A Solar Kite Mission to Study the Earth's Magneto-tail

Lappas, V.
Surrey Space Centre, University of Surrey, Guildford, Surrey, GU2 7XH, UK

Wie, B.
Arizona State University, Tempe, AZ 85287, USA

McInnes, C.
University of Glasgow, Glasgow, G12 8QQ, UK

Tarabini, L.
GMV S.A. C/Isaac Newton, Cantos, 28760 Madrid, Spain

Gomes, L
Surrey Satellite Technology Ltd, Guildford, Surrey, GU2 7NE, UK

and

Wallace, K.
ESA, ESTEC, Noordwijk, The Netherlands

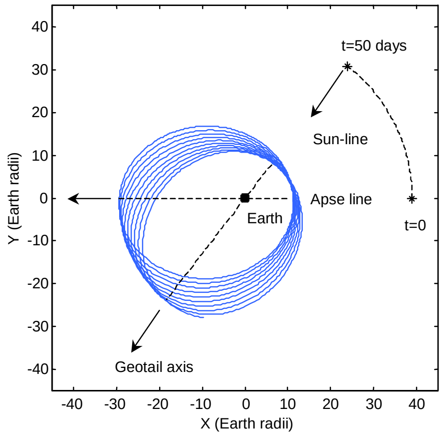
Abstract: Solar sails have been studied in the past as an alternative means of propulsion for spacecraft. Recent advances in solar sail technology and the miniaturisation of technology can drive these systems much smaller (< 5 kg mass, < 10 m sail diameter) than existing sails, while still having a high delta-V and acceleration capability. With these unique capabilities of miniature solar sails, called solar kites, some very unique space science missions can be achieved which are difficult to be implemented using conventional propulsion techniques. One such unique candidate mission is to study the Earth's magneto-tail. The paper lays out the main design features and technologies of a solar kite mission/platform and demonstrates that a cluster of solar kites with science payloads can provide multiple, in-situ measurements of the dynamic evolution of energetic particle distributions of the rotating geomagnetic tail of Earth. With a unique design, a solar kite proves to be an efficient, affordable and versatile solution for the mission analysed with a significant science return.

1.0 Introduction

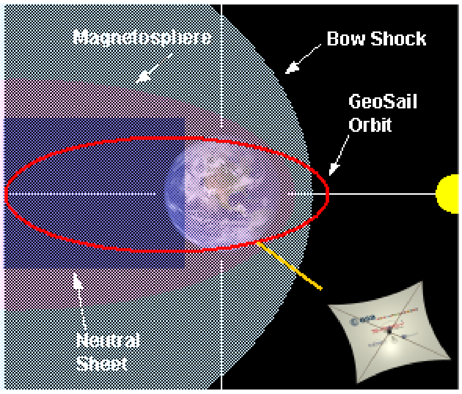
Many scientists in the space community have studied the idea to use solar pressure as 'wind' to propel a spacecraft, similar to a sailboat, to the far edges of our solar system. Most of the studies done to date assume that the largest obstacle in solar sail (SS) missions is the required development of the necessary solar sail specific technologies such as membranes, large stiff and light booms and pointing mechanisms, which is partly true. Adapting an ultra-miniature, agile, low cost and simple solar sail (nano-sail or solar kites-SK), it is possible to avoid to a large extent the technical challenges of large sailcraft whilst maintaining the benefits, most importantly an efficient and high ΔV capability. Using COTS technologies (including solar sail specific technologies available), it is possible to develop and demonstrate the principles of a smaller solar sail and still having significant and practical scientific return. Similar to the small satellite-engineering paradigm, a similar approach can be used in the larger versus small solar sails (solar kites). A 1.75 kg (2.275 with 30% margin), 5 x 5 m SK is proposed using COTS technologies with a 2-year lifetime. The case study mission selected is a mission to study the Earth's geo-tail. A constellation of 35-40 SKs is used to artificially precess the apse-line of 11 x 23 Earth radii orbit, thus stationing a fleet of miniature science payloads permanently within the geomagnetic tail and so providing continuous science returns.

2.0 Proposed Mission

The geomagnetic tail around Earth poses an important scientific problem related to weather conditions on Earth. There are a number of missions studied to date which focus on using a high number of nanosatellites (up to 100) for continuous multipoint measuring of the field. Conventional geomagnetic tail missions require a spacecraft to be injected into a long elliptical orbit to explore the length of the geomagnetic tail. However, since the orbit is inertially fixed, and the geomagnetic tail points along the Sun-Earth line, the apse line of the orbit is precisely aligned with the geomagnetic tail only once every year. Approximately 4 months of data can be acquired, with only 1 month of accurate data from the tail axis. To artificially precess the apse line of the elliptical orbit to keep the spacecraft in the geomagnetic tail during the entire year would be prohibitive using chemical propulsion. A scientifically interesting 11 x 23 Earth radii elliptical orbit would require a ΔV of the order 3.5 km/s per year of operation for apse line rotation. A perigee at 11 Earth radii meets the bow shock, while an apogee at 23 Earth radii is optimum to observe magnetic reconnection in-situ. Although the ΔV for apse line rotation is large, only a small acceleration continuously directed along the apse line is in principle necessary. For a solar sail, a characteristic acceleration of 0.11 mm/s^2 is required for an 11 x 23 Earth radii orbit. Since the precession of the apse line of the orbit is chosen to match that of the Sun-line, the sail normal can be directed along the Sun-line. This has significant operational advantages since such a Sun facing attitude can be achieved passively. A SK is used to



(a)



(b)

Figure 1: (a) Evolution of Elliptical Orbit at ~1 deg/day (b) SK Geosail Orbit

artificially precess the apse-line of 11 x 23 Earth radii orbit, stationing a miniature science payload permanently within the geomagnetic tail and so providing continuous science returns. Using multiple solar kites (~35), the entire geomagnetic tail could be populated by sensors which precess with the annual rotation of the geomagnetic tail, allowing real-time visualisation of the 3D plasma structure of the geomagnetic tail. Such a real-time visualisation would provide insight into the fundamental plasma physics of the geomagnetic tail [1].

2.1 Mission Analysis

In order to showcase the potential advantages of SKs and sailcraft in general, a comparison is presented of sailcraft and specifically a SK with other propulsion techniques for the Geosail mission. To perform the comparison with different types of propulsion, two types are used: Solar Electric Propulsion (SEP), Chemical propulsion, represented by a generic motor. The main inputs for the analysis are the total required ΔV and the acceleration. Since the bus platform mass is limited to 1.5kg (as this is the mass of the SK concept), and the characteristics of the sail and associated structure are pre-defined, the characteristics of the required sail can be obtained. The targets are presented in the following table:

SK Desired Characteristics	
Total ΔV (km/s)	3.5
Acceleration (m/s^2)	1.11E-04
Bus and P/L Mass (kg)	1.5

Table 1 - Targets for the GeoSail Mission

SK Sizing Parameters	
Solar Sail Mass (Ms)	0.235 kg
Total Mass	1.735 kg
Total Mass (+contingency)	2.256 kg
Sail Area	23.814 m^2
Sail Side	4.88 m
Sail Film Mass (m_f)	0.071 kg
Mass of Booms	0.137 kg
Mass of Mechanisms	0.027 kg
Sail Structure Mass (m_b)	0.164 kg

Table 2 - Solar Sail Performance

To reach the targets of the mission, the solar sail propulsion system would have to have the characteristics of Table 2. For the comparison with chemical and SEP, some assumptions need to be made. I_{SP} is the specific impulse for the propulsion system used (typical values of 300 s for chemical propulsion and 3300 s for

SEP are used throughout). If the assumption of a thrust to mass ratio of 625 is made, or for example, a 1 mN thruster is used, then the mass of the propulsion system will be 1.6 kg. In the case of chemical propulsion, it was estimated that for a low propulsion system total mass (propulsion system + propellant) the propellant mass is 2/3 of the total mass. For higher propulsion system total masses (> 20 kg) it is assumed that the propellant mass is 90% of the total mass. This heuristic approach is based on current and future SSTL missions. For an SEP system:

SEP Platform	
Mass of Propellant	0.354 kg
Mass of Motor	1.6 kg
Mass of Solar Panels	N/A
Total Mass	3.454 kg
Total Mass (+contingency)	4.490 kg

Table 3 - SEP Performance

The thrust selected for this engine is of 1mN, much higher than required for the mission acceleration, but it is not desirable to go below this value. The above assumptions assume that SEP technology is available for such small thrust, mass and power levels. The use of a chemical system is not realistic in this case as the total mass of the mission is likely to reach something in the order of 22 kg. In Figure 2 the comparison between the extra mass required by the solar sail and the SEP (not require contingency) is presented.

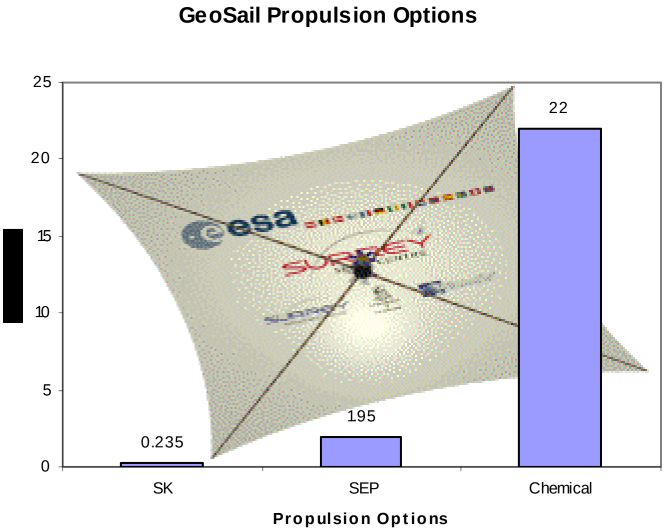


Figure 2 – SK Propulsion Extra Mass Required

The mass advantage of a mission based on the SK concept is evident, and in this case, since the duration of the mission is fixed there is no disadvantage due to the long time spans involved.

2.2 Payloads

The SK has a space science objective, to study the geomagnetic tail, allowing phenomena such as magnetic reconnection to be studied in-situ. The goal is to use a constellation of multiple solar kites (~35), thus the entire geomagnetic tail could be populated by sensors which precess with the annual rotation of the geomagnetic tail, allowing real-time visualisation of the 3D plasma structure of the geomagnetic tail. Such a real-time visualisation would provide insight into the fundamental plasma physics of the geomagnetic tail. The large number of SK can allow using different configurations of payload suites. For example if a constellation (~35) of SK's is used to study the earth's magnetic tail, most of them can carry magnetometers and plasma detectors but a small number can carry space dust detectors to complement and maximise the science return from the mission. The suggested ultra miniature payloads are presented in the following Table.

Payload	Science	Mass (kg)	Power (W)	Comm's (kbps)
Mag/meter	Earth/Planet Magnetic Fields	< 100 g	< 0.5 W	< 2 kbps
PIE Detector	Proton/Ion Detection	~ 400g	< 2W	< 28 kbps
Plasma Det/or	Plasma Bubbles	< 300g	< 2W	0.03 kbps
Env. Sensors	Space dust	< 50g	<0.2W	< 0.03kbps

Table 4: SK Candidate Payloads

3.0 SK Design

Reviewing existing solar sail technologies it is determined that a realistic assumption to begin designing a sailcraft is to use a Sail Assembly Loading (SAL) factor of 10 g/m^2. This value depends on the availability of solar sail technology. The SAL is defined as:

$$SAL = \frac{\text{Mass of Sail Structure}}{\text{Solar Sail Area}} = \frac{m_s}{A} \qquad (1)$$

Using Eq. (1) and some initial condition values such as the dimensions of the solar sail, one can deduce the design parameters of the SK: For a square sail of 5 m x 5 m, A = 25 m^2 and using Eq. (1) and the given SAL the mass of the sail structure m_s becomes m_s = 0.25 kg. The boom-sail structure has a 4 cm diameter and a length of L = 3.535 m. The mass of the film used is m_f = 0.05 kg. The mass of the SK platform including the platform subsystems and payloads is assumed to have a mass of m_{bus} = 1.5 kg or less. The mass of the bus, solar sail area and SAL are noted to be key in the design of the SK. Using the values above it is then deduced: For a SRP constant of P = 4.536 x 10^{-6} N/m^2 and a thrust coefficient η = 1.8, the maximum thrust of the SK is $F_{max} = \eta PA$ = 2.04 x 10^{-4} N. Then the area-to-mass ratio $r_{a/m}$ is 10 m^2/kg and the areal density $\sigma = m/A$ = 0.1 kg/m^2. The acceleration is then:

$$a_c = \frac{F_{\max}}{m} = \frac{\eta PA}{m} = \frac{\eta P}{\sigma} = 1.2 \times 10^{-4}\,\mathrm{ms}^{-2} \qquad (2)$$

The value for the acceleration of the SK is comparable to those for other sail missions currently under design. All values derived are summarised in Table 5. The acceleration calculated is able to produce the required acceleration of 1.1 x 10^{-4} m/s^2.

Solar Kite Parameters	Values
Sail film + Booms +Depl. Mech.	0.2 kg
Length of Booms L	3.535 m
Bus/Payload m_{bus}	1.5 kg
Total mass $m_{s/c}$	1.75 kg
Sail Area A	25 m^2
Thrust Coefficient η	1.8
Acceleration a_c	0.12 mms^{-2}

Table 5: Solar Kite Characteristics

3.1 SK Technology, State-of-the-Art
3.1.1 Solar Sail Booms

The analysis of existing and future developments on solar sail boom technology has led to a number of important conclusions:

1. The mass per length ratio for the booms is a critical, mission enabling factor
2. Conventional and current boom technologies can't be scaled down to an SK scale (3.535 m boom) and preliminary analysis indicated that this technology has a use threshold for solar sails of > 20 m
3. Sails of < 20 m will require mass per length ratio (specific mass) < 60 g/m
4. Deployment of solar sail booms is complex and has been analysed for large (> 40 m sails), making this technology difficult to implement on a SK
5. SK will need a simple, ultra light sail with a smaller life time from large sails

A SK with a 3.535 m boom will need to be a simple and optimised design to a 1.75 kg spacecraft mass. The small size of the boom can prove instrumental in this in that a simpler, less complex boom can be manufactured and deployed compared to existing 40 m booms with multiple motors, pulleys, supports that add risks to the sail design, mass overheads and complexity [2]. A semi-active deployed boom is proposed consisting of rigidized inflatable material with an integrated sail to the booms and with a simultaneous boom and sail deployment. This integrated approach brings significant mass/volume savings as well as a simple deployment strategy for the SK sail.

3.1.2 Solar Sail Membranes

Sail film and supporting structure technologies play a key role for the realisation of solar sail design concepts. Ultra-thin film of the order of 1-2 micrometer of polyimid basis have already been manufactured under laboratory conditions. This is an advantage for SK, since producing limited quantities in lab conditions is sufficient. The SK sail membrane is a 0.9

micrometer polymid based film, which is based on the DuPont polymid membrane. A similar version (1 μm) is used in the L'Garde solar sail mission [4].

3.2 SK Inflatable Sail/Booms

The main design requirements are the 5 m length of the SK sail, compact packaging, simplicity and robustness of deployment and a < 60 g/m mass per length factor. The most optimum material able to achieve this are rigidized inflatable structures. The SK team has chosen to use an integrated approach for the SK boom-sail film-deployment design. In this design the sail film/membrane is integrated with the booms. Deployment is achieved using an inflating gas. This integrated semi-active approach is able to bring significant savings in mass, volume and power to the SK, not requiring motors, extra electronics, pulleys or complicated mechanical structures for boom deployment [3]. The two biggest advantages of using the inflatable rigidized boom/sail are the high density packaging capability and the < 60 g/m mass per length factor. The SK rigidized boom is blended with the 1 μm sail film. A 4 cm diameter boom is able to provide the necessary structural rigidity of 200 MPa pressure needed to sustain various loads in space, as analyzed in various inflatable structures currently in design, including margins. Many institutions are working on the development of rigidisable inflatable structures with promising results. Nihon University has conducted experimental tests completed in microgravity conditions of a 1 m inflatable boom [8]. The goal in the Nihon experiments is to demonstrate inflatable technology using a 1 kg cubesat The only shortcoming of this technology is the need to completely study the phenomenon of wrinkles, an issue still researched for conventional sails. Deployment is achieved by two miniature valves, identical to the propulsion valves used in the SK ADCS system. A 9 g gas will inflate the structure and be able to provide continuous pressure for a minimum 2 year lifetime of the SK. The calculated volume for the SK boom/sail structure is the smallest possible since storage for the integrated 'structure' is much more compact and lighter than using a traditional CFRP design.

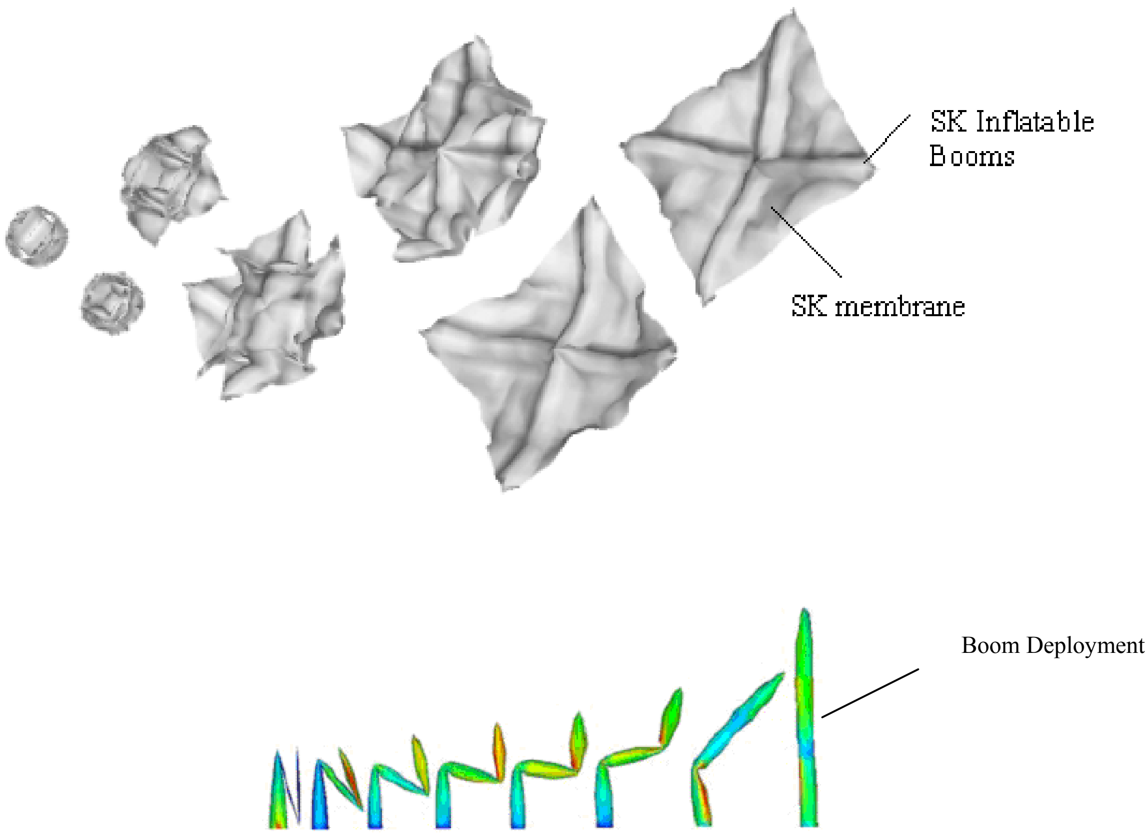


Figure 3: SK Booms, Sail and Deployment (Nihon Concept)

The technology readiness of the suggested technology, is at TRL 4 (i.e flown in space but in need of modification, customisation or optimisation for specific application) for inflatable structures and 5 for rigidized structures. Using the suggested sail-boom-deployment concept with the specified parameters above (4 cm boom diameter, 3.535 m length) the mass breakdown using the three available technologies (CFRP, coilable, inflatable) is depicted in the table below. The inflatable option provides significant savings in mass and volume on the overall SK design. A CFRP option is too large for a SK mainly due to its large mass/boom meter ratio and deployment mechanism. A coilable option is close to the 2.5 kg mass requirement though it comes with a high level of complexity in deployment. Minimum storage and an efficient ultra low mass/length ratio makes the inflatable option in its integrated design a mission enabling technology, with most of its technology available or tested.

SK Sail/Boom Parameters	CFRP (kg)	Coilable (kg)	Inflatable (kg)
Sail film m_f	0.05	0.05	0.05
Booms (4) m_b	0.34	0.25	0.10
Deployment Mechanism	0.1	0.1	0.1
Total	0.49	0.4	0.25

Table 6: SK Sail/Boom Technologies

3.3 SK Sail/Boom Deployment

The sail-boom integrated structure is deployed with a gas based inflation system. The inflation system is a continuous inflation system consisting of two simple gas valves slightly modified from the ultra miniature resistojet thruster used in the SK ADCS system. The system contains two valves, one per boom (two booms). A small gas tank in a ring configuration is used split in two parts, one side containing Helium and the other sealed side containing low-pressure liquid hydrazine (LHZ). The Helium gas is initially used for inflation of the sail/boom structure and then LHZ is used as a 'make-up gas' to continuously keep the inflated structure rigid. Hardening strips are also used with a special curing coating to assist a fast curing process when the SK sail is deployed and points to the sun.

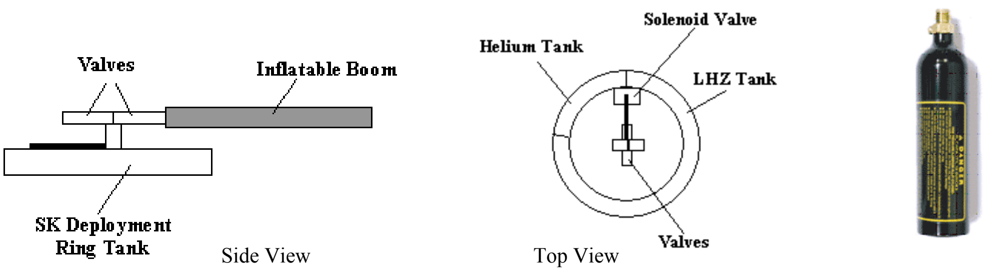
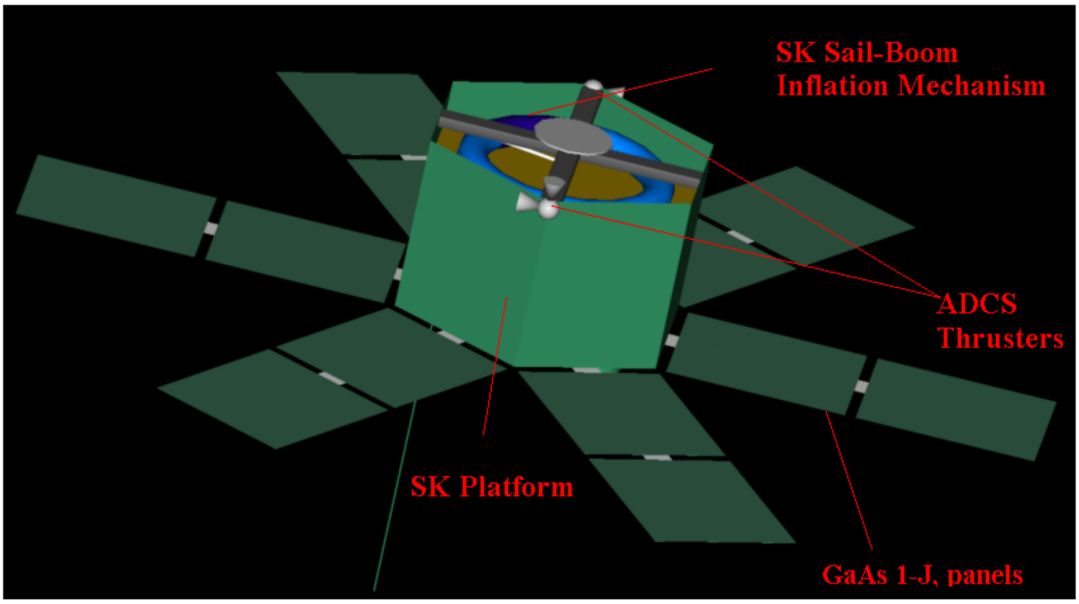


Figure 4: SK Sail/Boom Deployment Mechanism

A COTS canister has been proposed for similar applications and has been proposed to be 2.6 cm long, 0.8 cm in diameter, and have a volume of 8.2 cm^3, if using a Helium gas. The helium in the canister will be stored at 60.5 psi. Once the helium is released from the canister at 0.15 cm^3 per second, it will take five minutes for the canister to extinguish the helium supply. This will leave a final pressure in the canister of 0.5 psi. The SK will have a two-year lifetime and the LHZ required maintaining two inflatable booms (two diagonal) is calculated to be 15 g. With two valves and a spiral miniature tank made out of aluminum, the system will weigh 90 g. With such a small mass the deployment mechanism is to small to consider for ejection (if it was not necessary for use) and besides its task to inflate-deploy the sail/booms with helium it is needed to maintain the booms and sail rigid and deployed throughout its lifetime. Two pressure valves will be used to measure the gas pressure in the two SK booms and since related to the rigidity of the sail will be used to feed small amounts of LHZ when needed. Hardening strips are a new technology that will be used to assist making the SK a permanently rigid square sail after the sail has been deployed. It is necessary to make sure that the sail remains as rigid as possible in order to have maximum performance. The hardening strips to be used will consist of a tape-like substance that has the unique property that the tape will remain pliable and tape-like until it is exposed to solar radiation. When the strips are exposed to solar radiation, they will begin to harden and will permanently cure in approximately 15 minutes. The hardening strips will be placed on the solar sail in a spider web pattern and along the outer edges to minimize any warping or shape changing of the sail after deployment.

3.3 SK Platform

The SK consists of two parts: the SK structure and the SK platform (Figure 5). The SK platform uses as a basis the Surrey Palmsat 1 kg platform. However, the platform is tailored to the SK requirements and mission requirements. The 'bus' is a 6 x 9.5 cm hexagon structure made out of carbon-fibre and aluminum honeycomb structure machined carefully to save mass. The dimensions of the sail are 5 x 5 m with 3.535 inflatable booms integrated with the sail membrane in order to use a single deployment mechanism to save mass again. The thrusters are mounted as such as to be used both in SK sail-boom stored and deployed configuration for SK stabilisation, commissioning and operations. The SK uses three thrusters in a 1 pair plus single thruster configuration. The pair of thrusters are mounted opposite and anti-parallel to each other for spin-up and spin maintenance operations and the third thruster is used for precession.



Subsystem	Mass	Power
Payload	500 g	1.5 W
OBC	150 g	1.5 W
RF System	280 g	5 W
ADCS	220 g	1.1 W
Power	150 g	0.5 W
SK Sail/Boom	200	1.0 W
SK Structure	250 g	-
TOTAL	1750 g	10.6 W
Margin (30%)	525 g	3.18 W
SK Total	2275 g	13.78 W

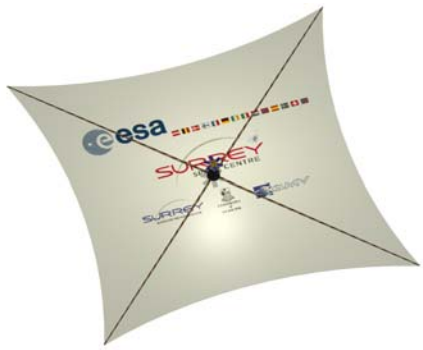
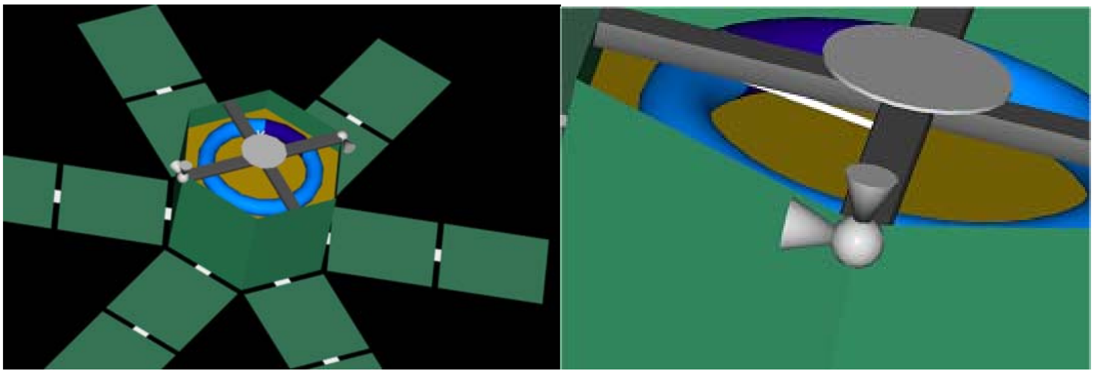


Figure 5: SK Platform and Sail-Booms Stored, Mass-Power Breakdown

The thrusters use miniature boards with a battery, solar array (1 x 1 cm) and a communication system based on Bluetooth, based on a distributed wireless link. The SK after being ejected from the launcher or transfer vehicle via SMA bolts and pre-tensioned springs, will switch on its power subsystem and de-tumble using the ADCS thrusters. Having established an RF link with the ground station, the SK will start to deploy its integrated sail-boom structure in less than seven minutes using a stored helium gas.



(a) (b)

Figure 6: (a) Internal View of the SK Sail-Boom Compartment (Membrane is Hidden) (b) SK ADCS Thrusters (Membrane is Hidden)

Figure 6 (a) details the internal view of the SK sail-boom compartment. The inflation gas ring tank is split into two parts one for the helium inflation gas and the other for the 'make up' LHZ gas. Figure 6 (b) details the SK ADCS thrusters when the SK sail-boom is stowed. The thrusters are mechanically fixed in their 'stowed' position and when the sail-boom inflates the tips of the sail-boom structure are freed from that position and move freely.

3.3.1 SK Attitude Determination and Control System

The SK ADCS system is considered with the RF system to be the most challenging mainly due to the technology needed as well as due to the complex nature of controlling large structures in space. The requirements for the SK ADCS system are presented in Table 7. Due to the 'affordable' payload pointing requirements of ~ 1 deg and due to the need to have a simple, light and robust ADCS system the team has selected a spin control scheme utilizing thrusters. Three thrusters are used mounted on the tips of the two booms: a pair of thrusters, one thruster anti-parallel to the other (diagonally) used for spin-up and spin maintenance of the SK and a third thruster placed perpendicular to one of the parallel thrusters, for precession. Attitude determination is done via a MEMS low power gyro, a star sensor based on an ultra miniature CMOS camera and a magnetometer used as a science payload as well.

Parameters	**Values**
Moments of inertia	(1.113, 0.556, 0.556) kg-m^2
cm-cp offset	0.01 m (0.2% of 5 meter)
SRP Thrust	0.2 mN
SRP Disturbance torque	2 microN-m
Angular momentum storage/dumping	0.0072 N-m-s / hour
Payload pointing accuracy	1˚

Table 7: SK ADCS Parameters

The SK thruster will utilise a modified valve designed by Lee Products which is ~6 mm diameter x 33 mm long, is rated to 375 psi (25Bar) has a mass of less than 6 g with an expected average draw power of 0.2 W. The EPSV valve is shown below:

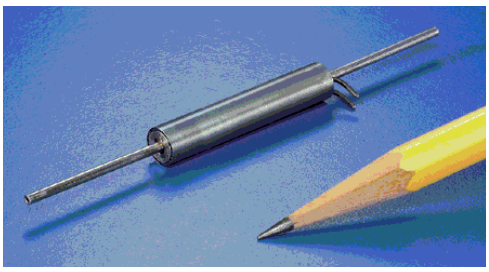


Figure 7: SK Thruster Valve

Component	**SK Thruster (mass, g)**
Propellant	Water (8g + 2g propellant management device)
Propellant tank	Ti tube as per SNAP-1, 180mm long, (~8g)
Thruster & isolation valves	The Lee Co. EPSV solenoid valves (~10g/pair)
Control electronics	SSTL board or ASIC (<10 g)
Structure	Integrated to SK structure
Total mass (g)	<50g

Table 8: SK Thruster Specifications

For a 1 deg pointing requirement and a 0.2-mN solar pressure force, a spin rate of Ω = 1.2 deg/s is needed. For the required SK/thruster parameters, the propellant mass is 7.5 g per thruster. Simulations conducted for the SK indicate that the required control and stabilisation requirements are feasible.

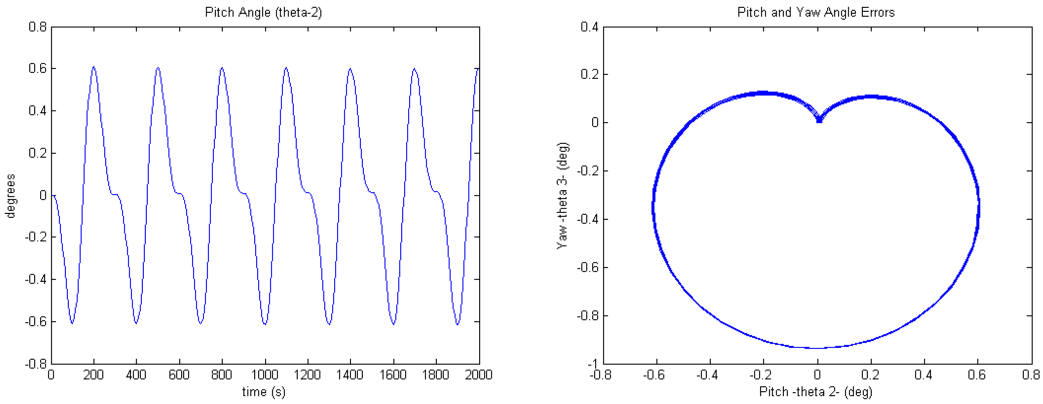


Figure 8: Simulation Results for a cm/cp offset of 0.01 m

3.3.2 SK Power System

During eclipse, the battery capacity is the limiting factor of the spacecraft design as it limits the operation time in eclipse. This is almost independent of the power generation capability of the spacecraft, and so the selection of the batteries is critical. The intention is to run the bus at as low a voltage as possible, thus reducing the requirements on the solar cells, but the minimum voltage is defined by the requirements of the other subsystems that need to run from the power bus. In order to progress the analysis, an overall efficiency of the power system was estimated at 80%, compatible with current small satellite power subsystem technology. The battery technology is also to be chosen in a future iteration as this will depend on what is available on the market at the time of implementation of the mission, since COTS technology is the baseline for this mission. Nevertheless the preference would be to use Li-Ion or Li Ion Polymer batteries. For the solar panels, several possible configurations have been analysed, in order to take into consideration the advances in cell technology that will take place until the mission is launched. For instance, at this moment in time, it is possible to procure GaAs 1-J (single junction) cells in sizes of 4cm x 2xm, 4cm x 4cm and 4cm x 6cm (there are other formats but these are the usual in space applications for small spacecraft). The new generation of cells though is likely to be available mainly in the 4cm x 8cm format, what means that if the solar panels have a dimension of 6cm x 9.5cm, each one of them can support one single cell, and so a design for the future, should be based on the 4x8 dimensions. Furthermore, it is likely that in the next few years, three and four junction GaAs cells become available at a cost compatible with small missions, and these will have a much higher efficiency than the current single junction cells. This is illustrated in the figure where the power generation capability of the mission for different technologies and configurations was plotted:

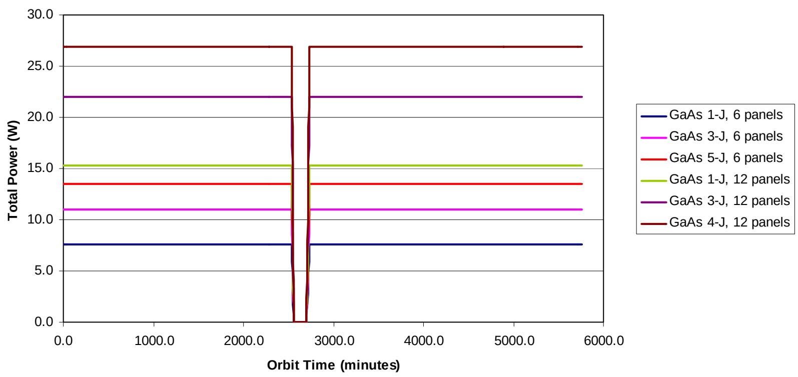


Figure 9: Orbit Power Profile

A 4 junction 6-panel configuration was chosen in the analysis, although in practice this could be replaced by a 1-junction 12 panel configuration.

3.3.3 SK RF

The availability of hardware for implementing the RF subsystem is a key concern as the SK mission will require, small low mass and low power subsystems, while at the same time trying to keep costs as low as possible. Like in the other subsystems, COTS components and units are preferred, but even in this category it is not likely that the required type of components and units is readily available, and hence it will be necessary to do some development work. Currently, it is possible to find on the computer hardware market, small PCMCIA sized WiFi devices that feature a full S-band transceiver, including in some cases a 0.5 W power amplifier. Such a technology would be ideally suited for the SK mission, but the main problem is that both the transmitter exciter and the receiver would need to be tailored to the needs of the SK mission, namely the type of modulation and the protocols used. As a baseline, in this study a, S-band 0.5 W transmitter is assumed and a S-band receiver is also assumed. A PSK modulation is assumed, although it should be noted that many COTS transceivers work on code modulation schemes, and a major alteration of the design would be required. To allow an initial design to progress, the baseline uplink data rate was selected as 9600 bps, for mainly two reasons:

- This is the typical uplink rate used by SSTL on its missions, and has shown to be enough for the usual operations of micro and nano-satellites. These include all the housekeeping tasks and software uploads required over the lifetime of the missions.
- Design of equipment for this rate is in general straightforward.

On the downlink side, the baseline at this stage, is to use a 38 k4 (38400bps) data rate, for the following reasons:

- Allows a fair amount of data to be downloaded. For instance, considering a link efficiency of 80% (which depends on many factors, including the type of packet used), it should be possible to downlink a total of 105 Mbit (approximately 13 Mbyte) of information; by contrast, a payload generating a 16 bit word every second during a full orbit, will only generate a total of 5.2 Mbit of data.
- Preliminary calculations indicate that it is possible to achieve it with a low requirement of power, important in a mission with a very limited power supply.
- It is a useful and easy to implement data rate, that is regularly used by SSTL on its missions.

A highly elliptical orbit such as the one selected for the SK, mission causes a large difference in the free path loss between perigee and apogee. The ground station assumed is one with an 11 m dish. This was chosen has an example and is not representative of any specific ground-station. Similarly, the RF power of the ground-station was set at 200 W, but in most ground-stations it should be possible to increase this if necessary. The link margin is possible to be calculated for the apogee, which in the case of the SK mission is at 23 Earth radii. This means that at this point the minimum range will be 140400 km. At this range, the free path losses are substantially higher than at perigee and the margin of the link budget can be expected to be lower.

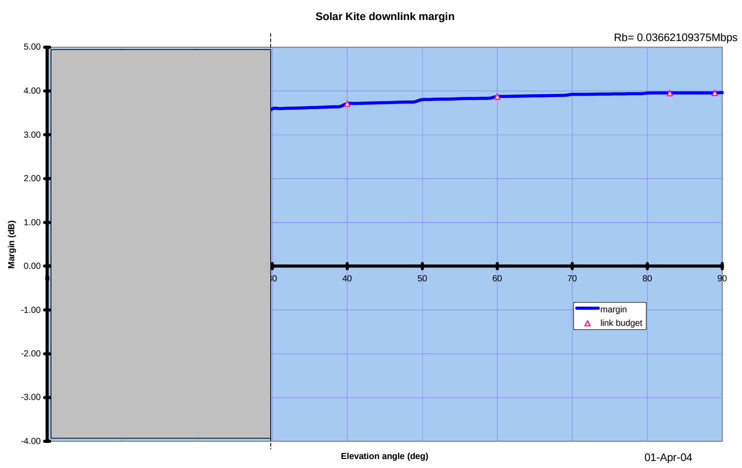


Figure 10: SK Downlink Margin at Apogee

In the downlink case for example, the margin is small and just about what is ideal (+3 dB to be safe). Although this margin is reasonable and should allow the implementation of the mission, with a RF solution that works, any changes such as not using RS coding or reducing the transmitter power are likely to have a major impact on the link margin.

4.0 Launch and Deployment

Surrey has worked on in-house transfer vehicles for such missions as the SK. A modified version of the Surrey Transfer Vehicle (STV) designed for the SK mission, will have a single 400 Newton, N_2O-HDPE Hybrid system based on the Daimler Benz S400/2. The STV-SK vehicle will have as a main requirement to take the SKs from a 580 x 35786 km and 7º inclination to the desired [(11x23) x Re] GeoSail orbit. The STV-SK vehicle will have to fit to an Ariane 5 ASAP mini-satellite space, which has a 150 cm diameter and 150 cm height, and the STV will need to achieve a 1400 m/s ΔV. For the selected Daimler Benz S400/2 engine with an *Isp* of 318 s, translates to 109 kg fuel. After some system design and analysis this leaves 80 kg for SKs (~35 SKs) and 111 kg for the STV-SK structure and subsystems. Surrey is currently analysing such a system to transfer SK's to the GeoSail orbit as part of a study to design a small satellite space weather-monitoring constellation for ESA.

5.0 Conclusions

Most of the studies done to date assume that the largest obstacle in solar sail (SS) missions is the required development of the necessary SS specific technologies such as membranes, large stiff and light booms and pointing mechanisms, which is partly true. One of the enabling factors though that make SS missions possible is the miniaturisation of the spacecraft bus, bringing the overall spacecraft mass down and thus enabling solar sails to materialize. A SK with a simple and robust design, equipped with niche scientific payloads can be a significant tool to space planners. It has become clear in the analysis designing a SK mission, that solar kites can provide a number of key advantages when compared to larger, more complicated and expensive solar sails:

- Complexity of solar sails can be reduced
- Sail deployment can potentially be simplified
- Ultra miniaturisation and MEMS technology increase sail acceleration
- Small size sails can use inflatable technology (ultra light) for sails < 7-10m
- Miniaturisation technology is near available
- Smaller spacecraft design times, multiple spacecraft available-constellations

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