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LOW COST MISSION OPPORTUNITIES USING A SOLAR SAIL IN ADDITION TO ARIANE V

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ABSTRACT

Some ARIANE V launches will provide slots for small payloads, for a delivery into Geostationary Transfer Orbits (GTO). Two contiguous locations can be used for a single auxiliary payload.
The navigation from a GTO to an heliocentric orbit can be achieved in several ways. What is presented here is a dual propulsion design, based on the use of a solid propellant motor to escape from the Earth gravitational field, followed by a solar sailing phase for the heliocentric orbit control.
Solar sails offer particular advantages for missions which are not requiring a very stringent navigation accuracy. This paper presents an innovative accommodation for a double module spacecraft and a set of solar sail missions, dedicated to the Space Weather monitoring, that could be achieved this way.

INTRODUCTION

The ARIANE V launch policy will offer attractive opportunities to deliver light spacecraft into Geostationary Transfer Orbits (GTO). A structure called ASAP (Ariane Structure for Auxiliary Payloads) is presently under development to carry and deliver small satellites into GTO [1]. Up to eight small spacecraft (less than 100 kg) can be installed on the ASAP ring. The possibility to use two adjacent locations, connected by a rigid structure, is also under study.
The design which is proposed here is to link two modules on contiguous ASAP locations by a loose connection made of an inflatable tube and a set of drawback cables in order to provide a more compact configuration of the spacecraft after separation of its two modules from the launcher.

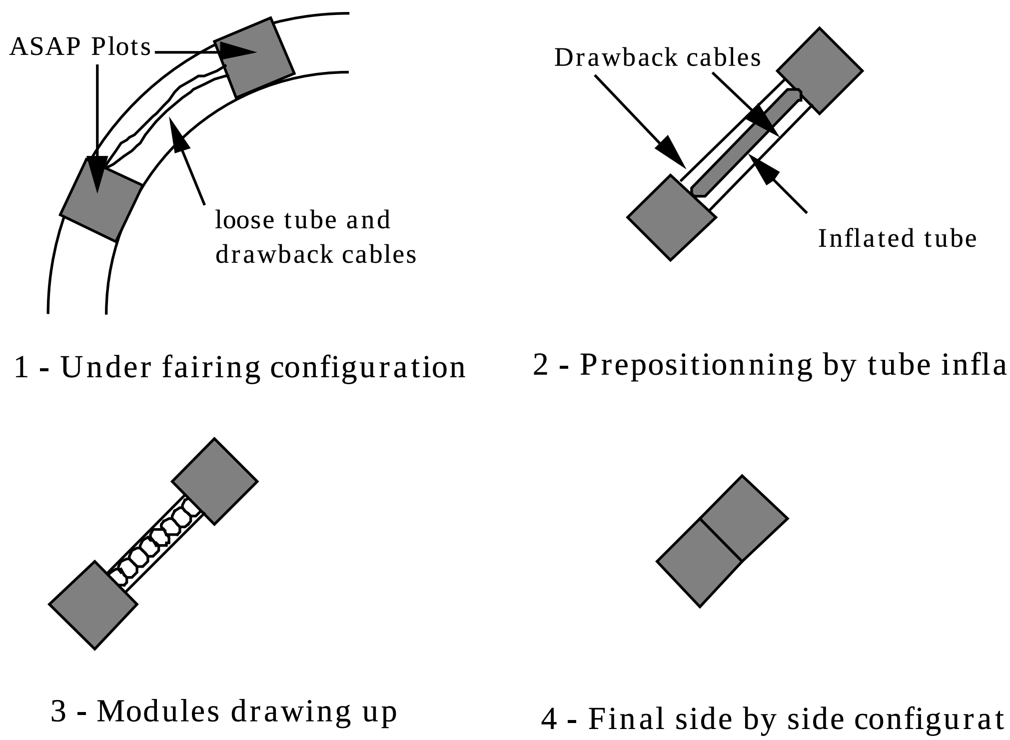
ASAP

The ARIANE V launcher is designed to deliver into GTO large commercial satellites. On most of its flights, there will remain quite a large mass margin that can be used to accommodate a set of small piggy-back passengers. Using the same philosophy with ARIANE IV has procured a cheap access to space to some 22 small spacecraft weighing up to 80 kg. The larger capacity of ARIANE V offers up to 8 auxiliary payloads with an individual mass up to 100 kg. The cost charged for such a passenger would be in the M$ (or MEuros) range. The ARIANE V ASAP platform is a ring structure with an outside diameter of 4 meters and a width of about 60 cm. The auxiliary payload are symmetrically placed on the ASAP ring on eight 30 cm diameter separation rings, the separation mechanism being provided by Arianespace. The payload envelope is 60cm x

60 cm x 80 cm (high). The auxiliary payload is part of a launch dedicated to a main passenger, therefore it has to adapt to the main passenger mission and launch operations.

BANDONEON DESIGN

From preliminary studies performed in different space agencies (CNES, JPL, ESA, DLR...) [2][3], it appears that 100 kg does not easily permit to design a deep space mission starting from a GTO. The situation would be much better if the launched mass could be in the 200 kg range. This is the origin of the ‘banana’ concept [4], which consists in connecting two adjacent attach locations with a rigid structure. This ‘banana’ configuration would offer a capacity of 180 kg but this configuration makes quite impractical the use of a solid kick motor to raise the apogee, the inertia of the resulting structure being unfavorable for the conservation of the spin axis direction, up to the time where the perigee kick motor can be fired. The concept which is presented in Figure 1 is an alternative to the ‘banana’ design. It is based on the use of a loose link between the two modules which, at the end, will form a compact spacecraft.



1 - during the launch, the two modules are connected by a deflated tube and three or four loose cables. To prevent any important motion, the tube and the cables can be clamped in a few places to the ring between the two ASAP plots,
2 - just after being jettisonned from the launcher, the bridging tube is inflated. The effect is to position the two modules in a stable face to face configuration.
3 - the inflated tube is gently deflated while the cables are rewound to draw up the modules. The shape of the tube is corrugated so the modules are remaining in a fixed orientation while getting closer.
4 - when the cables are fully rewound, the tube is completely deflated and, thanks to its corrugated shape, occupies a very limited volume between the two modules which can then be mechanically locked.

Fig.1 . The bandoneon concept

The main advantages of the bandoneon design is to be simple and reliable, to provide an acceptable ratio of inertia and to comply with the single ASAP structural design. The layout of the final configuration of the spacecraft is much less constrained by the launch configuration in this configuration than in the 'banana' configuration.

OVERALL MISSION DESIGN

As the time of launch cannot be imposed by the interplanetary mission to the commercial customer, the orbit control strategy of the spacecraft is split in two phases: a geocentric phase, which ends when the Earth gravitational pull becomes neglictible and an heliocentric phase.

Earth Departure Phase. It is fully possible to spiral around the Earth with a solar sail, but it is quite long (more than one year with a medium size solar sail) to escape from the Earth gravitation. On the order hand, from a geostationary transfer orbit (GTO), a perigee motor capable to deliver an impulse of about 770 m/s will provide a small but positive C_3. As its magnitude will be low, the direction of the corresponding infinite velocity V_∞ vector is of secondary importance. For a total mass of about 160 kilogrammes, a Thiokol STAR 13B for instance can do the job.

This strategy makes possible a departure on an heliocentric leg with a velocity very close to the Earth's one whatever is the launch date and the orientation of the GTO line of apsis.

Heliocentric Orbit. As the date of launch and, as a consequence, the orientation of the line of apsis are unsettled, the amount of fuel of any conventional propulsion system cannot be a priori defined. So, it is required to use a much more efficient low thrust propulsion system to shape the heliocentric orbit. Two technologies can be used for providing orbit control: electrical propulsion and solar sailing.

Solar sailing [5] is a good answer to the heliocentric navigation for a mission which does not require a very accurate orbit control: at least for the first solar sail mission, the actual thrust of a solar sail will not be known very precisely, thus it is wise to reject its use for planetary or celestial body encounter missions.

SPACE WEATHER MONITORING MISSIONS

SOLAR WIND UPSTREAM MISSION

Mission requirements. The interaction mechanisms between the interplanetary solar wind and the Earth's magnetosphere are very complex and still the target of many scientific space missions.

The power provided to the Earth magnetosphere by its interaction with the solar wind can be determined [6] from two observable parameters

- the magnetic field, fluctuating in direction, of magnitude between 5 and 10 nT,
- the solar wind particles velocity.

In situ measurements are required and the further upstream from Earth they are performed, the longer will be the warning delay. A good location, that is already used, is the L1 Libration point lying 1.5 million kilometers upstream from the Earth. Augmenting the delay would mean to orbit closer to the Sun but then, with a classical spacecraft design, the angular velocity of the spacecraft would be higher than the Earth's so that the configuration would not remain stable with time, unless a permanent pull is given to the spacecraft. Then a solar sail would be an excellent candidate for providing this thrust [7].

Mission Phases. After the launch and the near Earth phase, where the spacecraft is mostly under the influence of the Earth gravitational field, the spacecraft is escaping the Earth gravitational field. From then, the mission can be split into two phases:

- a heliocentric leg, roughly covering half of an ellipse, the aphelium being the Earth departure and the perihelium the operational station keeping location. This phase is about 6 months long,

- the station keeping phase, where the spacecraft actually fulfills its mission and which is limited in time by the ageing of the sail material and the possible failures of the onboard equipment.

As the operational phase is constraining the transfer one, they are addressed in the reverse order.

Station Keeping. The operational orbit can be seen as an ordinary Keplerian orbit around the Sun, but with a reduced value for the central body gravitational constant.
From the Kepler's third law $T=2\pi\,(a^3/\mu)^{1/2}$ [T being the orbit period, a the orbit semi major axis of the orbit and μ the Sun's gravitational constant - 1.327 10^{11} km^3/s^2-], the requirement to define the sail performance is straightforward: the term (a^3/μ) has to be equal to the Earth's one. Considering a circular orbit of radius r, the pull from the Sun is μ/r^2 (5.9 mm/s^2 at 1 AU from the Sun) so the radial acceleration γ_r to be applied to a spacecraft in order to have an Earth synchronous orbit around the Sun, is

$$\gamma_r = \mu/a^2\,[(1-\eta^3)/\eta^2]$$

η being the ratio between the range from the sail to the Sun and the Earth orbit radius a.
Defining the lightness number, λ, of a sail as the ratio of solar thrust to the solar gravitational force, we obtain the required performance of a sail

$$\lambda=1-\eta^3$$

As a dimensionning target for a 'first generation' solar sail, a range of 3 Millions of kilometers is considered, corresponding to a characteristic acceleration of 0.37 mm/s^2, or a lightness number λ of 0.0588. This figure corresponds to a Surface to Mass ratio (*S/M*, *S* in square meters, *M* in kilograms) of about 40. For a targetted total mass of 175 kilogrammes, this leads to a surface of 6.400 m^2 that is a circle with a radius of about 45 meters, depending on the considered efficiency of the reflective material.
It must be noticed here that the equivalent ΔV, if provided by a more conventional propulsion system, is worth 32 m/s per day. After three months, the amount of wasted fuel would be the equivalent of a circularization impulse from a GTO to a geostationary orbit...

Heliocentric Orbit Transfer Options. Different scenarios of navigation can be considered:
- a two impulse mission, where the sail is not deployed before being delivered into its operational orbit [8]. The first impulse provides the path to reach L1, the second is a braking maneuver for providing the required angular velocity,
- a single impulse mission, where the braking maneuver is given during the transfer leg by the sail,
- a purely sail based strategy without any help of a classical motor after the Earth departure [7].

A two impulse mission is actually a Hohmann transfer between the Earth's orbit and the operational orbit. The velocity at departure, V_∞, has to be about 300 m/s lesser than the Earth's velocity to reach the targetted perihelium, in the rear direction with respect to the Earth motion.
At arrival on the operational location, a braking maneuver of about 950 m/s is needed to provide the required velocity. Then, before the sail can be unfurled, a 90° steering maneuver has to be executed in order to direct the spin axis in the sunward direction.
The main drawbacks of this solution are the mass of propellant needed for the maneuvers (about half of the launched mass) and the distance which is limiting the telemetry data

rate between the Earth and the sail at the most crucial phase of the mission, when the sail is unfurled.

On the other hand, a purely sailing strategy would allow to decrease the launched mass and also to unfurl the sail quite close from the Earth. The main drawback of this solution is that two steering laws have to be implementd onboard, as the angle between the normal to the sail and the velocity vector should be about 35 degrees for an optimal deceleration efficiency during the transfer phase and 90° for the operational phase.

A single impulse strategy would be almost as heavy as the double impulse scenario while also needing a specific sail steering capacity for the transfer leg.

Solar Sailing Scenario. After the early departure phase, the sail will enter a braking phase of about 6 months, in order to reach its operational position with the required velocity. The angle between the sail surface normal and the velocity vector that is optimal for reducing the orbital velocity is 35°. Then, the sail has to be rotated sunwards in order to acquire its operational orientation.

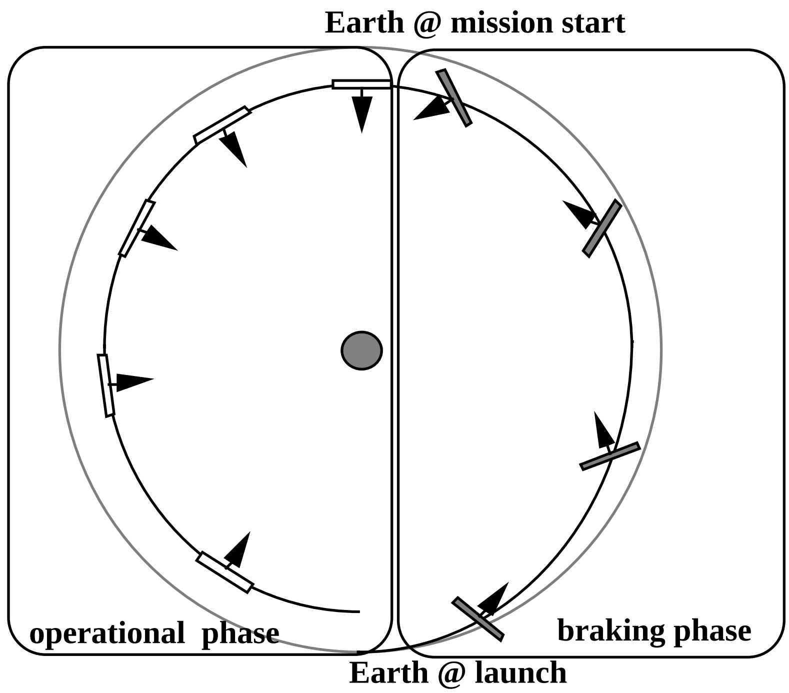


Fig.2. Solar Sail steering strategy

These two phases are presented on Figure 2 as fully separated ones for clarity reasons. In fact, the transition between the first phase and the second can be much smoother. Further studies will search for an optimal sail steering law in order to obtain the operational characteristics as early as possible.

To cope with the scientific requirement of having a spinning rate close to 1 rpm, the sail has to be spun up after its 35° rotation maneuver. Once this has been achieved, the curvature of the sail is sufficient to ensure a permanent sunwards pointing. The only attitude control maneuvers then will be dedicated to maintain the spin rate.

In order to keep the design as simple as possible, the attitude will be controlled by jet thrusters. A couple of small thrusters (a few Newton thrust) with a lever arm of about 1 meter will be sufficient to provide attitude control for both phases of the mission. The total mass budget allocated to the attitude control system is 10 kilograms.

System design. The instrumental payload is about 8 kg [9]. The module supporting it and providing all the operational resources is less than 60 kg. The sail is 30 kg and the solid motor 50kg. The suggested design is to put the first two items in one module and the sail and the solid motor in the second module.
The proposed sail design relies on inflatable technology. The inflatable structure includes a torus and 4 out of plane radial masts, of smaller diameter, that give the sail its final shape. These inflatable pipes are made of prepreg Kevlar, rigidized under the action of solar heating and of a gaseous catalyst mixed to the pressurant [10].
The reflecting material, chosen for its lightness characteristics, is aluminized Mylar™, manufactured by Dupont de Nemours, of thickness 1 μm (1.4 g/m^2). This film is reinforced by a mesh of strips.

Table 1
PRELIMINARY MASS BUDGET

Item	Content	Mass (kg)
Platform		57
Attitude sensors	Sun sensor, CCD, Electronics	1
Comms	Receiver, Transmitter, Antenna, Harness	2
Power	Solar panel, Distribution	8
Thermal	Paint	1
Stucture and mechanisms	Central tube, Platforms	30
Attitude control	Tank, Thrusters, Tubing	10
Miscellaneous	Harness, Balancing mass	5
Payload	FluxGate Magnetometers, Boom, Hot ion analyzer, Ion gun, Radio receiver	8
Sail		30
Inflatable pipes	Torus (radius 45 m), 4 radial	9
Sail material	6400 m^2, Mylar ® 1μ, reinforcement	12
Stowage elements	Structure, Mechanisms, Separation system	6
Pressurisation system	Tank, Gas, Valves, Plumbing	3
Total sailcraft mass (without margin)		95
Margin	15 %	15
Total sailcraft mass (including margin)		110
STAR 13B motor (^{2}V~ 775 m/s)		48
Connecting structure		4
Total launch mass (including margin)		162

Operational S/M ratio 45

(efficiency ~80%)

MAGNETOTAIL MISSION

The same way a sail can benefit a mission to L1, it can be used for a mission to L2 in a very similar way, to place a spacecraft between the Earth and L2. The gravitational pull of the Earth has now to be considered. The two diagrams of Figure 3 depict the range from the Earth (expressed in Earth radii - R_e) as a function of the S/M index for a L1 and a L2 vicinity mission.
Placing one or more spacecraft, in a stable location, in the Earth magnetotail would provide a monitoring of the time variability of its energetic state. A set of solar sails located at different ranges between the Earth and the 'natural' L2 Lagrangian point could monitor the dynamics of the magnetotail and the release of energy from the magnetosphere.

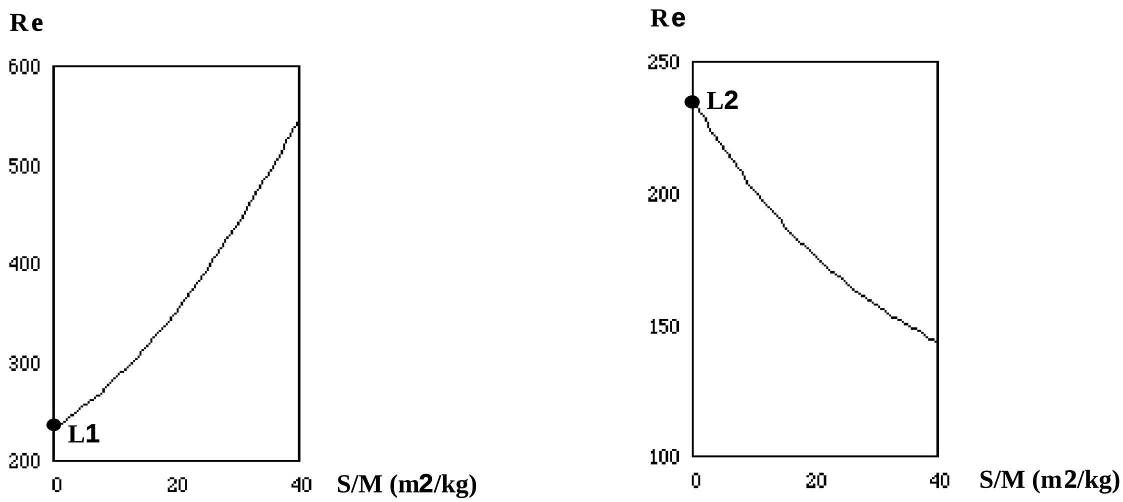


Fig.3 Changes to L1 and L2 by a Solar Sail

STEREO TYPE MISSION

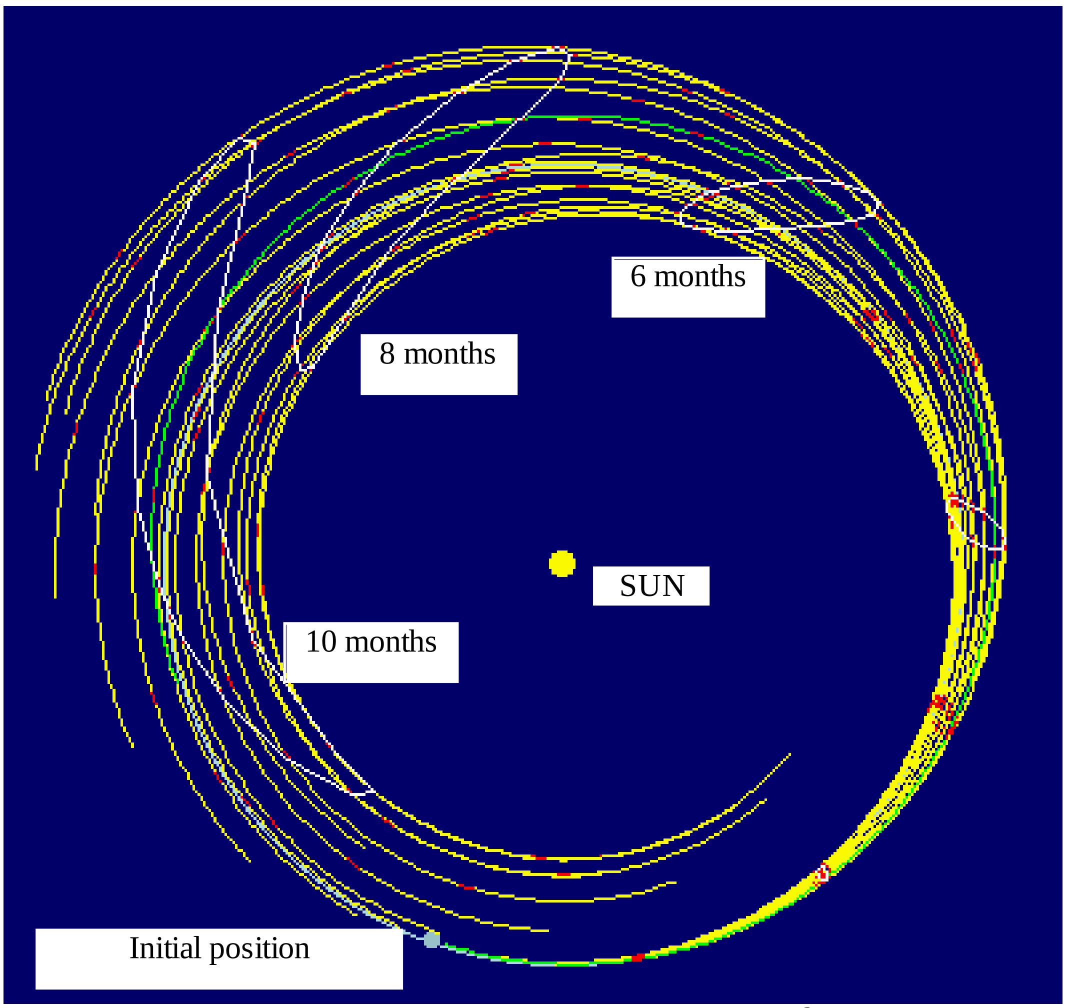


Fig.4. Bundle of achievable trajectories with a S/M=40m^2/kg Solar Sail

In order to get a complete 3D reconstruction of the coronal mass ejections (CMEs), a twin spacecraft mission, named STEREO, is presently under investigation by NASA. Using a solar sail approach could be a valuable option for a STEREO next generation

mission. The Figure 4 shows the achievable locus for a solar sail leaving the Earth with a neglictible V_{∞}. The assumed S/M is worth 40 m^2/kg. Each trajectory corresponds to a constant steering angle with respect to the Sun direction. Every two months (from 6 to 10 after the departure), the achievable positions are connected.
It is worth to note that the two spacecraft could be launched on a same ASAP ring, the modules occupying two opposite pairs of plots.
From the Figure 4 above [5], it is highly visible that after a year or so, two sails simultaneously launched can be located at very different positions with respect to the Earth, one leading the Earth, the other lagging behind. Instead of opening the stereoscopic angle with time, as will be the case with STEREO, a solar sail based mission could be designed in such a way that once a given stereoscopic angle has been achieved, solar sail are maneuvered in order to maintain its value over time.

CONCLUSIONS

Solar sails have been envisaged since several decades for travelling in the solar system but no project ever could mature. The main advantage of a solar sail is to be a cheap and long duration orbit control system. Its main drawback is that it is difficult to accurately modelize the resulting thrust. So solar sails are very well suited for missions that require a long duration flight, a high ΔV and of which orbit is not too constrained by accuracy requirements. Solar sailing preferably applies to light spacecraft of the hundred kilograms range. The ASAP opportunity is mainly dedicated to the same category of light spacecraft.
A combination of these two concepts through the proposed ‘bandoneon’ configuration offers an efficient way for achieving low cost deep space missions for monitoring the space weather.

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