HIGH PERFORMANCE SOLAR SAILS FOR LINEAR TRAJECTORIES AND HELIOSTATIONARY MISSIONS

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ABSTRACT

High performance solar sails could offer the capability to travel along linear trajectories throughout the solar system and to stop at any desired location, thus providing an 'heliostationary' position. A second type of mission would be to release small solar probes which would freely fall into the sun and thus provide in-situ information about its corona. Different probes could also be used for fundamental physics experiments. After these probes have been released, the sail part would be even lighter and would then be able to escape the solar system.

INTRODUCTION

Several solar sail demonstration flights are presently planned and solar sail technology is now acknowledged by the main space agencies world-wide. The first generation of solar sails will be of relatively modest size (a few tens of meters in diameter) and quite heavy (tens of kilograms). The next step will be to improve the performance of the sail and reduce the payload mass. We can expect that within a few decades the state of art will be such that solar sailcraft able to exceed the gravitational pull of the Sun with the solar photonic push will be feasible. This will open the way for a new class of trajectories, rectilinear ones, and even allow to stop in the solar system.

The fundamental measure of performance for a solar sail is its characteristic acceleration, defined as the solar radiation pressure acceleration experienced by the solar sail while oriented towards the Sun at a distance of 1 AU (the radius of Earth orbit). At this distance, the Sun gravitational pull is 5.9 mm s^{-2} . To counterbalance the gravitational pull with the photonic pressure, a sail loading (i.e. the ratio of the reflective surface to the total mass of the sailcraft) of 1.53 g m^{-2} is needed. Taking into account the efficiency of the sail, which can be estimated to 0.9 at best, this leads to a sail designed for a sail loading of 1.38 g m^{-2} . This value is the threshold to exceed for obtaining a lightness number (the ratio of the solar photonic force to the gravitational pull, both varying with the inverse square of the range to the Sun) higher than unity. Just to give an idea, a lightness number λ of 1.1 would be obtained with a circular sailcraft of 100 meter radius and 40 kg of total mass.

Which technology to use for obtaining such performance, when will it be ready, what will be the geometry of the sail, how the optical ageing will diminish its efficiency are obviously fundamental questions, but they will not be addressed in this paper. These issues are considered in many papers or books, for instance in *Solar Sailing*, by Colin R. McInnes. The topics addressed here are how to use solar sail with lightness number higher than one, why are rectilinear trajectories interesting and what can be the applications of such navigation scenarios.

SOLAR SAIL NAVIGATION BASICS

Mission analysis for solar sail trajectories is not a simple task compared to ordinary ballistic navigation. The difference is that ballistic navigation is determined by a finite sequence of manoeuvres, each of them being fully defined by 5 parameters (the time they are executed, the intensity of the pulse and the 3 angles determining its direction). Between manoeuvres, Keplerian theory applies fully.

Solar sailing, on the contrary, is a continuous process and the mathematics for reaching final conditions is far more complex, even more than in the case of electric propulsion, since the thrust intensity is related to the sail orientation: the orientation of the force vector applying to a perfectly reflective solar sail is normal to the sail, in the anti solar direction. Its intensity is proportional to the square cosine of the angle between the normal to the sail and the Sun-line.

The principle for shaping straight trajectories with high performance solar sails (HPSS) is elementary: the orientation angle of the sail is such that its component along the anti sunward direction is exactly counterbalancing the gravitational pull from the Sun. When respecting this simple orientation law continuously, the resulting trajectory is a straight line, oriented along the initial velocity vector of the HPSS . Depending on the sign of the component along the velocity vector of the HPSS, the HPSS is permanently accelerated (when the contribution of the solar pressure is to increase the velocity of the sail) or decelerated (component against the velocity vector).

In the later case, after a while (see further discussion), the velocity vector will be reset to zero, meaning that the HPSS is immobile with respect to the Sun. This configuration can be simply maintained either by orienting the sail in a sun facing position and reducing the sail surface in order to get an exact unity lightness number or by gently balancing the sail in such a way that in average, over a given period of time, the gravitational pull is exactly zeroed.

Whether this navigation strategy is optimal for stopping a HPSS is not demonstrated, but it is at least very simple to modelize and implement with commercially available software. The results which are obtained with this strategy are already adequate to envisage actual straight trajectories.

LINEAR TRAJECTORIES

From Earth to an Immobile Position along a Linear Path

It is first assumed that the HPSS is deployed in the last stage of the launch sequence, on an Earth escape trajectory leg. The infinite velocity is assumed to be close to zero. This could be achieved for instance with a launch by an ARIANE 5 to GTO, using an ASAP structure (Prado et al., 1999).

For achieving a straight trajectory, the steering angle of the sail, defined as the angle between the sail's normal and the sunwards direction, has to be set in such a way that at any time, the resultant force of the sun gravitational pull and the photonic push is aligned and opposed to the HPSS velocity vector (see geometry figure 1). The trajectory can then be calculated using a classical 4th order Runge-Kutta integration method.

Once the velocity has been zeroed, the steering angle has to be changed in order to maintain a motionless position. This can be achieved through at least two strategies: by reducing the effective surface of the sail or by oscillating the sail in such a way that the average resulting force over a given period of time is identical to the stable value. The selected strategy will also counterbalance some residual accelerations, such as planetary perturbations.

The figure 2 hereunder shows the trajectory obtained by following this strategy with a HPSS of λ=1.1. Leaving the Earth with a C_3 =0, corresponding to an heliocentric velocity of 29.8 km/s at 1 AU, the immobilisation is obtained after a 235.5 days cruise, at a range of 2.05 AU from the Sun. The following figures (Fig. 3 - 6) provide details about the trajectory and the steering strategy.

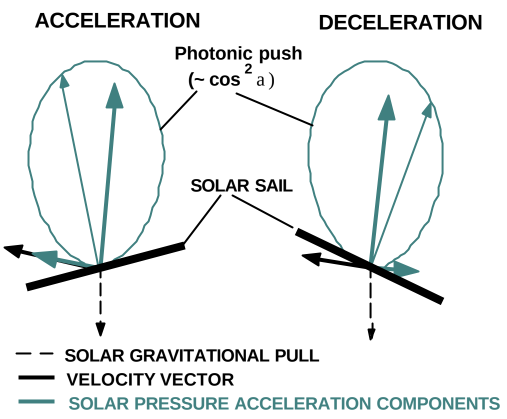


Fig. 1 Orientation of the solar pressure force

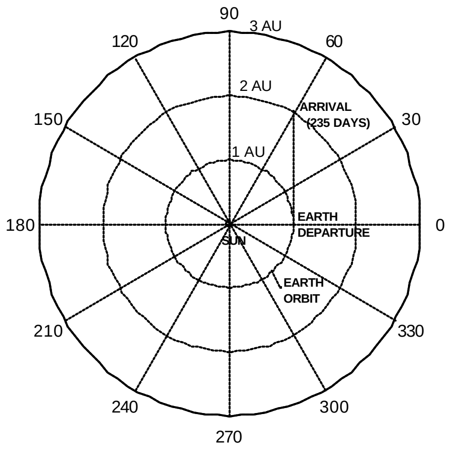
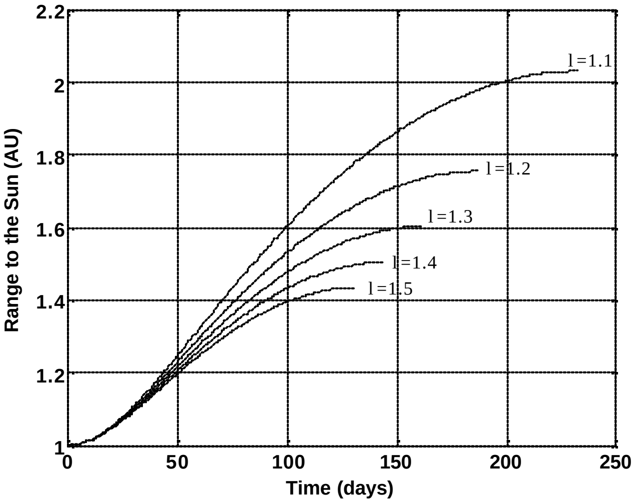


Fig.2 Rectilinear trajectory for a λ=1.1 HPSS

with a C =0 Earth departure



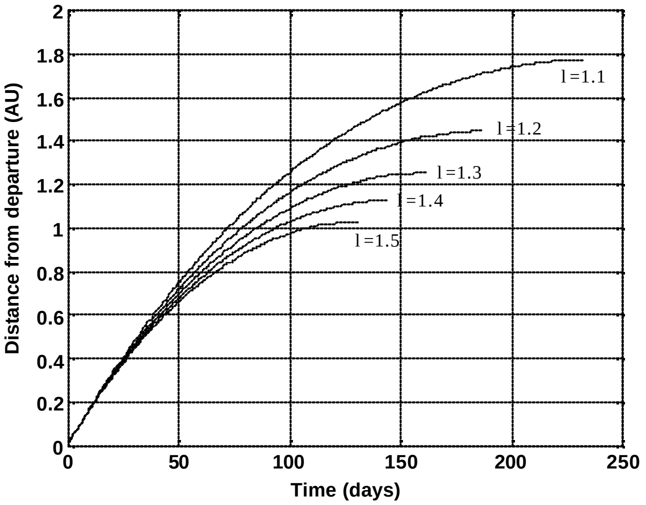
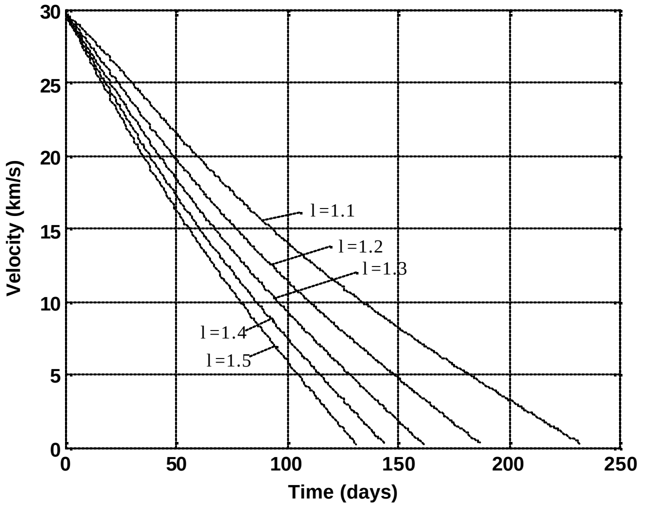


Fig. 3 Evolution of the HPSS – Sun range

Fig. 4 Distance from departure



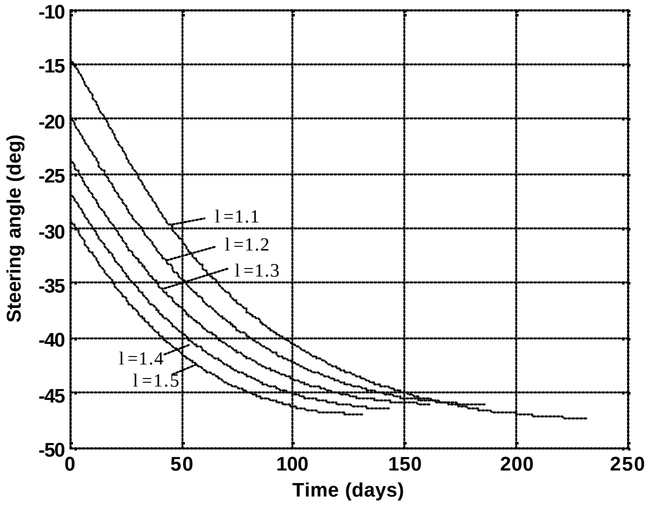


Fig. 5 Evolution of the velocity

Fig. 6 Evolution of the steering angle

Accessible Domain from the Starting Point

Once the sailcraft has been stopped, rectilinear trajectories can be envisaged in any direction.

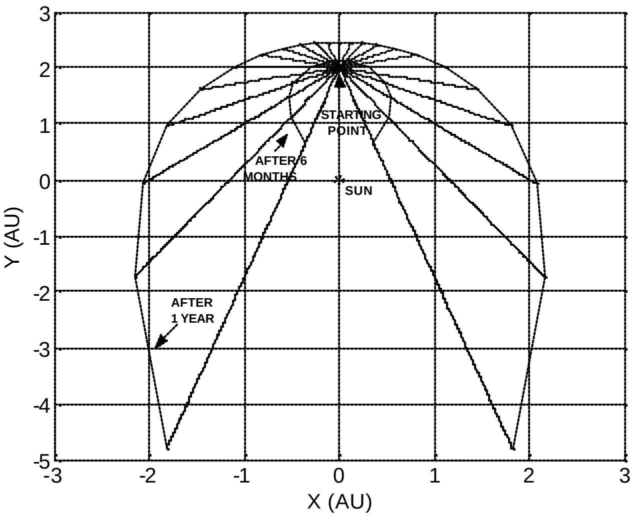


Fig. 7 Accessible domain in 6 months and 1 year with (for λ=1.1)

The figure 7 above shows the domain that can be accessed from a starting immobile position at 2 AU from the Sun (with λ=1.1), after 6 months and one year respectively. Note that the X and Y axes correspond to any plan passing by the Sun, not only to the Ecliptic. It is noticeable that the closer the trajectory grazes the Sun, the farther the sail can travel in a given period. The limitation will be given by the thermal behaviour of the sail material and can be estimated to a minimum distance of 0.2 AU.

Stopping anywhere within the Solar System

Rectilinear trajectories can also be envisaged to link two motionless points, as it can be seen in figure 8. This kind of trajectories can be interesting to reach immobile positions everywhere in the Solar System, out of the Ecliptic plane and especially above the Sun poles.

The four figures (Fig. 9 – 12) show that such a trajectory is divided in two phases: firstly an acceleration phase and then the steering angle changes its sign in order to slow down and stop the sail craft. The trajectory is calculated for λ=1.1, from a starting point at 2 AU from the Sun and the final position at 1 AU is reached after 325 days.

Considering what we mentioned before, it would be possible to evaluate the duration of a broken line transfer from Earth to the point situated at 1 AU above the Sun pole:

- From Earth to an immobile position at 2 AU (in the Ecliptic plan): 235 days
- Transfer between 2 AU and 1 AU immobile positions (perpendicular to the Ecliptic): 325 days

Although this broken line trajectory is not optimal, it shows the performance of a HPSS: the transfer time is equal to only 1.5 year.

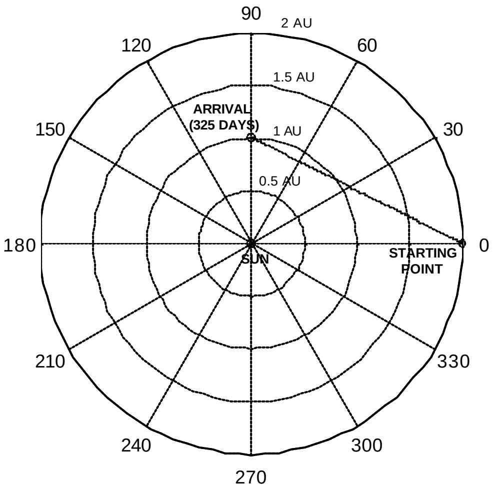
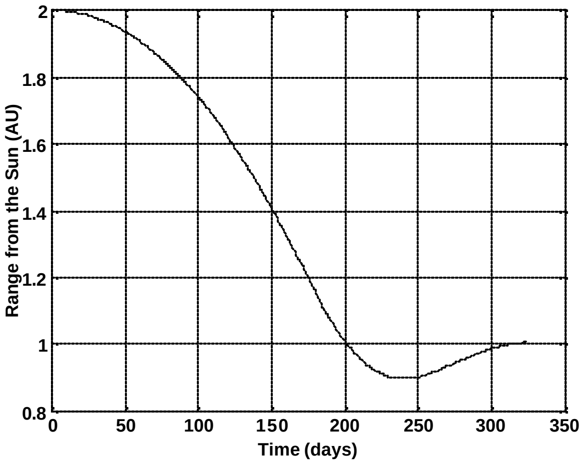


Fig. 8 Trajectory between two immobile positions (for λ=1.1)



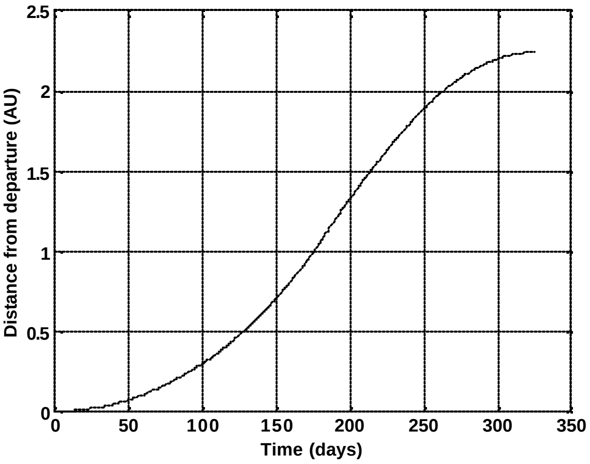


Fig. 9 Range from the Sun (for λ=1.1) Fig. 10 Distance from departure (for λ=1.1)

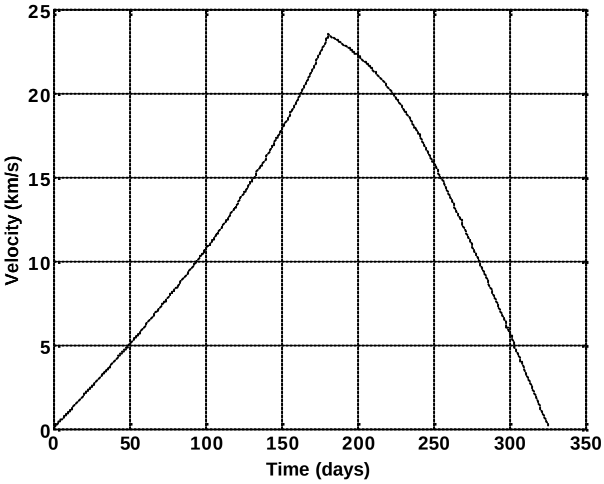


Fig. 11 Velocity (for λ=1.1)

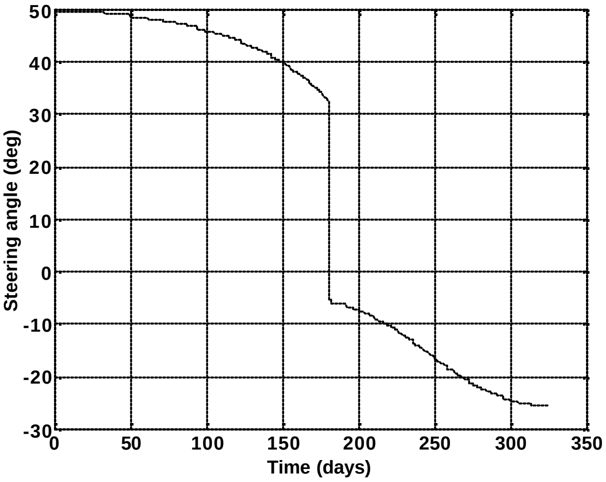


Fig. 12 Steering angle (for λ=1.1)

POSSIBLE SCIENTIFIC MISSIONS

Heliostationary positioned spacecraft at high solar latitudes are ideal for observing the solar poles, that are not visible from within the ecliptic plane. The only available high solar latitude observations come from the Ulysses spacecraft, which performed two orbits around the Sun. Ulysses data have shown that the mid-latitude solar wind structure is increasingly complex as solar activity increases, and that the solar poles are the source of the high-speed solar wind. Positioning stationary spacecraft above the poles would allow to monitor the high-latitude corona in a continuous way and thus better understand its dynamics as a function of the solar cycle. Solar corona images supplied by such high solar latitude spacecraft, when combined with images taken from the ecliptic plane, would allow a tomographic analysis of CMEs (Coronal Mass Ejections) in three dimensions and thus a better understanding of their structure and evolution. The minimum payload would be a coronagraph (imaging), a solar wind monitor and a magnetometer (in-situ measurements).

Such heliostationary positioned spacecraft are also ideal for releasing small solar probes, that would freely fall into the Sun. Equipped with particle detectors and a magnetometer, they would provide in-situ information about the corona, giving access to the altitude profile of the solar wind parameters.

Other types of mission that can be performed using solar sail equipped heliostationary spacecraft include :

- The monitoring for NEOs (Near-Earth Objects). Positioning a few such spacecraft at stationary orbits inside the Earth orbit and equipping them with a small telescope pointing at the anti-solar direction, could allow a comprehensive survey of such objects.
- The testing of the equivalence principle (general relativity). In order to test that different bodies at the same place, in a gravitational field, experience the same acceleration, a solar sail equipped mother spacecraft could be positioned at several AU. It would then release small test masses, made out of different material, which would free fall towards the Sun. The releases would be simultaneously performed from the opposite tips of the solar sail masts, so as to have the maximum separation between the test masses and thus minimise the mutual gravitational attraction between them. Their trajectories would be monitored by a daughter free-falling microsatellite, equipped with a high precision ranging system, that would be released after the test masses and would follow them.
- A solar-sail equipped spacecraft could gain enough acceleration, on a trajectory towards the outer solar system (cf. next section). Equipped with a solar wind monitor, a magnetometer and a cosmic ray monitor, it could explore the outer limits of the heliosphere, and intercept the heliopause in any freely chosen direction.

LEAVING THE SOLAR SYSTEM

The earlier study of the accessible domain when using linear trajectories~~,~~ shows that the best scenario, for an escape mission (leaving the Solar System), is first to fall towards the Sun in order to use the gravitational pull and to increase the velocity. The figure 13 hereunder shows the performance of a rectilinear trajectory starting from a motionless point at 2 AU from the Sun with the closest distance from the Sun equal to 0.5 AU. The higher the lightness number the faster the sailcraft (the escape velocity from the Solar System is increasing with λ).With a $\lambda=1.5$ HPSS it would be possible to reach the Final Shock (at 100 AU from the Sun) in less than 7 years. A closer pass from the Sun would even shorten this duration.

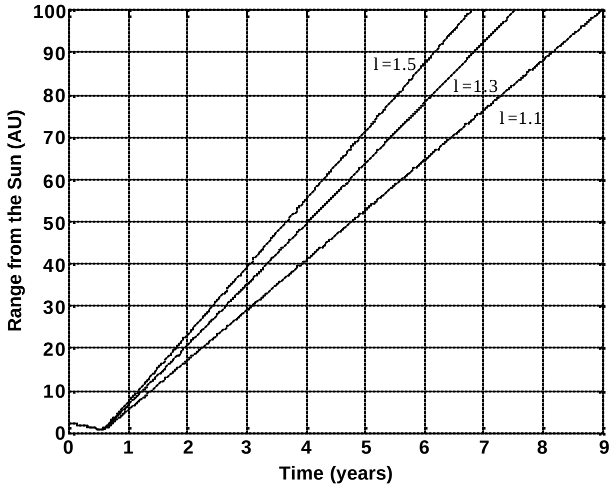


Fig. 13 Range from the Sun

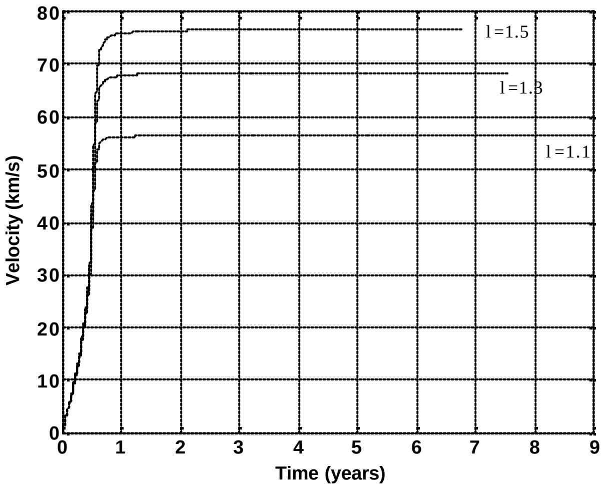


Fig. 14 Evolution of the velocity

CONCLUSIONS

Although High Performance Solar Sails are beyond the current technological state of the art, an improvement of less than two orders of magnitude is necessary to reach the 1 g/m^2 sail loading, from the present 40 g/m^2. If we consider the pace of progress for space telemetry data rates or on-board memory capacity, for instance, we can bet that such a progress can be achieved quite fast, maybe within a decade.

The *sine qua non* condition for solar sail technology to be accepted is to achieve an in-flight demonstration of a sail deployment. Several projects are in progress and the first demonstration can occur a few months after this paper has been written.

The deployment of HPSS will be even more difficult because the sail material itself will be much thinner. Two options for solving this problem can be envisioned: a first one would be to give the task to assemble the sail to astronauts, the second would be to design a fully automated process for assembling it. The material for manufacturing the solar filters of some sun pointing telescopes is made of a mesh of threads on which a 0.15 μm layer of aluminium is deposited. This filters are able to sustain launch environment and spend several years in space. An automated way for producing in space large surface of such material, possibly based on a spider-like robot, could allow to shape a web in space and then fill it with an aluminium film. Deployment issues would then just not apply.

Macte animo, generose puer, sic itur ad astra... *(Virgile)*

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