacecraft than the tether tips, the need for spinup propulsion in them is larger because a shorter armlength is used to produce the angular momentum than in other models.

Despite these problems, because they provide some technical benefits, the near-ring models could be taken into reconsideration later when the knowledge of E-sail flight dynamics has matured through improved simulations and practical experience in space, so that the need of active flight control is no longer a no-go direction. We will not consider these models further in this EU project, however.

3. Discussion and conclusions

Many E-sail geometries were considered from a multitude of viewpoints and the stretched auxtether model was selected as the new baseline, the centrifugally stabilised auxtether model (the old baseline) acting as the fallback solution. The winning configuration was finally easy to select and we are very satisfied by its properties. Table 1 summarises some of the properties of the analysed configurations. Stretched auxtether option provides very good performance, is technically almost as simple as the old baseline (the only complication is the need to provide auxtethers with engineered and durable elasticity), can be made to tolerate main tether breakage events without performance penalty and it provides remarkably stable flight dynamics which also contributes towards high performance. Its only drawbacks are that (i) all auxtethers are single-point failure points (as in all auxtether models except Emil's) and (ii) if a maintether reel gets stuck during deployment, the maintether may have to be jettisoned (avoided only in the near-ring models). The first two drawbacks would not exist in the solar blade model (Fig. 7), but the solar blade model would on the other hand require Remote Units that remain operable with moving parts (e.g., a momentum wheel) throughout the mission.

	Jettisonable design possible	Jettisonable without performance penalty	Flight stability	Moving parts during flight	Single-point failure parts
Length fine-tuning	yes	yes	?	yes	All reels
Centrifugally stabilising	yes	no	good	no	Auxtether
Edgy	no	no	reasonable	no	Auxtether
Emil	yes	no	rather bad	no	-
Stretched	**yes**	**yes**	**very good**	**no**	**Auxtether**
Solar blade	yes	yes	?	yes	-
Near-ring	No need	yes	not robust	no	Ring

Table 1: Some properties of considered models. New baseline shown by boldface.

The above three drawbacks of the stretched auxtether model are not severe. The single-point failure nature of auxtethers is something that one can straightforwardly deal with by overdesigning them against meteoroid damage and expected transient mechanical loads by a large margin. As it happens, this overdesigning of the elastic auxtethers does not carry a significant mass penalty (the details of this are dealt with in WP2.4). Lastly, if a maintether reel gets stuck during deployment, one can jettison the maintether to save the mission.