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Moving an asteroid with electric solar wind sail

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Abstract. The electric solar wind sail (E-Sail) is a new propulsion method for interplanetary travel which was invented in 2006 and is currently under development. The E-Sail uses charged tethers to extract momentum from the solar wind particles to obtain propulsive thrust. According to current estimates, the E-Sail is 2-3 orders of magnitude better than traditional propulsion methods (chemical rockets and ion engines) in terms of produced lifetime-integrated impulse per propulsion system mass. Here we analyze the problem of using the E-Sail for directly deflecting an Earth-threatening asteroid. The problem then culminates into how to attach the E-Sail device to the asteroid. We assess alternative attachment strategies, namely straightforward direct towing with a cable and the gravity tractor method which works for a wider variety of situations. We also consider possible techniques to scale up the E-Sail force beyond the baseline one Newton level to deal with more imminent or larger asteroid or cometary threats. As a baseline case we consider an asteroid of effective diameter of 140 m and mass of 3 million tons, which can be deflected with a baseline 1 N E-Sail within 10 years. With a 5 N E-Sail the deflection could be achieved in 5 years. Once developed, the E-Sail would appear to provide a safe and reasonably low-cost way of deflecting dangerous asteroids and other heavenly bodies in cases where the collision threat becomes known several years in advance.

1 Introduction

The electric solar wind sail, from here on referred to as E-Sail, is a new method for producing propulsion in space (Janhunen, 2010; Janhunen, 2004; Janhunen and Sandroos, 2007). Contrary to the more traditional solar sail that utilises solar photon pressure, the E-Sail extracts momentum from charged solar wind particles (Janhunen, 2004; Janhunen and Sandroos, 2007). A number of positively charged tethers are radially deployed from a rotating spacecraft and stretched by the centrifugal force. Because the tethers are charged, they deflect charged particles of the streaming solar wind (from here also referred to as SW), thus producing a Coulomb drag interaction which transfers momentum from the particles to the tethers. Most of the momentum comes from the protons, where the majority of the solar wind momentum flux is. Solar wind electrons will continuously impact the positively charged tethers, making it necessary to maintain the tether charging by actively pumping out electrons from the system. The onboard electron gun, typically of few hundred watts of power, is used to keep the spacecraft and the wires in a high (typically 20 kV) positive potential.

Figure 1 illustrates the E-Sail concept. The modest amount of electric power required to operate the electron gun is typically created by solar panels. The sail rotates so that the centrifugal force keeps the wires stretched and prevents them from colliding with each other. By varying the relative charging of the individual tethers, the direction of the total force can be altered and the spacecraft thus steered (Janhunen and Sandroos, 2007). Although this inevitably causes some fluctuations within the tethers, the mutual repulsive forces between them and the centrifugal force keep the sail roughly in shape. This ability to adjust both the direction and the amount of the force independently of each other gives the E-Sail superior steering possibilities when compared to the traditional solar sail, for which the force vector direction and magnitude change in unison. Like a conventional solar sail, an E-Sail spacecraft can also work its way towards the Sun by inclining the sail so that the resulting force has a component which tends to brake the spacecraft in its orbital motion around the Sun and thereby lose angular momentum and descend deeper into the solar gravity well.

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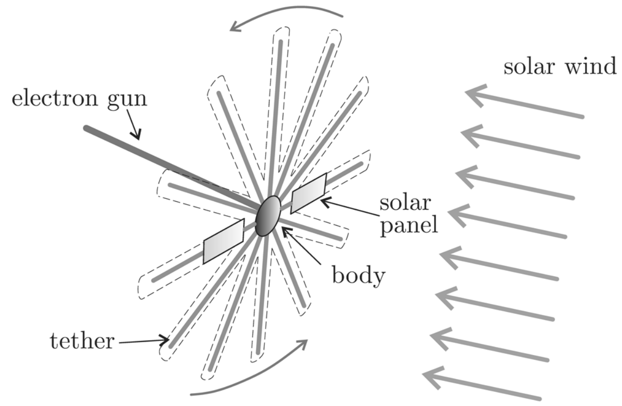

Fig. 1. The electric solar wind sail transforms the momentum of the solar wind into an acceleration of the spacecraft. Figure courtesy of Alessandro Quarta.

The E-Sail can effectively work at angles of operation (normal of E-Sail tether spin plane with respect to the SW) up to at least about 60°. At higher angles the sail's projected area towards the solar wind diminishes markedly resulting in decrease of the pulling force respectively. The thrust force direction is approximately halfway between the solar wind (radial from the Sun) direction and the spin plane normal, so the maximum coning angle of the thrust vector is usually kept to about 30°at most. In other words, the E-Sail thrust vector direction can be changed by up to 30°away from the SW direction. The SW direction is usually radially away from the Sun. Typical variations are 2°with maximal fluctuations deviating up to 10°from radial (OMNI data from CDAWeb, 2009).

A typical E-Sail powered spacecraft might weight 200 kg and have 100 charged tethers, each of 20 km in length. The sail tethers are themselves knitted out of four $25-50\mu$m diameter metal wires in a crossed "Hoytether" pattern in order to minimise the possible destructive effects of micrometeoroids cutting a vulnerable single wire (Hoyt and Forward, 2001). These tethers, if made out of aluminium (ρ=2.7 g/cm^3) wires, would weigh less than 30 kg for the whole E-Sail. Here the central 25 μm wires are assumed to have a 30° angle with respect to the bordering 50 μm wires. With 70 kg reserved for the mass of the spacecraft bus, electron gun, solar panels and other E-Sail system parts, one would be left with a payload of 100 kg. With other tether materials of lower density or thickness, the mass taken by the wires can be significantly reduced or the length of the wires risen to produce more force for the same mass.

Newest results show that the force produced by the solar sail is five times larger than what was estimated at first, 500 nN/m (Janhunen, 2009). For our default E-Sail this would amount to a force of about 1 N.

The effectiveness of E-Sail will be tested in 2012 onboard the Estonian satellite ESTCube-1. Although only deploying one 10 m tether and operating it at a low Earth orbit (LEO) conditions (no solar wind, but using the relative velocity between the satellite and the ionosphere as the plasma flow providing momentum source), this test is expected to give a quantitative measurement of the E-Sail force which can be compared with theory and scaled to solar wind conditions.

The total impulse produced over the lifetime with the baseline 1 N E-Sail is 300 MNs assuming 10 year mission duration and that the spacecraft does not move too far from 1 AU solar distance. To produce the same total impulse one would need 100 tons of chemical fuel (specific impulse 300 s) or 10 tons of ion engine propellant (specific impulse 3000 s). The E-Sail mass is expectedly only in the range of hundreds of kilograms, hence the E-Sail is 100 – 1000 times more efficient than traditional techniques. The E-Sail is so efficient that it becomes feasible to consider deflecting dangerous asteroids directly. Video 1 (see the supplement) portrays direct asteroid deflection by E-Sail.

2 Target asteroid

The target example asteroid has been chosen to represent a realistic asteroid and to fit the guidelines of the Space Generation Advisory Council's (SGAC) 'Move an Asteroid' contest, of which this papers ancestor was victorious in 2009. This paper is an expanded and further studied version of the contest entry. Our subject has thus been chosen to be a fictitious asteroid on its way towards Earth with 140 m of effective diameter and a bulk density of 2.1 g/cm^3 (relatively low because porosity typical of small asteroids, see Britt et al., 2003), resulting in a total asteroid mass of $3.0\cdot10^9$ kg, assuming a volume equivalence with a spherical object. An asteroid with this mass, hitting Earth with a velocity of 30 km/s, would yield an energy release equivalent of 300 MT of TNT explosive.

There are an estimated 100 000 Near Earth Objects (NEO) of this size or bigger sharing space with us (NASA Report to Congress, 2007). One fifth of these are assumed to be potentially dangerous to us (NASA Report to Congress, 2007). Detection and classification of these objects is an ongoing and yet unfinished project. Even if the orbits of all larger NEOs were known accurately, their collisions with smaller meteoroids and each other would still occasionally and unpredictably alter the orbits and potentially render a previously benign object dangerous. Mitigation of asteroid threat is extensively discussed in Belton et al. (2004). There are also several recent studies that summarize and compare differing techniques of asteroid deflection conceived thus far, see e.g. Sanchez et al. (2009), Barbee et al. (2009), and Radice (2009).

The chosen mass of our asteroid is 15 million times larger than originally considered as that of a typical spacecraft propelled by the E-Sail. However, the task is feasible because one only has to deflect the asteroid from its orbit so that it will not hit the Earth, in contrast to taking a tiny spacecraft all the way around the solar system.

3 Avoiding the Earth

To avoid the impact with the Earth, one has to change the asteroid's orbit. Let us consider the asteroid that is being accelerated or decelerated along its track by aligning the force vector produced by the E-Sail with the velocity vector of the asteroid. The E-Sail either follows (brakes) or leads (accelerates) the asteroid on its track. Let us take the maximum usable operational angle to be 60°with respect to the SW (meaning that towing, e.g., coning angle is 30°). Pure braking or pure orbit-aligned acceleration is not possible for circular orbits. On a circular orbit the maximum angle between the Sun direction and the towing force can momentarily reach 40°during some 10°SW-fluctuation. Periods of higher impact angles can last several days and by manoeuvring the E-Sail to take advantage of these, a careful E-Sail operator might gain some extra orbit-aligned acceleration. For simplicity, however, we shall ignore this possibility and assume a steady solar wind coming directly from the Sun, thus limiting the steering angle to 30°and below from the radial.

To model the asteroid motion, we have used the so called leapfrog method, in which the time is divided into discrete steps on which the location and the velocity of the asteroid are calculated in turns on every other step (Hut and Makino, 2009). For simplicity, relativistic effects have been neglected as are all gravitational anomalies. The modeling was performed on Matlab with a time step of 100 s. For the target asteoids orbit we have chosen one with perihelion slightly below that of the Earth's track (1.0 AU) and aphelion of 1.23 AU. As the E-Sail is most powerful closer to the Sun, it should be stressed that there is a large population of asteroids with near Earth orbits for which the E-Sail should work better than in our example.

For our models, we have considered the operation angles θ of 0°(E-Sail force vector going through the Sun), 30°, 50°and 70°, corresponding to the coning angles of 0°, 15°and 25°and 35°respectively. E-Sails of 1 N, 5 N and 10 N have been considered. In Table 1 the deflection distance from the center of the Earth acquired with the method in question is shown. It can be seen that already with a modest 1 N E-Sail we would in an optimum case ($\theta=50°$) be able to deflect the asteroid by two Earth radii in ten years. Less suitable steering angles would make the task manageable for the default sail only after 15 years of towing. With more powerful E-Sail, the time requirement decreases rapidly. Regardles of the E-Sail power, pulling the asteroid directly outward in an operating angle of 0°does not lead in to a desired results. With a combination of high power 10 N sail and most effective steering angle of 50°, our model asteroid could be swayed at a safe distance of 6 Earth's radiuses away from our planet's surface within five years.

Table 1. Asteroid deflection distances for different force strength and directions and for thee different mission durations.

Asteroid deflection	Deflection, [Re]		
Operating angle	5 yr	10 yr	15 yr
0°outwards 1 N	0.1	0.2	0.3
0°outwards 5 N	0.5	0.9	1.5
0°outwards 10 N	1.0	1.8	3.0
30°, 1 N	0.5	1.9	4.1
30°, 5 N	2.6	9.4	20.7
30°, 10 N	5.2	18.9	41.4
50°, 1 N	0.6	2.2	4.9
50°, 5 N	3.0	11.0	24.5
50°, 10 N	5.9	22.1	48.9
70°, 1 N	0.4	1.6	3.5
70°, 5 N	2.0	7.9	17.5
70°, 10 N	4.1	15.7	34.9

We also have to take into account, and add to the numbers, the time taken to fly the E-Sail from the Earth to the asteroid, which could be several years. Also designing and building the E-Sail suitable for asteroid towing can take years, which is why the technology and readiness should be developed now, hopefully well ahead of the imminent danger.

With larger bodies on more energetic orbits, the E-Sail will require more time, but the continuous acceleration of an E-Sail will increase the advantage over other propulsion systems with increasing mission duration. In some cases it is possible to decrease the amount of propulsion needed to change the asteroid's orbit by taking advantage of close planetary flybys (NASA Report to Congress, 2007), but these are omitted in this concept study.

4 Anchoring E-Sail to asteroid

Due to its low weight, an E-Sail vessel is easily carried to any asteroid. According to the simple model of the previous chapter, the E-Sail has potential for moving an asteroid. This leaves us with the problem of relaying that pulling force between the E-Sail and the asteroid. Continuous gentle pull of an E-Sail facilitates this task when compared with more violent means such as ordinary rocketry.

4.1 Harpoon attachment

Direct means of relaying the force, i.e. directly fastening the E-Sail on the asteroid with a cord would have to take into account the rotation of the asteroid. A simple harpoon shot at the asteroid's pole might work well enough for a regularly rotating asteroid. E-Sail can be directly attached only close to the poles of the asteroid, which limits the possibilities of steering the pull direction. If the force is applied in a direction differing from radial (line along the centre of the mass of the asteroid and the towing cord's surface anchoring

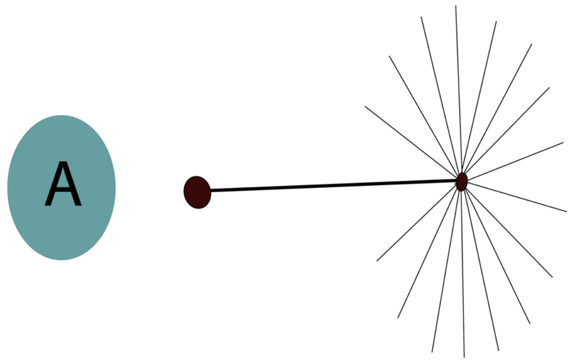

Fig. 2. Gravity tractor with one E-Sail tugging the asteroid ‘A’. The E-Sail wires and the towing cord are not shown to scale. In reality they would scale hundred times larger than the asteroid.

point) the asteroid’s rotational state will change (Scheeres and Schweickart, 2004). Typically, the original rotational state of the asteroid will be almost completely erased and replaced by a new one by the end of the mission. This is not a problem, since the new rotational state tends to be aligned with the pulling direction.

Connecting the cord anywhere else besides close to either of the rotational poles will result in problems with the cord wrapping around the asteroid. If a single towing cord is attached with a harpoon, it might thus be necessary to cut the cord and readjust it several times during the mission.

In general the asteroid’s rotation axis is not directed in the desired pull direction. Therefore, if one attaches the E-sail with a cord at the asteroid’s pole, a suboptimal pulling direction results. The most effective pulling direction with respect to the asteroid’s rotational axis is changing continuously throughout the asteroid’s orbit as the rotation axis direction relative to the Sun also changes. This has to be taken into account on longer asteroid hauling missions, whose duration is a considerable fraction of the asteroid’s orbital period. In asteroid deflection with an E-Sail this usually is the case.

More freedom in tug direction can be achieved by attaching a towing cord to both rotational poles, thus minimizing the impact on asteroids rotation. The cords could then at a safe distance come together and be united into one towing cord. Contrary to the one harpoon solution, this method works best when the desired pull direction is perpendicular to the asteroids rotational axis as then physical contact (abrasion) between towing cords and the asteroids surface can be minimized. This method requires a relatively smooth asteroid with regular spin and elevated pole regions and will thus most likely be impossible for the majority of the asteroids. Modest alteration of the pulling direction is possible by altering the relative lengths of the cords coming from the poles. If the rotational axis of the asteroid happens to coinside with its orbital plane normal, this configuration would allow choosing the towing direction at will within the orbital plane.

In addition to relaying the pulling force itself, the towing cord has to be able to withstand possible tugs resulting from the line getting slack and then tightening again due to tumbling of the asteroid and changes in the E-Sail operations. One space-proven, lightweight and highly durable option would be to use the polyethylene (Dyneema®) tether (DSM Website, 2010). In 2007 The 2nd Young Engineers Satellite (YES2) successfully deployed 31.7 km of Dyneema® tether that was 0.5 mm of diameter (Kruijff et al., 2008). With yield strength of 2.4 GPa, this cable can withstand pull of 470 N. Density of Dyneema is 0.97 g/cm^3, which leads in a 100 km long cable of 0.5 mm diameter weighting 19 kg. However, surfaces of asteroids are often fluffy with sand or composed of small stones, which might make it hard to get the harpoon attached to the surface in the first place. This issue needs to be further addressed and could be tested on laboratory conditions with mock-up asteroid surface.

4.2 Gravity tractor

There is one method with which the problems of harpoon attachment and of controlling the asteroid’s rotation could be circumvented. By levitating a mass close to the surface of an asteroid, their mutual gravity pull can be used to transfer the towing force of the E-Sail wirelessly onto the asteroid (see Fig. 2) (Edward and Stanley, 1995). Having no need to attach anything on the asteroid simplifies things considerably and removes any constraints on the erratic rotational movements, or on the surface composition of the asteroid (Edward and Stanley, 1995). Additionally, the force of the pull is now always directed close to the center of the mass of the asteroid (for spherical asteroids directly towards the center of mass), which minimizes the impact on the asteroids rotation. The biggest advantage of gravity tractor solution over simpler harpoon solutions is however, that the coning angle can be adjusted independently of the direction of asteroids rotational axis, which allows for optimal pulling direction throughout the asteroids orbit around the Sun.

The towing force T is dependent on the gravity constant G, the mass of the asteroid M, the mass of the tractor m as well as on the distance between the asteroid’s and the tractor’s center of mass, d:

$$T = \frac{GMm}{d^2} \tag{1}$$

In order to transfer the 1 N force of one default E-Sail, the mass of the tractor held a sphere equivalent diameter from above the center of mass (one radius above the surface) would thus need to be:

$$m = \frac{Td^2}{GM} = \frac{1\mathrm{N}\ (140[\mathrm{m}])^2}{6.674\cdot10^{-11}[\mathrm{m}^3\mathrm{kg}^{-1}\mathrm{s}^{-2}]\ 3\cdot10^9[\mathrm{kg}]} = 98\,000[\mathrm{kg}] \tag{2}$$

For a nonspherical steadily rotating asteroid it might be possible to take the tractor even closer, but on the other hand an erratic circulation and safety considerations probably force us to keep a higher distance. For a safe limit of one diameter away from the surface (210 m from the center of mass), the required tractor mass would rise up to 220 000 kg, for two diameters above surface up to 400 000 kg, and so on rising in the square of the distance. For an advanced E-Sail pulling with 10 N instead of 1 N, these masses would rise tenfold but on the other hand for larger asteroids the tractor mass requirement would decrease. In order to avoid any risk of the E-Sail tethers getting into unwanted contact with the surface of the asteroid, the station would be best to position itself farther away from the asteroid, only connected with a lengthy towing cord to the gravity tractor mass.

The mass of the Rosetta spacecraft, currently flying towards comet 67P/Churyumov-Gerasimenko, will be about 1400 kg when it reaches its target asteroid (ESA Rosetta website). Our gravity tractor's mass demand to tow our model asteroid with one Newton force could thus be satisfied with seventy Rosetta sized spacecraft. With new heavy launchers, like Ares V being currently developed by NASA, the tractor mass could be delivered with only a few launches. Ares V will be capable of delivering over 50 tons of mass into escape track from Earth (Stahl et al. 2009).

Surely, in an hour of need, transporting this mass from the Earth to the asteroid would not be a major resource issue, but there might be a yet cheaper way: If one can land controllably to the asteroid, also using the mass of the asteroid itself to fill the tractor's containers might be plausible. Some part of the asteroid could be mined by exploding or digging and then collected into nets or bags that would be connected to the tow of the electric sail. This would erase the trouble of flying the passive tractor mass from Earth to the asteroid. The overall mission might thus be expedited and the cost lessened. Instead of hauling the whole tractor mass from the Earth into the vicinity of the asteroid, we would now only need the rubble bags, some collection method of the rubble and the towing cord for towing the tractor.

Should the mass of the tractor be slightly smaller or larger than planned, the situation could easily be rectified by holding the tractor correspondingly closer or farther away from the asteroid.

On some asteroids containing enough loose rocks one might get enough mass simply by carrying these rocks into containers (bags or nets). These containers would then be levitated from the surface of the asteroid by small chemical propulsion rockets, after which they can be attached to the E-Sail vessel using a similar harpooning procedure as proposed in the previous sub-section. Simple robots could be placed on the surface to haul loose rocks and rubble in to waiting nets or containers. This method wouldn't produce as much a risk of loose rubble flying around, but would require development of complex robots working with artificial intelligence in addition to taking more time to fulfil their mission. This style of controlled mass gathering might easily increase the mission duration by an half a year or more. If there wouldn't exist enough loose rubble, minor explosions or drilling machines could be used to loosen it from the asteroid.

In all of these methods the energy for surface operations might come from the Sun. In that case the inevitable raising of dust from the surface of the asteroid may produce problems in blocking the solar panels and some cleansing system might be necessary. Also the rotation of the asteroid would periodically bring the surface robots into shadow, slowing down their work. Nuclear or fuel cell energy could go around this problem but would require more mass to be transferred from the Earth.

Biggest foreseen problem with the gravity tractor method is the controlling of the system. Two masses pulling each other with gravitational attraction is an unstable system requiring active and continuous tuning. If the distance between the masses is not just right to relay the precise pulling power of the E-Sail, the masses will either pursue to approach or recede from each other. Also, a real asteroid has an uneven gravitational field which complicates the system even more. This makes it paramount that the distance and E-Sail pulling power are monitored and adjusted accordingly, so that the balance is kept. One way of performing this would be to adjust the E-Sail voltage and thus pulling power as required to keep the towing configuration intact. Controlling a system of an asteroid and a gravity tractor with thrusters has recently been found to be plausible (Yeomans et al., 2008) and the issue is also discussed by Olympio (2010) and Wie (2008). The question arises whether the E-Sail force can be adjusted rapidly enough in order to counteract the gravitational instability and the possibly time-varying gravity-field of a rotating and irregularly shaped asteroid. According to preliminary simulations this is not a major problem as the big masses of both the asteroid and the tractor make allowance also for slower response times. However, if this proves to be a problem for a specific asteroid, it can be mitigated by adding to the tractor mass and by placing it farther away from the asteroid.

Gravity tractor method works even better with larger asteroids as the required tractor size is inversely proportional to the mass of the asteroid itself. But for a larger asteroid, a proportionally larger towing force is required in order to produce similar acceleration. For these bigger bulks a system of multiple E-Sails, discussed in the following chapter, could become necessary in order to scale up the towing force.

5 Scaling E-Sail force

For bigger asteroids and tighter time-constraints, 1 N tugging force from a default E-Sail might not be enough and thus we need to consider options for scaling up the E-Sail force. This could be achieved either by attaching multiple E-Sails onto

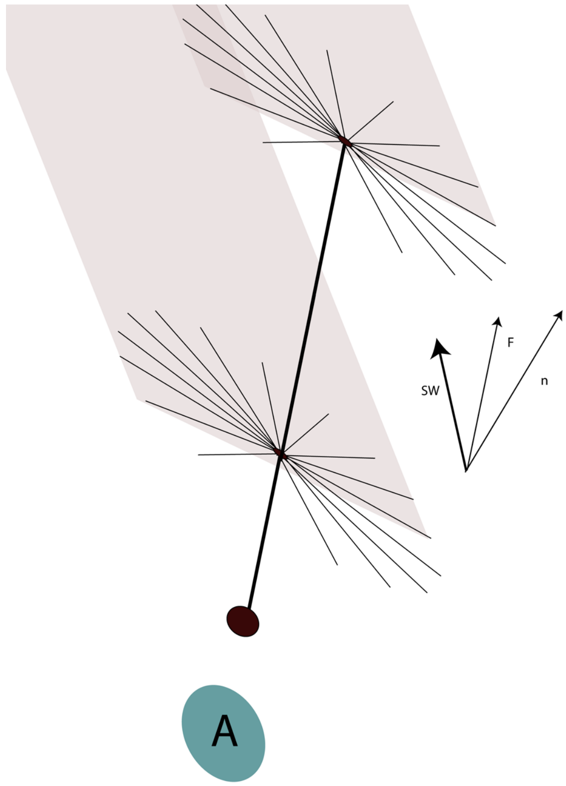

Fig. 3. Connecting E-Sails together in a line is one possibility for scaling up the towing force. Sails do shadow each other, but with long enough connecting cords losses due to this can be diminished. The towing force (F) is aligned with the towing wire and cuts in half the angle between the solar wind (SW) and normal of the sails (n). At maximum this angle can be around 60 degrees for the sail to continue to be effective, giving ample of opportunities for positioning the sails. Figure is not in scale.

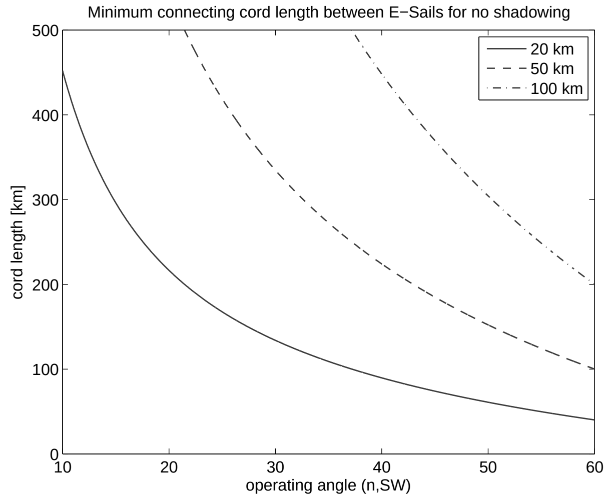

Fig. 4. The minimum distance between two E-Sail stations positioned in the Fig. 3 arrangements so that all the shadowing is avoided. The minimum connecting cord length is plotted as a function of the E-Sail operating angle (the angle between E-Sail plane normal and the solar wind). Three tether-lengths are considered, the default E-Sail 20 km, an advanced 50 km case and the 'as big as possible with current technology' 100 km. Obviously, with a longer tether length also the 'no shadow' -cord length in-between stations grows proportionally.

the asteroid and/or by making the E-Sails themselves bigger and more efficient.

In order to attach more E-Sails and thus to scale up the force, it could be possible to launch several smaller E-Sail stations that would then transfer their pulling power to the asteroid by separate or shared towing cords. This would look like a cosmic equivalent of towing boats, but would introduce technical challenges into steering and controls of the E-Sails to prevent them from clashing with each other. The stabilisation of the rotation of an asteroid might also be an issue. If the rotation is out of control, there is a risk of multiple wires getting distorted and knotted. A gravity tractor discussed in the previous chapter would not have this problem, although some issues might arise with controlling the heavy tractor mass itself.

The best option though might be to tie several E-sails onto the same towing cord (Fig. 3). This would only demand one attachment point on the asteroid (which could be achieved with either a gravity tractor or by a harpoon close to the pole). In this system there is a possibility of separate layers of E-Sails shadowing each other in terms of solar wind, but as the angle of operation (normal of E-Sail plane with respect to the SW) can be up to 60°(Janhunen, 2004; Janhunen and Sandroos, 2007), this problem can be circumvented with long enough connecting cables in-between individual stations. For an E-Sail with tether length of r km and the operating angle of θ, the minimum no-shadowing station separation is given by:

$$L = \frac{2r\ \sin(\pi/2-\theta)}{\sin(\theta/2)} \tag{3}$$

The outcome of this equation is illustrated in Fig. 4. It should be noted, however, that while this equation assumes perfect 100% shadow, especially at the ends of the tethers they are more loosely separated from each other and some ions will inevitably pass through the plane of tethers. So some shadowing is well endured before thrust starts to significantly drop, as the next layer of the sail would in real situation be influenced by these passing ions.

Enlarging the size of one E-Sail would directly transfer into higher towing force. The maximum length achieved with normal metals used as E-Sail tether wires is around 100 km, beyond which both the resistivity of the wire and its tensile strength might become an issue. Greater lengths might be achieved with novel materials having much improved strength and lower density when compared to the copper considered here. 100 km long tethers would produce five times the tow of our default sail with 20 km long tethers. Tethers could also be spaced in higher angular density, for example 200 tethers around the sail instead of the default 100 proposed, again roughly doubling the tow. The steering of high number of such a long wires could be problematic though. It might even be possible to upgrade the E-Sail force up to hundreds of Newton's and even beyond, which would make the E-Sail technology very attractive for various other uses as well as for towing bigger asteroids.

Also, different kinds of net deployment possibilities might be considered. For example assisting tethers could be inserted between individual radial tethers connecting them with each other. This approach might allow better coverage of the now empty space between the furthest ends of the tethers. It could also provide more stability to the system, even helping the sail in keeping its overall form for example in that undesired scheme where one tether was to loose its maneuvering ability or be cut by a micrometeorite impact. The lines connecting the tethers with each other would need to have some part of them insulated so that individual tethers could still be steered by simply varying their voltage. Packaging and deployment problems might cause some trouble, but if they can be solved, this approach could considerably increase the effectivity of a single E-Sail without increasing its dimensions. Moreover, an E-Sail with more compact dimensions should be easier to manoeuvre (for example when adjusting the plane of operation).

6 Discussions

The E-Sail provides a relatively cheap way to mitigate asteroid threats. It needs however some time to work, so advance detection systems remain of utmost importance. For longer warning times (>10 years), the E-Sail is a very good choice, but for close calls we need also to develop some fast response systems. The ESTcube-1 (http://www.estcube) test will show us some direction whether the E-Sail effect in reality obeys the theories and is usable in real space projects.

Several other methods of deflecting an asteroid or a comet include exploding the target into smaller pieces. This might induce more risk-objects as the sizes and trajectories of the ejecta are hard to control (Sanchez et al., 2010). E-Sail proposes to take the risk object away as a whole, thus saving us the trouble of mapping the trajectories of hundreds or thousands of new space debris.

The options for scaling up the E-Sail power are numerous and provide ample amounts of capacity for further considerations of the usability of an E-Sail powered solution. More research and modeling is needed to study the most effective ways on using the E-Sail for asteroid towing.

To advance the gravity tractor method of asteroid towing, one would need to develop an advanced controlling systems to manage the mining and gathering of the tractor mass from the asteroid surface. During operational stage there is a need to stably control the distance between the asteroid and the tractor. The long distance of the asteroid from the Earth causes the need for the tractor mining and stabilization units to work autonomously, at least during time constrained operations.

To advance the harpoon method of asteroid towing appears as more straightforward than advancing the gravity tractor method. One would need to build one or two auxiliary satellites for shooting the harpoon into the pole of the asteroid, and to do that multiple times if needed. A good opportunity to practice harpooning in space would be to apply the harpoon method to fastening the recently proposed electrostatic plasma brake (Janhunen, 2010-2) to space junk objects on Earth orbit for controllably de-orbiting them. This would have the benefit of removing space debris and simultaneously give an opportunity to practice harpooning of diverse objects in an environment which is faster and cheaper to access than asteroids.

Supplementary material related to this article is available online at: http://www.astrophys-space-sci-trans.net/6/41/2010/ astra-6-41-2010-supplement.zip.

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