JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 44, No. 4, July–August 2007

Microsolar Sails for Earth Magnetotail Monitoring

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DOI: 10.2514/1.23456

Solar sails have been studied in the past as an alternative means of propulsion for spacecraft. Recent advances in solar sail technology and the miniaturization of technology can drive these systems much smaller (<5 kg mass, <10 m sail diameter) than existing sails, while still having a high ΔV 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 implement using conventional propulsion techniques. One such unique candidate mission is to study the Earth's magnetotail. The paper describes 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 analyzed with a significant science return.

I. 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 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. Recent advances in microelectronics and solar sail technology have led to a new and more practical approach into designing nanosolar sails. Smaller solar sails with mast lengths less than 5–10 m can be easier to develop and manufacture. Adapting an ultraminiature, agile, low-cost, and simple solar sail [nanosail or solar kites (SK)], it is possible to avoid to a large extent the technical challenges of large sailcraft while maintaining the benefits, most importantly an efficient and high ΔV capability. Using commercial off-the-shelf (COTS) technologies (including solar sail specific technologies available), it is possible to develop and demonstrate the principles of a smaller solar sail, while still having significant and practical scientific return. Similar to the small satellite-engineering paradigm, a similar approach can be used in the larger vs smaller solar sails (solar kites).

Solar sails have been studied thoroughly in the past [1–7]. The principle of the work of a solar sail is simple: it is based on the fact that photons, coming from the sun, hit a particular area (surface) of some kind of thin film and propel this particular structure along with the rest of its components by imparting a small force. Although this force is relatively small compared with other propulsion methods, it still can be useful to propel spacecraft for long distances without carrying consumables (propellant). This translates into a significant mass reduction for the spacecraft and overall mission and an increase in payload mass. Another key advantage of solar sails is the buildup of acceleration, which can be significant, and which is ideal for high ΔV missions. The principle of solar sails has also been implemented as part of attitude/orbit control systems of spacecraft in a variety of space missions, especially communications satellites [4–7]. These satellites have used their large asymmetrical solar arrays to perform station-keeping tasks. INSAT, OTS, TELECOM 1 and INMARSAT 2 used the feature of windmill torques to create roll/yaw torques. Mariner 10 also used twisting solar panels to control its roll during its flight to Mercury resulting in major fuel savings [4–7].

Many missions have been considered in the literature for solar sails. One of the most recent proposals is a NASA study on developing a large solar sail for chasing comet Halley studied at Jet Propulsion Laboratory, California Institute of Technology in 1977 which required an 800×800 m solar sail for an 850 kg payload/bus and a solar sail mission in our solar system planned by the Team Encounter group [1,4,8]. Development of new solar sail technologies, small satellites, and microelectronics has led to a sustained effort on both sides of the Atlantic on developing key technologies for near-future solar sail missions, efforts mainly handled by NASA and ESA [1,4,8–16].

The Cosmos 1 solar sail mission of The Planetary Society, with two failed launches in 2002 and 2005, was to become the first experimental flight mission for solar sailing in an Earth-centered orbit. The sailcraft development for the Cosmos 1 mission was conducted in Russia [8].

A 76×76 m square sailcraft is currently under development by Team Encounter [9]. It is scheduled to be launched as a secondary payload on an Ariane 5 in 2006. A combination of passive and active

Received 24 February 2006; revision received 30 November 2006; accepted for publication 18 December 2006.

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attitude control techniques are employed for this 76×76 m square sailcraft. The Team Encounter sailcraft of a total mass of 18 kg is required to achieve solar system escape within 3–5 years. Its sun-pointing orientation is passively stabilized by means of "trim tabs." A spin-stabilized, 76×76 m square sailcraft was proposed for the New Millennium Program Space Technology 5 Geostorm warning mission, which would provide real-time monitoring of solar activity [4]. It would operate inside the $L1$ point of the sun-Earth system toward the sun and increase the warning time for geomagnetic storms compared with a vantage point closer to the Earth. A concept of articulating a two-axis gimbaled control boom was investigated for a 40×40 m square sailcraft proposed for the New Millennium Program Space Technology 7 sail flight validation experiment. This mission with a gimbaled control scheme (with thrust vector control) is detailed in Wie [4] with other control concepts, spin stabilization, control vane, and sailcraft using translating and/or tilting sail panels. In Murphy et al. [14] and Wie et al. [15] Able Engineering and Wie present a new robust and redundant attitude control scheme for three-axis sailcraft based on mass ballasts for yaw and pitch control sail tilting for roll axis control and micropulsed plasma thrusters placed on the tips of the sail. Leipold et al. [12] presents part of the European perspective in solar sail design. Kayser–Threde and DLR have demonstrated a number of key technologies for solar sails. A 20 m sail deployment has been achieved using carbon fiber reinforced polymer (CFRP) booms developed by DLR [12].

Besides the development of new solar sail technologies and control systems, new mission concepts have also been recently studied. McInnes et al. [16] presents the possibility of ejecting an 80 kg solar sail into an elliptic orbit to monitor the Earth's geomagnetic tail. Apse-line precession of the orbit is achieved using solar sail propulsion. This mission concept is the basis of the mission detailed in the present paper. Jack and Welch [17] first introduce the concept of ultraminiature solar sails or solar kites and examine the design of a solar sail with no moving parts and for mainly imaging missions around the Earth and the moon. Leipold et al. [18] detail a study to develop an interstellar probe based on a solar sail platform to reach a distance of 200 astronautical units (AU) in 25 years. After 6.5 years the sail is ejected having completed two photonic assist maneuvers around the sun. The spin-based platform equipped with a highly integrated payload suite will then operate autonomously to produce a three-dimensional mapping of the interstellar medium. Wie [19] details a novel mission concept based on solar sails used to impact and deflect asteroids that can potentially collide with Earth.

This paper details a novel mission concept based on solar kites. A constellation of 35–40 solar kites is used to artificially precess the apse line of 11×23 Earth radii orbit, thus stationing a fleet of miniature science payloads permanently within the geomagnetic tail and so providing continuous science returns. Multiple solar kites will enable real-time visualization of the three-dimensional plasma structure of the geomagnetic tail. Such a real-time visualization would provide insight into the fundamental plasma physics of the geomagnetic tail. The solar kite has a 1.75 kg mass (2.275 with 30% margin), with a 5×5 m sail and uses COTS technologies with a two-year lifetime. The paper is organized as follows: Sec. II presents the mission analysis for the geotail monitoring mission. A comparison is presented between different propulsion options (chemical, electric) and solar sails, and the comparison shows the advantage of using solar sail propulsion to place a 0.5 kg payload at the Earth's geotail. Section III details the trajectory used for the solar kites and the ability to efficiently artificially precess the apse line of the elliptical orbit in a sun-synchronous manner thus keeping the spacecraft in the geomagnetic tail for an entire year. The following section details the solar kite design with its platform and all subsystems. Launch and deployment of the constellation of solar kites is then briefly presented.

II. Mission Analysis

To compare different propulsion concepts, different simplified models for each propulsion scheme are required. The main inputs for the analysis are the total required ΔV and the acceleration. Because the bus platform mass is limited to 1.5 kg (as this is the initial mass of the solar kite), and the characteristics of the sail and associated structure are assumed to be predefined, the characteristics of the required sail can be obtained. The main expression used for the required area of the sail is

$$A = \frac{a_c m_{p+b}}{\eta P_s - a_c \sigma_f} \tag{1}$$

In this expression, A is the area of the sail required to achieve an acceleration a_c for the platform mass (including boom and sail structure but not the sail film) m_{p+b}. The sail is assumed to have an efficiency η (fixed at 1.8 for this analysis) and an area density of film σ_f, which was considered to be 3×10^{-3} kg/m^2. The parameter P_S is the solar radiation pressure as 1 AU, assumed to be constant (4.563×10^{-6} N/m^2), although this is not accurate for missions that leave the Earth vicinity. The calculation of the platform mass is based on a two-step iteration: first, a calculation of the mass of the sail is performed without including the mass of the sail structure and mechanisms; second, this value is used to estimate a mass for those elements and a new calculation is performed. Because this method is not very accurate and some parts of the structure are not accounted for, it was assumed that an engineering factor of two will be used and the value used is then double from the one estimated. The booms and other structures are calculated assuming a length density of 10^{-2} kg/m^{-1}, and used for estimating the length of booms. The same logic is used for calculating the mass of the mechanisms, m_m, used on the sail. For this analysis, a square sail is considered with four radial booms. An interesting aspect of Eq. (1) is that there is a limit to the acceleration that can be achieved for a given type of material, independently of the area of sail used:

$$a_c \leq \frac{\eta P_S}{\sigma_f} \tag{2}$$

This expression demonstrates the interest of reducing σ_f as much as possible (because $\eta < 2$ and P_S is limited). The mass of the required film is calculated using the simple relation

$$m_f = \sigma A \tag{3}$$

The total mass of the spacecraft is then given by

$$m_{\text{total}} = m_p + m_b + m_m + m_f \tag{4}$$

To perform the comparison with other propulsion systems, it is necessary to calculate what would be the required propulsion system characteristics. The two types of propulsion being considered beside solar sails are solar electric propulsion (SEP), mainly ion propulsion systems, and chemical subsystems. These units are typical in spacecraft design but no specific dimensioning was done for this case and only estimates are used on the analysis. In general, the required propellant mass to achieve a certain ΔV is given by

$$m_{\text{prop}} = (m_p + m_{\text{dry}})(e^{\Delta V / g I_{\text{SP}}} - 1) \tag{5}$$

where m_{dry} is the mass of the propulsion system when empty, m_p is the platform mass not including the propulsion system, 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). The total ΔV is calculated either from the requirements for the orbit transfer or from the acceleration requirements. The time it takes to achieve a certain ΔV is dependent on the thrust of the motor, which is related to the acceleration it can provide. It should not be assumed that the thrust of a motor will be tailored to provide the same acceleration as the solar sail. It is very likely that this cannot be achieved as thrust levels cannot always be tailored to the desired level, and a "creative" set of operations has to be implemented. The total mass is then given by

$$m_{\text{total}} = m_p + m_{\text{prop}} + m_{\text{dry}} \tag{6}$$

The issue of what value to use for m_{dry} is a complex one without a simple answer. For the SEP, it is difficult to estimate this, but it is possible to use a reasonable assumption:

$$m_{\mathrm{dry}} = 1.6 \times 10^3 \times \mathrm{Thrust} \tag{7}$$

For example, if a 1 mN thruster is used, then the mass of the propulsion system will be 1.6 kg. It should be noted that for high thrust levels, this relation becomes more favorable but by then the I_{SP} starts to decrease substantially, and the consequence is that the required propellant mass increases. This is a limiting factor for some missions that require high levels of acceleration, because certain levels of thrust just cannot be achieved. In the case of chemical propulsion, it was estimated that for low propulsion system total mass (propulsion system and propellant) the propellant mass is two-thirds 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 Surrey Satellite Technology, Ltd. small satellite missions. The mission investigation involves a constellation of solar kites used to artificially precess the apse line of 11×23 Earth radii orbit, stationing miniature science payload permanently within the geomagnetic tail and so providing continuous science returns [16]. The permanent residence of the payload in the geomagnetic tail would allow phenomena such as magnetic reconnection to be studied in situ. Using multiple solar kites, the entire geomagnetic tail could be populated by sensors that precess with the annual rotation of the geomagnetic tail, allowing real-time visualization of the three-dimensional plasma structure of the geomagnetic tail. Although only a low sail characteristic acceleration is required of 1.1×10^{-4} m/s^2, the effective ΔV for the mission is 3.5 km/s per year of operation. The targets for the mission are presented in Table 1.

For the mission requirements and following the sizing process detailed previously, the preliminary total mass required for a solar sail including contingency (30%) is 2.256 kg. A detailed mass breakdown is presented in Table 2.

For an SEP system, the total estimated mass is found as 4.49 kg (Table 3). The thrust selected for this engine is 1 mN, much higher than required for the mission acceleration, but as stated before it is not desirable to use a thruster below this value. No mass was used for the solar panels, as given the strategy envisaged for this mission, using an SEP does not require extra solar panels. Given the low acceleration required, a short impulse firing of the electric motors would be used, with short bursts at continuous intervals (although SEP is not really intended to be used like this and it is likely there would be some difficulties in using it in this way). The energy stored in the batteries would be used to drive the SEP during this period, although a viability study would be required to check that this would be possible in the very limited power budget of such a small spacecraft. The use of a chemical system is not realistic in this case as the propellant mass of the mission is likely to reach something on the order of 22 kg.

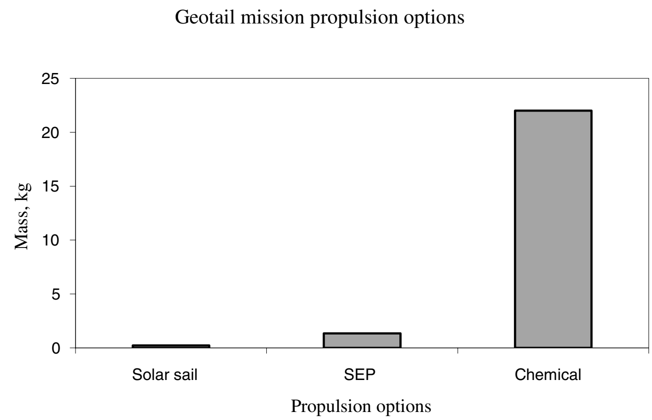

Fig. 1 Propellant mass required.

The comparison between the extra mass required by the solar sail, the SEP, and chemical is presented in Fig. 1. The mass advantage of a mission based on the solar kite concept is clear for the two-year mission duration.

The solar kite mission 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 visualization of the three-dimensional plasma structure of the geomagnetic tail. Such a real-time visualization 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 (~35–40) of solar kites 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 maximize the science return from the mission. The suggested ultraminiature payloads are presented in Table 4 along with mass, power, and communications requirements.

Table 1 Targets for the geotail mission

Targets	
Total ΔV, m/s	3.5×10^3
Acceleration, m/s^2	1.11×10^4
Bus and P/L mass, kg	1.5

Table 2 Solar sail performance

Solar kite sizing parameters	
Solar sail mass, m_s	0.235 kg
Total mass	1.735 kg
Total mass, margin 30%	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 3 SEP performance

SEP platform	
Mass of propellant	0.354 kg
Mass of motor	1.6 kg
Total mass	3.454 kg
Total mass, margin 30%	4.490 kg

III. Mission Trajectory

Conventional geomagnetic tail missions require a spacecraft to be injected into a long elliptical orbit to explore the length of the geomagnetic tail. However, because 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 four months of data can be acquired, with only one 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 11×23 Earth radii elliptical orbit would require a ΔV of order 3.5 km/s per year of operation for apse-line rotation. A perigee at 11 Earth radii meets the bow shock, whereas 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 [16]. For a solar sail, a characteristic acceleration of 0.11 mm/s is required for an 11×23 Earth radii orbit. Because 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.

For the mission orbit discussed in the preceding paragraph, the solar sail will orbit within the ecliptic plane, so that only three osculating orbital elements (a, e, ω) are required to describe the

Table 4 Solar kite candidate payloads

Payload	Science	Mass, kg	Power, W	Communications, kbps
Mag/meter	Earth/planet magnetic fields	<100 g	<0.5 W	<2 kbps
Proton ion electron detector	proton/ion detection	~400 g	<2 W	<28 kbps
Plasma detectors	plasma bubbles	<300 g	<2 W	0.03 kbps
Environmental sensors	space dust	<50 g	0.2 W	<0.03 kbps

evolution of the trajectory. The sail normal is also assumed to be directed within the ecliptic plane so that there will only be an in-plane perturbing acceleration due to solar radiation pressure. To investigate steering laws for apse-line precession, the following variational equations are therefore used

$$\frac{da}{df} = \frac{2pr^2}{\mu(1-e^2)^2}\left[Se\sin f + T\frac{p}{r}\right] \tag{8}$$

$$\frac{de}{df} = \frac{r^2}{\mu}\left[S\sin f + T\left(1+\frac{r}{p}\right)\cos f + Te\frac{r}{p}\right] \tag{9}$$

$$\frac{d\omega}{df} = \frac{r^2}{\mu e}\left[-S\cos f + T\left(1+\frac{r}{p}\right)\sin f\right] \tag{10}$$

where (S, T) represent the radial and transverse components of the perturbing solar radiation pressure acceleration experienced by the solar sail, as shown in Fig. 2, and $p = a(1-e^2)$ is the orbit semiparameter. A simple steering law will now be considered in which the sail normal is directed along the major axis of the ellipse.

The solar radiation pressure acceleration experienced by the solar sail is a function of the sail orientation with respect to the sun line. If $\boldsymbol{n}$ is the unit vector normal to the sail surface and $\boldsymbol{s}$ is the unit vector directed along the sun line, the solar radiation pressure acceleration experienced by an ideal solar sail on an Earth-centered orbit may be written as $a = a_o(\boldsymbol{s}\cdot\boldsymbol{n})^2\boldsymbol{n}$, where a_o is the characteristic acceleration of the solar sail. The characteristic acceleration is defined as the acceleration experienced by the solar sail at a heliocentric distance of 1 AU, whereas the sail normal is directed along the sun line. Then, if the sail normal is directed along the major axis of the ellipse, the components of the solar radiation pressure acceleration experienced by the solar sail are given by

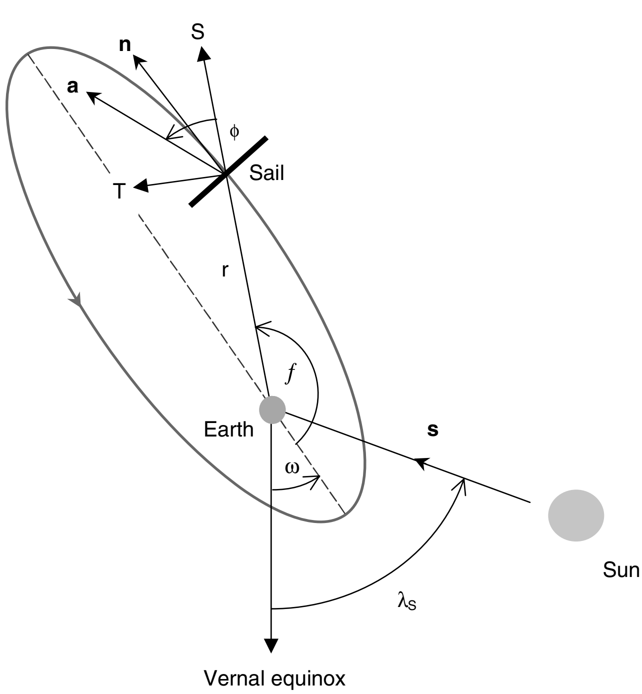

Fig. 2 Orbit geometry.

$$\begin{bmatrix} S \\ T \end{bmatrix} = a_o\cos^2(\omega - \lambda_S)\begin{bmatrix} -\cos f \\ \sin f \end{bmatrix} \tag{11}$$

where ω is the argument of perigee of the orbit, λ_S is the position of the sun within the ecliptic plane from the vernal equinox, and f is the true anomaly of the solar sail, again shown in Fig. 2.

For the apse line of the orbit to be synchronous with the annual rotation of the sun line, it is clear that the identity $\omega = \lambda_S$ must always hold. In this case, the sun line is directed along the major axis of the ellipse and so the sail normal is always directed along the sun line. This provides an extremely simple steering law to implement in practice. The change in orbital elements over a single orbit with this simple sail steering law can now be obtained by integrating Eq. (8) to obtain

$$\Delta a = \int_0^{2\pi}\frac{\mathrm{d}a}{\mathrm{d}f}\,\mathrm{d}f = 0 \tag{12}$$

$$\Delta e = \int_0^{2\pi}\frac{\mathrm{d}e}{\mathrm{d}f}\,\mathrm{d}f = 0 \tag{13}$$

so that the orbit averaged semimajor axis and eccentricity remain unchanged by the solar radiation pressure acceleration experienced by the solar sail. Again, integrating over a single orbit the change in argument of perigee of the ellipse is found to be

$$\Delta\omega = \frac{3\pi}{\mu}a_o a^2\sqrt{\frac{1-e^2}{e^2}} \tag{14}$$

so that the apse line of the orbit will rotate due to the perturbing solar radiation pressure acceleration. The mean rate of precession of the apse line of the ellipse can now be obtained by dividing Eq. (14) by the ellipse orbit period T_o to obtain

$$\frac{\Delta\omega}{T_o} = \frac{3}{2}a_o\frac{\sqrt{1-e^2}}{e}\sqrt{\frac{a}{\mu}} \tag{15}$$

where $T_o = 2\pi\sqrt{a^3/\mu}$. Therefore, for the sun-synchronous condition that $\Delta\omega/T_o = \dot{\lambda}_S$, the required solar sail characteristic acceleration is found to be

$$a_o = \frac{2}{3}\dot{\lambda}_S\frac{e}{\sqrt{1-e^2}}\sqrt{\frac{\mu}{a}} \tag{16}$$

where $\dot{\lambda}_S = 0.9856$ deg per day. This provides a compact expression to size a solar sail for a given elliptical orbit with the condition for sun-synchronous apse-line precession.

For sun-synchronous apse-line precession it can be seen that the required solar sail characteristic acceleration is only a function of the orbit semimajor axis and eccentricity, both of which remain unchanged over a single orbit. A convenient way of representing the required characteristic acceleration is therefore through the orbit apogee and perigee radii, as shown in Fig. 3. For the range of orbits of interest, it can be seen that a solar sail characteristic acceleration of order 0.1 mm/ s is required. This level of performance is typical of current concepts for solar sail technology demonstration missions. The evolution of an 11×23 Earth radii orbit over six months is shown in Figs. 4–6 using a two-body simulation. It can be seen that the orbit averaged semimajor axis is zero as expected, whereas the apse line of the orbit precesses at a mean rate of 0.9856 deg per day to track the sun line and geomagnetic tail, as required.

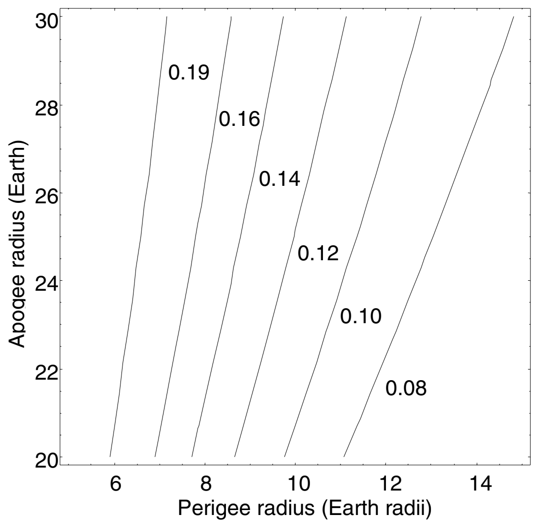

Fig. 3 Characteristic acceleration required for sun-synchronous apse-line precession (mm/s^{-2}).

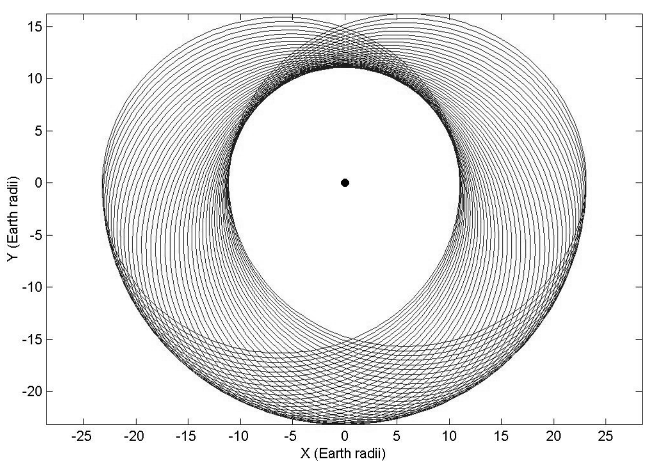

Fig. 4 11 × 23 Earth radii orbit evolution over 6 mo. (inertial frame).

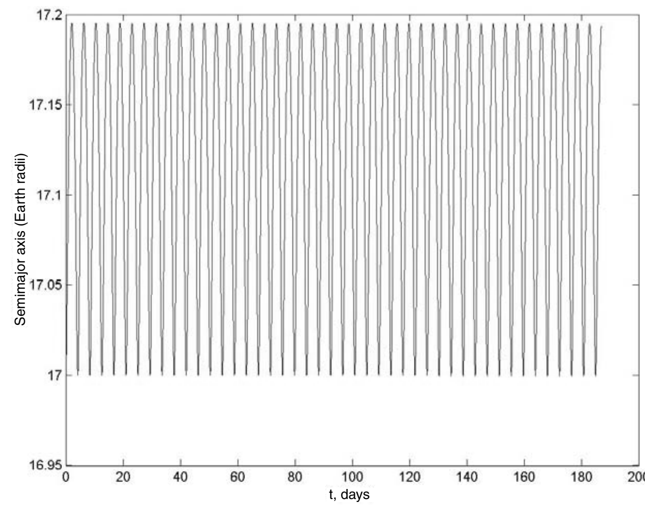

Fig. 5 Orbit semimajor axis evolution over 6 mo.

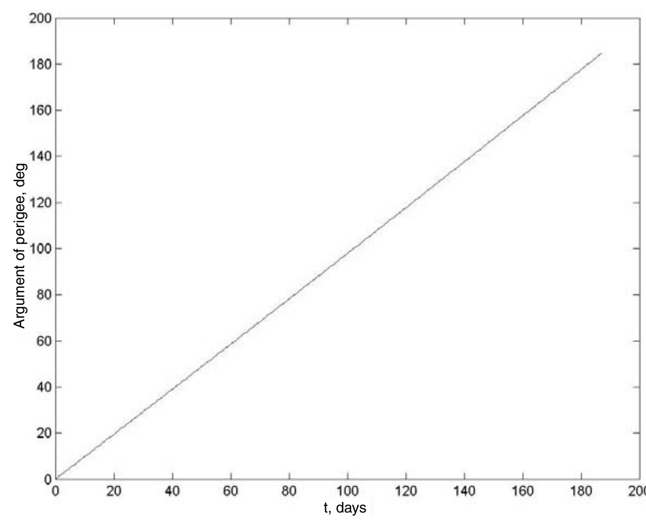

Fig. 6 Apse-line evolution over 6 mo.

IV. Solar Sail Design/Platform

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

$$\mathrm{SAL} = \frac{\text{mass of sail structure}}{\text{solar sail area}} = \frac{m_s}{A} \tag{17}$$

Using Eq. (17) 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 5×5 m, $A = 25$ m^2 and using Eq. (17) 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 diam and a length of $L = 3.535$ m. The mass of the film used is $m_f = 0.05$ kg. The mass of the solar kite platform including the platform subsystems and payloads is assumed to have a mass of $m_{\text{bus}} = 1.5$ kg or less. The mass of the bus, solar sail area, and SAL are noted to be key in the design of the solar kite. Using the preceding values, it is then deduced that for a solar radiation pressure (SRP) constant of $P = 4.536 \times 10^{-6}$ N/m^2 and a thrust coefficient $\eta = 1.8$, the maximum thrust of the SK is $F_{\max} = \eta PA = 2.04 \times 10^{-4}$ 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

$$a_c = \frac{F_{\max}}{m} = \frac{\eta PA}{m} = \frac{\eta P}{\sigma} = 1.2 \times 10^{-4}\ \mathrm{ms}^{-2} \tag{18}$$

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

A. Solar Sail Booms and Membrane

The analysis of existing and future developments on solar sail technology (rigidizable or inflatable booms, structural and dynamics analysis of deployed 20 m sails in vacuum, sail membranes) has led to a number of important conclusions [1–4,9,12–20]:

1) The mass per length ratio for the booms is a critical, mission enabling factor.

2) Conventional and current boom technologies cannot be scaled down to a solar kite 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 analyzed for large (>40 m sails), making this technology difficult to implement on a solar kite.

5) A solar kite will need a simple, ultralight sail with a smaller lifetime than large sails.

A solar kite with a 3.535 m boom will need to be a simple and optimized design to a 1.75 kg spacecraft mass. The small size of the boom can prove instrumental in this, as a simpler, less complex boom can be manufactured and deployed compared with existing 40 m booms with multiple motors, pulleys, supports that add risks to the sail design, mass overheads, and complexity [1–3]. 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 solar kite sail. Sail film and supporting structure technologies play a key role for the realization of solar sail design concepts. Ultrathin film on the order of 1–2 μm of polymid basis have already been manufactured under laboratory conditions. This is an advantage for the SK because producing limited quantities in lab conditions is sufficient. The solar kite sail membrane is a 0.9 μm polymid based film, which is based on the DuPont polymid membrane.

B. Solar Kite 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 materials 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 [1–3]. 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-diam 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 rigidizable inflatable structures with promising results. Nihon University has conducted experimental tests completed in microgravity conditions of a 1 m inflatable boom [21]. 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 attitude determination and control system (ADCS). 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 because storage for the integrated "structure" is much more compact and lighter than using a traditional CFRP design.

The technology readiness of the suggested technology is at technology readiness level four (i.e., flown in space but in need of modification, customization or optimization for specific application)

Table 5 Solar kite characteristics

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 mm/s^{-2}

Table 6 Solar kite sail/boom technologies

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

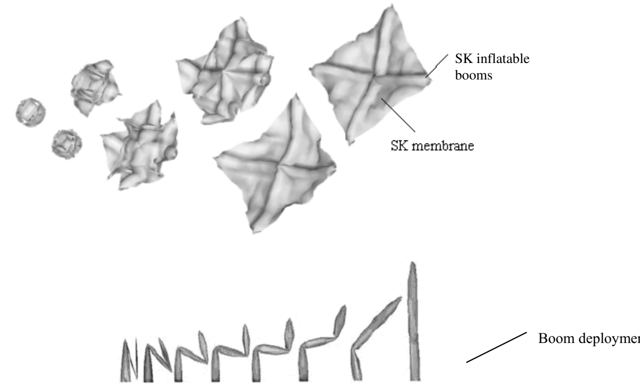

Fig. 7 Solar kite booms, sail, and deployment (Nihon concept).

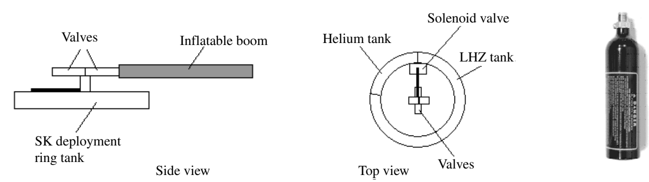

Fig. 8 Solar kite sail/boom deployment mechanism.

for inflatable structures and five for rigidized structures. Using the suggested sail-boom-deployment concept with the preceding specified parameters (4 cm boom diameter, 3.535 m length) the mass breakdown using the three available technologies (CFRP, coilable, inflatable) is depicted in Table 6. The inflatable option provides significant savings in mass and volume on the overall SK design. A CFRP option is too large for an 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.

C. Solar Kite 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 ultraminiature resistojet thruster used in the SK ADCS. 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 "makeup 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.

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 to maintain 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 too 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, because 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 to have maximum performance. The hardening strips to be used will consist of a tapelike substance that has the unique property that the tape will remain pliable and tapelike 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 min. 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. Figures 7 and 8 show the proposed SK deployment concept.

D. Solar Kite Platform

The SK consists of two parts: the SK structure and the SK platform (Fig. 9). The SK platform uses as a basis the Surrey PalmSat 1 kg platform [22]. However, the platform is tailored to the SK requirements and mission requirements. The "bus" is a 6×9.5 cm hexagon structure made out of carbon fiber and aluminum honeycomb structure machined carefully to save mass. The dimensions of the sail are 5×5 m with 3.535 inflatable booms integrated with the sail membrane 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 stabilization, commissioning, and operations. The SK uses three thrusters in a one pair plus single thruster configuration. The pair of thrusters is mounted opposite and antiparallel to each other for spinup and spin maintenance operations and the third thruster is used for precession.

The thrusters use miniature boards with a battery, solar array (1 cm^2) 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 pretensioned springs, will switch on its power subsystem and detumble 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. Table 7 summarizes the solar kite mass and power breakdown for the full sail/platform design.

E. Attitude Determination and Control Subsystem

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 8. Because of the "affordable" payload pointing requirements of $\sim$1 deg and due to the need to have a simple, light, and robust ADCS system, the team has selected a spin control scheme using thrusters. Three thrusters are used mounted on the tips of the two booms: a pair of thrusters, one thruster antiparallel to the other (diagonally) used for spinup 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 microelectromechanical systems (MEMS) low-power gyro, a star sensor based on an ultraminiature complementary metal-oxide semiconductor camera, and a magnetometer used as a science payload as well.

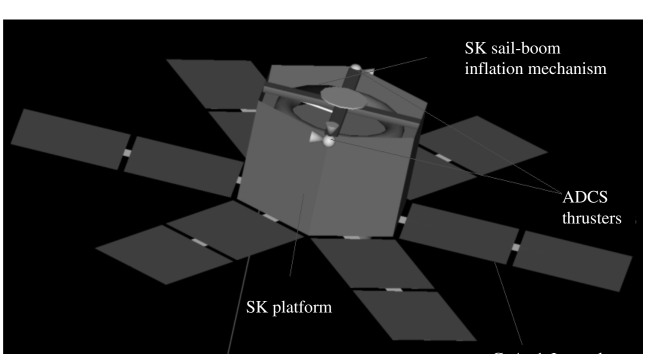

Fig. 9 Solar kite platform.

Table 7 Solar kite mass and power breakdown

Subsystem	Mass	Power
Payload	500 g	1.5 W
Onboard computer	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 g	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

Table 8 SK ADCS parameters

Parameters	Values
Moments of inertia	$(1.113, 0.556, 0.556)$ kg/m^2
cm/cp offset	0.01 m (0.2% of 5 m)
SRP thrust	0.2 mN
SRP disturbance torque	2 $mN \cdot m$
Angular momentum storage/dumping	0.0072 Nms/h
Payload pointing accuracy	1°

The SK thruster will use a modified valve designed by Lee Products which is $\sim$6 mm diam $\times$ 33 mm long, is rated to 375 psi (25 bar), and has a mass of less than 6 g with an expected average draw power of 0.2 W. For a 1 deg pointing requirement and a 0.2 mN solar pressure force, a spin rate of $\Omega = 1.2$ 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 stabilization requirements are feasible as indicated in Fig. 10. A more detailed analysis of the dynamics and control of solar sails is presented in Wie [4].

F. 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 requirement 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. An overall efficiency of the power system was estimated at 80%, compatible with current small satellite power subsystem technology. The battery technology is based on Li-ion or Li-ion polymer batteries. For the solar panels, several possible configurations were analyzed to take into consideration the advances in cell technology that will take place until the mission is launched. Currently GaAs single junction cells are available in sizes of 4×2, 4×4, and 4×6 cm, which are the most common in space applications for small spacecraft. The new generation of cells though is likely to be available mainly in the 4×8 cm format, which means that if the solar panels have a dimension of 6×9.5 cm, each one of them can support one single cell, and so a design for the near future should be based on the 4 cm $\times$ 8 cm dimensions. Furthermore, it is likely that in the next few years, three and four junction GaAs cells will 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 Fig. 11, in which the power generation capability of the mission for different technologies and configurations was plotted.

A four-junction, six-panel configuration was chosen in the analysis, although in practice this could be replaced by a single junction, 12-panel configuration.

G. Radio Frequency Subsystem

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

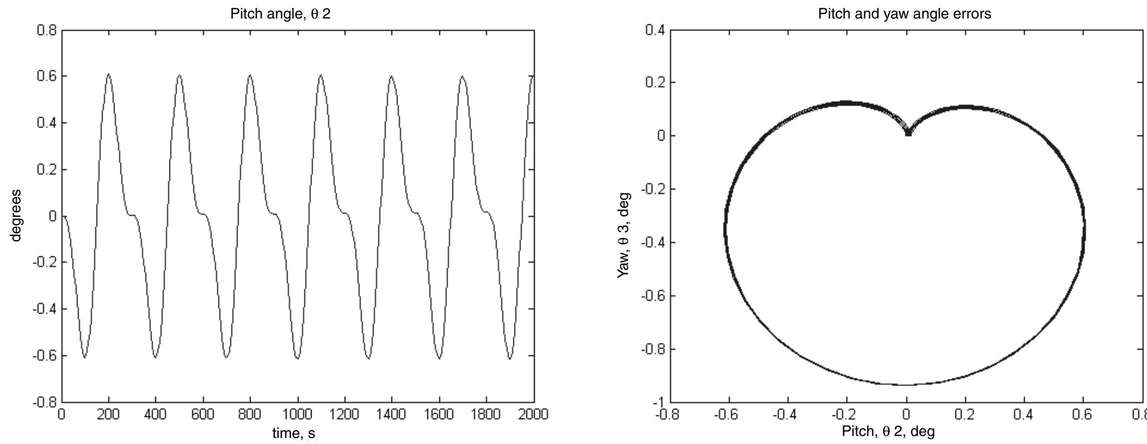

Fig. 10 Simulation results for a cm/cp offset of 0.01 m.

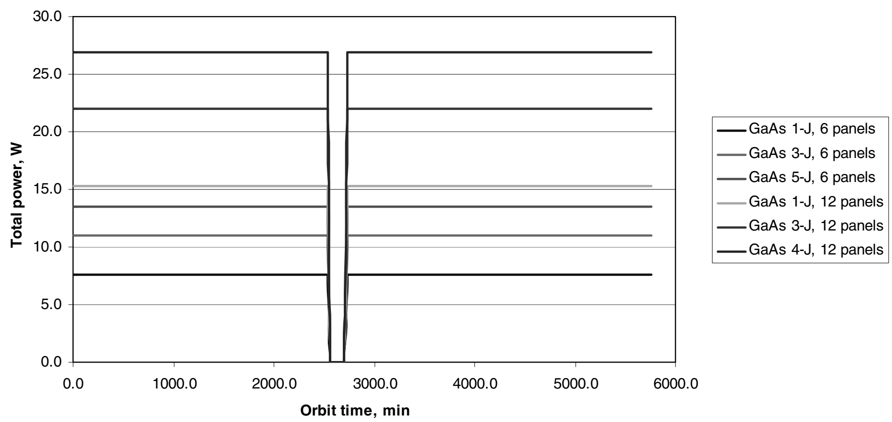

Fig. 11 Orbit power profile.

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 PC card-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 an S-band 0.5 W transmitter is assumed and an S-band receiver is also assumed. A phase-shift keying 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:

1) This is the typical uplink rate used by Surrey on its missions, and has shown to be sufficient for the minimum of operations of micro- and nanosatellites. These include all the housekeeping tasks and software uploads required over the lifetime of the missions.

2) Design of equipment for the required rate is straightforward.

On the downlink side, the baseline at this stage is to use a 38,400 bps data rate, for the following reasons:

1) This 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 MB) of information; in 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.

2) 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 (Fig. 12.

3) It is a useful and easy-to-implement data rate, which has become a standard on Surrey and most other small satellite 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 as 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 140,400 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.

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

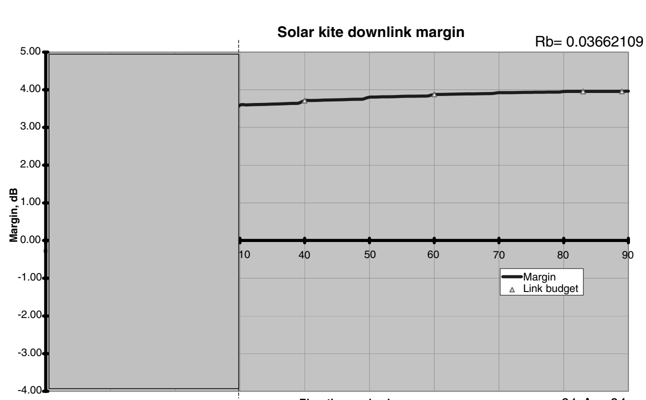

Fig. 12 SK downlink margin at apogee.

reasonable and should allow the implementation of the mission, with a RF solution that works, any changes such as not using Reed–Solomon coding or reducing the transmitter power are likely to have a major impact on the link margin.

V. Constellation Launch and Deployment

Surrey has worked on inhouse 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 N, N_2O high-density polyethylene hybrid system based on the Daimler–Benz S400/2. A main requirement for the STV-SK vehicle will be to take the SKs from a 580×35786 km and 7 deg inclination to the desired (11×23) Re orbit. The STV-SK vehicle will have to fit to an Ariane 5 auxiliary payloads minisatellite space, which has a 150 cm diam 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 I_{SP} of 318 s, this translates to 109 kg of 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.

VI. Conclusions

Most of the studies done to date assume that the largest obstacle in solar sail 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. One of the enabling factors though that make solar sail missions possible is the miniaturization of the spacecraft bus, bringing the overall spacecraft mass down and thus enabling solar sails to materialize. An 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 of designing an SK mission that solar kites can provide a number of key advantages when compared with larger, more complicated, and expensive solar sails. Cost and complexity can be substantially reduced and sail deployment can be simplified. Small size sails can use existing inflatable technology (ultralight) for sails with a size of <5–10 m. Miniaturization technology is available and more applicable to small sails and can thus take advantage of smaller design/manufacture times enabling constellations of small solar sails.

Acknowledgment

The work was supported by the European Space Agency under contract European Space Research and Technology Center No. 17679/03/NL/Sfe.

References

[1] McInnes, C. R., *Solar Sailing: Technology, Dynamics and Mission Applications*, Springer-PRAXIS Series in Space Science, Springer–Verlag, New York, 1999.

[2] Friedman, L., *Star Sailing: Solar Sails and Interstellar Travel*, Wiley, New York, 1988.

[3] Wright, J. L., *Space Sailing*, Gordon and Breach, New York, 1992.

[4] Wie, B., "Solar Sail Attitude Control and Dynamics: Parts 1 and 2," *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 4, 2004, pp. 526–544.

[5] Renner, U., "Attitude Control by Solar Sailing: A Promising Experiment with OTS-2," *ESA Journal*, Vol. 3, No. 1, 1979, pp. 35–40.

[6] Sohn, R. L., "Attitude Stabilization by Means of Solar Radiation Pressure," *ARS Journal*, Vol. 29, May 1959, pp. 371–373.

[7] van der Ha, J. C., and Modi, V. J., "Analytical Evaluation of Solar Radiation Induced Orbital Perturbations of Space Structures," *Journal of the Astronautical Sciences*, Vol. 25, No. 4, Oct./Dec. 1977, pp. 283–306.

[8] Cosmos 1 Solar Sail Mission, http://www.planetary.org/solarsail, retrieved July 18, 2005.

[9] Rogan, J., Gloyer, P., Pedlikin, J., Veal, G., and Derbes, B., "Encounter 2001: Sailing to the Stars," *15th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 13–16, 2001*, AIAA Paper SSC01-II-2, 2001.

[10] Lappas, V., Wie, B., McInnes, C., Tarabini, L., Gomes, L., and Wallace, K., "Solar Kite Mission to Study the Earth's Magneto-tail," *Journal of the British Interplanetary Society*, Vol. 58, Nos. 1–2, Jan./Feb. 2005.

[11] Jack, C., Wall, R., and Welch, C. S., "Spacefarer Solar Kites for Solar System Exploration," *Journal of the British Interplanetary Society*, Vol. 58, Nos. 5/–6, May/June 2005.

[12] Leipold, M., Garner, C. E., Freeland, R., Herrmann, A., Noca, M., Pagel, G., Seboldt, W., Sprague, G., and Unckenbold, W., "ODISSEE: A Proposal for Demonstration of a Solar Sail in Earth Orbit," *Acta Astronautica*, Vol. 45, Nos. 4–9, 1999, pp. 557–566.

[13] Lyngvi, A., Falkner, P., Kemble, S., Leipold, M., and Peacock, A., "Interstellar Heliopause Probe," *Acta Astronautica*, Vol. 57, 2005, pp. 104–111.

[14] Murphy, D. M., Murphey, T. W., and Gierow, P. A., "Scalable Solar-Sail Subsystem Design Concept," *Journal of Spacecraft and Rockets*, Vol. 40, No. 4, 2003, pp. 539–547.

[15] Wie, B., Murphy, D., Paluszek, M., and Thomas, S., "Robust Attitude Control Systems Design for Solar Sail Spacecraft: Parts 1 and 2," *AIAA Guidance, Navigation, and Control Conference, Providence, RI*, AIAA Paper 2004-5010, 2004; also AIAA Paper 2004-5011, 2004.

[16] McInnes, C. R., Macdonald, M., Angelopolous, V., and Alexander, D., "GEOSAIL: Exploring the Geomagnetic Tail Using a Small Solar Sail," *Journal of Spacecraft and Rockets*, Vol. 38, No. 4, 2001, pp. 622–629.

[17] Jack, C., and Welch, C., "Solar Kites-Small Solar Sails with No Moving Parts," *Acta Astronautica*, Vol. 40, Nos. 2–8, 2005, pp. 137–142.

[18] Leipold, M., Lappas, V., Lyngvi, A., Falkner, P., Fichtner, H., and Kraft, S., "Interstellar Heliopause Probe: System Design of a Solar Sail Mission to 200 AU," *AIAA Guidance, Navigation, and Control Conference, San Fransisco, CA, August 13–18, 2005*, AIAA, Paper 2005-6084, 2005.

[19] Wie, B., "Solar Sailing Kinetic Energy Interceptor (KEI) Mission for Impacting/Deflecting Near-Earth Asteroids," *41st AIAA Joint Propulsion Conference, Tucson, AZ, July 10–13, 2005*, AIAA Paper 2005-3725, 2005.

[20] Lichodziejewski, D., Derbes, B., Sleight, D., Mann, T., "Vaccum Deployment and Testing of a 20 m Solar Sail System," *47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials, Newport, Rhode Island*, AIAA Paper 2006-1705, 2006.

[21] Miyazaki, Y., Isobe, H., Kodama, T., Uchiki, M., and Hinuma, S., "Nihon University CubeSat Program," *15th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, 2001*, AIAA Paper SSC01-VIIIb-2, 2001.

[22] Underwood, C., Lappas, V., da Silva Curiel, A., Unwin, M., Baker, A., and Sweeting, M., "Using "PalmSat" Pico-Satellite Technologies to Meet Mission Scenarios," *55th International Astronautical Congress, Vancouver, Canada*, IAC Paper 04-P.5-A.01, Oct 2004.

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