ESA CONTRACT 17679/03/NL/SFe

Solar Kite Mission Feasibility Study

EXECUTIVE SUMMARY

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ESA STUDY CONTRACT REPORT

ESA CONTRACT No: 17679/03/NL/SFe	SUBJECT: Solar Kite Mission Feasibility Study – Executive Summary		CONTRACTOR: Kingston University
*ESA CR() No:	*STAR CODE	No of Volumes: 1 This is Volume No: 1	CONTRACTOR'S REFERENCE:

ABSTRACT:

A solar kite is a small solar sail which can be deployed and controlled with a minimum of moving parts. The purpose of the study was to determine whether useful scientific returns could be obtained from kites; whether suitable launch opportunities for them exist; and whether they could be constructed using off-the-shelf components to minimize development costs.

A variety of high-value missions have been found which could be performed by kites. These include in particular lunar-related tasks: high resolution imaging of the lunar surface from very low altitude; multispectral imaging of the surface; and imaging the surface at high latitudes, including polar craters, with the aid of light reflected from the kite itself. A kite could also inspect for dust at Earth-Moon Lagrange points, return good quality flyby images of NEO objects such as Earth-transiting asteroids, and conceivably return physical samples to Earth acting as its own low-temperature re-entry parachute. Such missions would have both major scientific utility and significant outreach potential.

There are suitable low-cost launch opportunities for kites, in particular as piggyback payloads on GTO vehicles such as Ariane 5. Kites can be built largely from available space qualified components.

A certain amount of development work will be necessary. A kite cannot carry the mass of a standard transponder, and must instead use RF components familiar from modern mobile communications technology. It will be necessary to space qualify such components, selecting in particular for radiation hardness. Such research will be of great use to the wider microsat/nanosat community.

The conclusion is that kites could be deployed to perform innovative and inspiring near-Earth missions in as little as three years time.

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NAME OF ESA STUDY MANAGER	ESA BUDGET HEADING
Ms Kotska Wallace Div. : TEC-MMO	H1/100.060/600.5100/DMG/RD100/03S60

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1. Introduction

A solar kite is a small solar sail which can be deployed and controlled with a minimum of moving parts. It is an ideal piggyback payload, as it has low mass and poses negligible hazard to other payloads due to its inert nature and absence of on-board energy sources or volatiles.

The purpose of the Solar Kite Mission Feasibility study was to determine whether:

- Scientifically valuable missions could be accomplished with solar kites
- Suitable (cheap) launch opportunities could be found for solar kites
- Solar kites could be designed using off-the-shelf components and materials, minimizing development time and cost.

The project has involved assessing suitable payloads for solar kites, designing a general mission concept, ascertaining the subsystems that will be needed for navigation, data transmission, etc., and determining mass and energy budgets for an outline design.

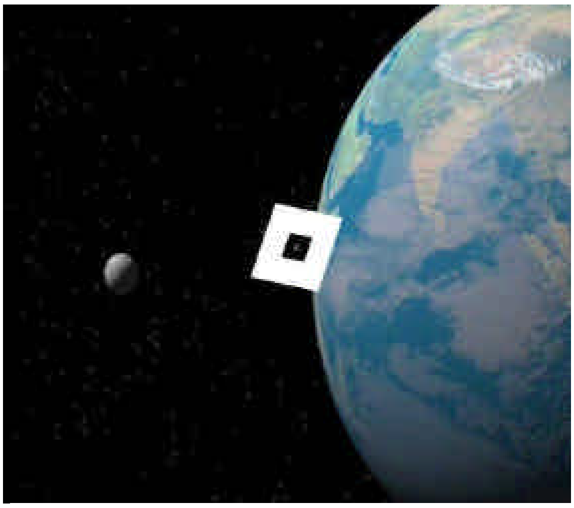
2. Kite mission classes

Solar kites can be launched to Low Earth Orbit (LEO), to higher orbits such as Geostationary Transfer Orbit (GTO), or as passengers on interplanetary missions. Of these three options:

- LEO is a hostile environment for kites. A kite is vulnerable to atmospheric drag-induced re-entry unless its apogee is at least 700 km, limiting low-cost launch opportunities. A kite in LEO also suffers frequent eclipse, high tidal torques and rapid change in the optimal propulsion angle which places heavy demands on the manoeuvring system. There are few useful missions for a kite in LEO, and climbing to higher orbits takes a long time and incurs a high radiation dose.

- Interplanetary missions pose onerous communication problems. At interplanetary distances, data relay by other spacecraft is required to return useful volumes of data.

- From GTO, mission times and radiation doses to reach distances ranging from a few hundred thousand to a few million km are acceptable, and data can be returned directly to Earth. Relatively cheap piggyback launch opportunities to GTO are regularly available, e.g. using a microsat or minisat bay on the Ariane-5 auxiliary payload bus (ASAP-5). This was identified as the most promising option.



Solar Kite in GTO

3. Kite size and payload capacity

Four methods of kite unfurling were considered:

- Umbrella-style unfurling
- Triply coiled self-uncoiling hoop
- Central frame with self-opening STEM hinges
- Inflatation with subsequent rigidizing

Only an inflatatable can expand to more than about three times the diameter of its container without complicated mechanisms. Unfortunately all attempts to use such designs in space have been problematic: either heavy elaborate equipment is required for rigidizing (e.g. for thermal curing); or the final shape is not precise and/or stable.

It was concluded that a near-future kite would be restricted to a few square metres in area, thus restricting the payload it can carry to a few hundred grams at most.

4. Scientific payloads

The limitation on payload mass drastically restricts the useful science instruments a kite can carry. Any instruments must not only be light but extremely radiation hard, for very little shielding can be provided.

A variety of instruments, including radiation and particle sensors and various types of imager, were evaluated. Only one highly capable instrument satisfying the mass and radiation criteria has been found: the FillFactory STAR-250 CMOS-based imaging chip. This can be used in cameras of various designs. Applications found for such cameras include:

- High-resolution imaging - returning close-up images of lunar surface, near-earth asteroids, etc.
- High-resolution multispectral imaging - in conjunction with a linear variable interference filter.

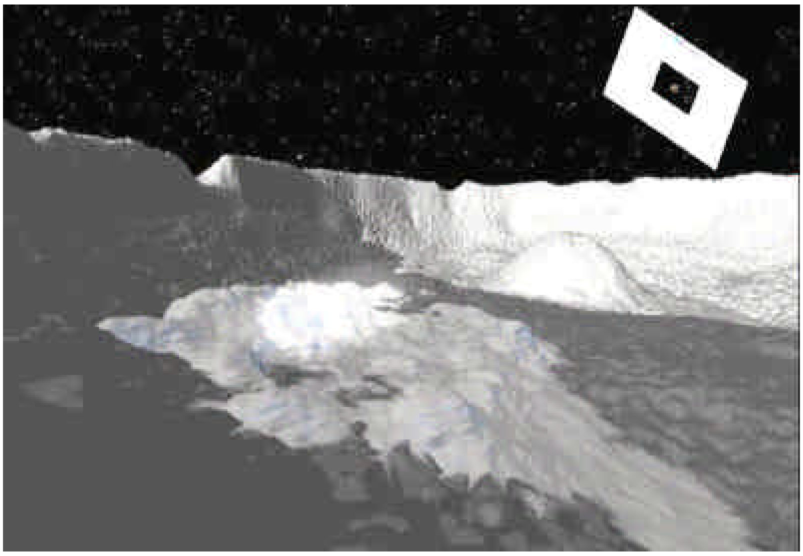
Where the field-of-view (FOV) requirement is similar, the same physical camera can perform several roles, e.g. attitude control and navigation as well as data collection. It is also feasible for the kite to carry several cameras with different optics (lenses, filters, etc.) each of which use the same type of chip as their image sensor. The same electronics, switchable between cameras, can then provide control and frame grabbing capabilities for all of them.

5. Missions

Several types of high-value mission have been identified for a kite using a capable imager such as the STAR-250.

5.1 Lunar surface imaging

A kite can readily enter a highly elliptical lunar orbit with a very low perigee – as low as a few hundred meters. With modest optics, and without slewing, it can capture images of the lunar surface of resolution down to 15 cm. Unlike other types of spacecraft, a kite can continuously adjust its orbit without using fuel, so compensating for the effects of mascons etc. and selecting different targets for each perilune approach.



Solar Kite Performing a Low Lunar Pass

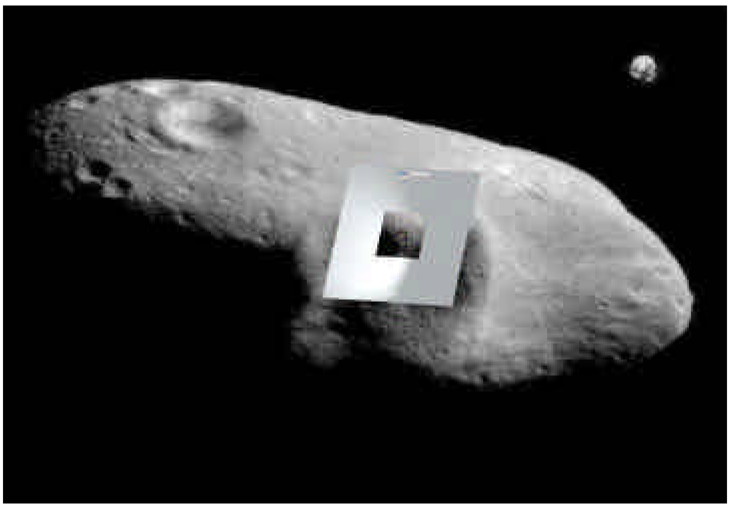
5.2 Lunar surface multispectral imaging

Using a camera fitted with a linear interference filter, the kite could capture multispectral images of the lunar surface, with resolution down to a few metres and covering wavelengths from the near IR through the visible. This is vastly better resolution than any previous lunar spacecraft. Fine multispectral imaging of the Moon's surface would be particularly informative due when linked with lunar surface data from Apollo.

5.3 Imaging at high lunar latitudes

Permanently dark lunar craters at the lunar poles are difficult or impossible to image by conventional spacecraft. Such areas are of great interest: they may conceivably house frozen volatiles. A kite flying over the lunar poles can be tilted so as to reflect sunlight downwards, providing the equivalent of a powerful searchlight. Surfaces which are normally permanently dark, or poorly illuminated, can be imaged at high resolution and with multispectral capability.

5.4 Imaging of Near-Earth Objects.



Solar Kite Imaging a Near Earth Object

A kite could perform a flyby of a Near Earth Object (NEO), or of several NEOs consecutively, returning images including multispectral images of a resolution of a few tens of centimetres. Time to transmit each picture would be long (days per picture, as opposed to ~1 hour per picture at lunar distance) but a selection of images could be transmitted during the months it will take the kite to reposition for each successive target. Possible targets include Atens, Apollo, and Amor asteroids.

5.5 Detection of dust at the Earth-Moon L4/L5 Lagrange points

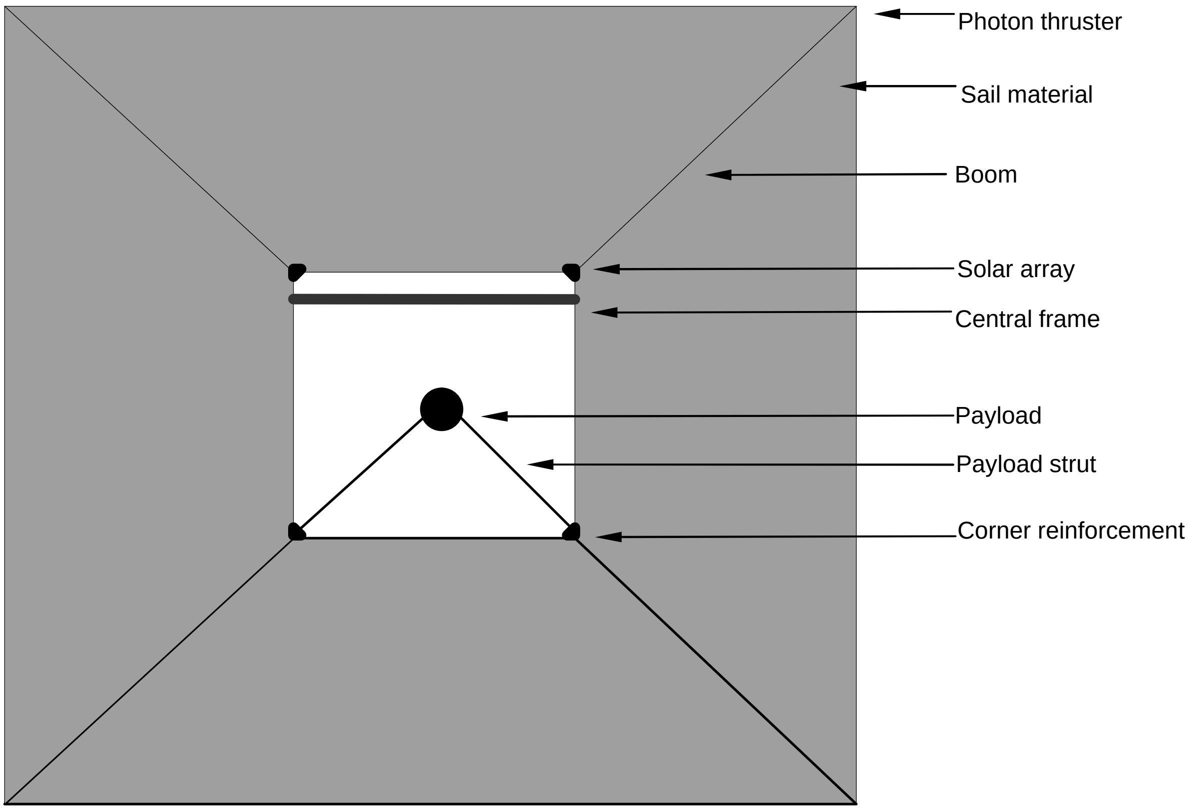
It is hypothesised that meteoric dust may collect at these stable Lagrange points. A kite can perform a slow flyby during which its camera can detect particles down to < 1 micrometer in size. The size and mass of any particles detected can be inferred from (1) their apparent speed and (2) their tendency to be accelerated by reflected light from the kite's surface.

5.6 Dust sample return

Due to its small size and low mass per unit area, a kite is intrinsically able to re-enter the Earth's atmosphere at relatively modest temperatures and g-forces (~230^{o}C, 10 g). An otherwise unmodified kite with a Kapton sail should be able to return a dust sample to soft landing on Earth.

6. Kite design

A concept for the design of a solar kite is shown in below. The central rectangular frame is rigid; the four diagonal booms unfold on hinges to deploy the sail fabric. Total mass is 400-500 gm, of which most is in the central payload. Sail area ranges from about 4.7 to 10 m^2 (depending on the height of the available microsat bay), giving a peak solar acceleration in the range 0.1-0.2 mm/sec^2.



Solar Kite Schematic

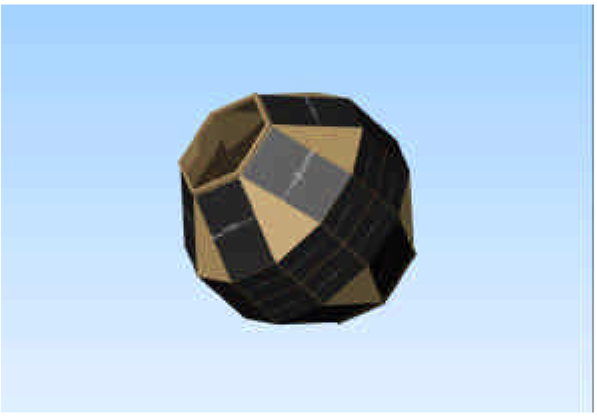
The solar kite component list/mass budget is as follows:

Item	Unit mass	Number/amount	Mass (g)
Solar Kite			
CFE rod, ø 2mm	5.6 g/m	7.44 m	42
PET film, 2 µm	2.87 g/m^2	4.70 m^2	14
Boeing Spectrolab thin film solar cells	84 mg/cm^2	360 cm^2	36
Dural rod, ø 2mm	8.8 g/m	1.06 m	10
STEM hinges/reinforcement	2.5 g	4	10
Wiring	10 g	1	10
Heated wire photon emitter	4 g	4	16
		Solar Kite Sub-Total	138
Payload module			
Wiring, circuit board incl. power conditioning, battery	25 g (estd.)	1	25
Boeing Spectrolab thin film solar cells	84 mg/cm^2	360 cm^2	36
Uppsala OBDH electronics module	25 g each	1	25
Fillfactory STAR250 CMOS APS CCD	30 g each	2	60
Radio transceiver	40 g	1	40
Optics and structure	30 g per imager	2	60
Piezoelectric drivers	2 g	2	4
		Payload module sub-total	250 + 20% structural allowance = 300 g
		TOTAL	438 g

Two particular advantages of the open central frame design relate to power generation and the thermal environment of the central payload.

Mounted within the central 'hole', the central payload does not have sunlight reflected onto it by the sail, even at high angles of inclination. Nor is it ever shadowed by the sail, and it is free to reradiate heat into space in every direction. Thus it remains at a relatively constant temperature. Thermal analysis has confirmed that the central payload temperature remains within acceptable bounds even during eclipse by Earth, and during close approaches to the sunlit lunar surface.

The central payload is set within a roughly spherical cage of solar cells which generate an orientation-independent 2W at all times when the kite is not in eclipse, maintaining a constant voltage to the on-board data handling (OBDH) system and cameras. The open central frame provides support for a further unidirectional strip of cells which generate an additional 10 W when the kite is face-on to the Sun, allowing data to be transmitted at a relatively high rate.



Central Payload Solar Cell Cage

7. Kite launch/deployment system

A pallet system has been designed which would allow two kites to be accommodated within a single ASAP-5 microsat payload bay. The two folded kites are stowed in two identical facing pallets which are initially latched together. Each pallet consists of a hard outer case with a foam-filled interior. The folded kites are pinioned in the plane between the pallets by the pressure of the foam.

The pallet system is jettisoned from the ASAP-5 by the standard mechanism provided by Arianespace: on reaching a safe distance, the pallet separates into two symmetrical halves, from which each kite subsequently deploys independently. The low density of the pallets ensures that they rapidly suffer atmospheric re-entry, so that the kite deployment system does not contribute to long term space debris

This system reduces the launch cost to about €1 million per kite.

8. Kite Attitude and Orbit Control System

The kite detects its orientation and position using a wide-angle STAR-based camera. The kite periodically transmits to ground control a small data package giving the pixel positions and brightnesses of the brightest stars currently visible to this camera; ground control works out the actual orientation of the kite, and tells the kite which pair of stars to use for attitude tracking, with a list of the pixel addresses at which they should be located at each subsequent time interval. The kite then tracks these stars continuously, without the need for either a starfield recognition algorithm or further communication with the ground. This minimizes the intelligence required on the kite, while also keeping ground monitoring and data transmission to a minimum.

The attitude actuation system involves three elements:

- Piezoelectric actuators which enable the payload position to be adjusted after initial deployment to compensate for any centre-of-mass/centre-of-pressure misalignment.
- Heating of the struts holding the central payload to adjust its position to induce a turn force by varying the centre-of-mass/centre-of-solar-pressure alignment.
- Photon thrusters at the sail corners which allow smaller but rapidly switchable 3-axis turn forces to be applied.

Analysis confirms that the sail can be controlled to better than the required accuracy by these means. The three mechanisms are provided to enable authoritative control while minimizing the power required for steering.

9. Kite data return capability

With the use of a 10 m diameter ground antenna, a kite can return 380 bits/sec from lunar distance (about one uncompressed image per two hours). Image transmission time at greater distances of course increases in proportion to the square of the distance. In the case of NEO flybys, it is anticipated that ~10 images per encounter would be transmitted over a subsequent period.

The kite transmitter has an output power of 2W. It does not use a standard transponder (which would be too heavy) but a lighter set of components drawn from current mobile communications technology. Space qualifying these components is the only significant research and development required for the kite project.

10. Kite performance and mission times

Analysis has established that a kite of performance 0.2 mm/s^2 starting from Ariane GTO can achieve any of lunar orbit, NEO flyby or Lagrange point rendezvous in about 300-500 days. It is anticipated that each kite will have a subsequent operational lifetime of several years.

In the lunar case, the kite will remain in a high-apolune/low-perilune orbit, inclined so as to avoid eclipse, but continually varying the position of the perilune point in a controlled way. Over its lifetime it can return high-resolution images of many selected points on the lunar surface.

In the NEO flyby case, the kite will typically loiter in the vicinity of Earth, but repositioning itself for flybys of several different NEOs during its lifetime. This strategy allows data to be returned at a reasonable rate by minimizing the transmission range.

In the Lagrange point case, the kite might subsequently proceed on another mission, or conceivably return to Earth with a captured dust sample: the kite's low areal mass will allow it to re-enter Earth's atmosphere at a comparatively modest temperature.

11. Recommendations

The following research and development tasks need to be performed before kites become a flight-ready technology:

1. Identify components from current generation of mobile communications technology which can withstand space conditions, including radiation to ~1 krad.

2. Develop and test flight control software, for use on the kite itself and at the ground control end. This could be done in a university environment to minimize costs.

12. Conclusions

Kites could be developed and launched within a short timescale, 3 - 4 years. They could provide a variety of extremely valuable scientific returns, with high public outreach appeal, at low cost and with surprisingly compact mission times.

The only significant research and development involved would be space-rating mobile communications components for use on kites. However the results of this investigation would be potentially useful to all other projects using micro- and nano- spacecraft.

A kite development project would be an extremely effective way to further the development of small low-cost spacecraft capable of scientifically useful work.