GEOSAIL: EXPLORING THE MAGNETOSPHERE USING A LOW-COST SOLAR SAIL

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ABSTRACT

GeoSail is a small, low cost, innovative mission designed to exploit the versatility of solar sail propulsion for the exploration of magnetic reconnection and electron dynamics in the Earth's magnetotail. The GeoSail mission requires only a very low performance solar sail to precess the major axis of an otherwise inertially fixed orbit, thus maintaining payload alignment within the geomagnetic tail. This constant rotation enables a near continuous observation window with the opportunity to probe the rapid dynamic evolution of energetic particle distributions in this critical region of geospace. An end-to-end system design study has been concluded and the key performance requirements identified. The level of solar sail performance required for GeoSail is typical of that currently being discussed within Europe for a near-term technology demonstration mission. GeoSail is therefore capable of providing both technology validation within the cost restrictions of a SMART mission while also returning unique science data from a first solar sail mission.

1. INTRODUCTION

GeoSail is motivated by the desire to achieve long residence times in the Earth's magnetotail, enabling high resolution statistical characterisation of the plasma in a region subject to a variety of external solar wind conditions. This is accomplished by the novel application of a solar sail propulsion system to precess an elliptical Earth-centred orbit at a rate designed to match the rotation of the geomagnetic tail, the orientation of which is governed by the Sun-Earth line. Conventional, inertially fixed orbits with an apogee inside the geomagnetic tail will provide less than three months of science data, due to the rotation of the geomagnetic tail with the Sun-Earth line, while the orbit remains inertially fixed. It has been shown previously that the requirements to precess such orbits by chemical propulsion are prohibitively large, while electric propulsion significantly curtails the potential mission duration [1] [2] [3].

With the recent interest in the mission-enabling features of solar sailing comes the requirement to lay down a clear route towards the realisation of these possibilities [4]. A significant volume of prior work has been performed on the GeoSail mission concept, primarily at the University of Glasgow and Lockheed Martin's Advanced Technology Centre in Palo Alto, in cooperation with NASA/JPL and the Space Science Laboratory at the University of California, Berkeley. Prior work became focused on utilisation of NASA technology, programmes and funding. However, a revised analysis of GeoSail in the context of a SMART mission is reported here. The GeoSail mission concept requires a low-level of sail performance, similar to or less than levels being discussed currently in Europe for technology demonstration missions [5]. With the low-level of sail performance required, GeoSail is an ideal candidate for a first operational European solar sail mission, following a successful deployment demonstration in low-Earth orbit. This revised analysis was performed on the mission concept in order to quantify the technology requirements and to provide an initial step along the route towards enabling more advanced solar sail missions as analysed in [4].

2. SCIENCE OBJECTIVES

Long duration residence in the geomagnetic tail allows very high time resolution instruments to temporally resolve the processes within the many regions of interest, providing a breakthrough in the understanding of the physical processes in the magnetotail. Long duration residence is difficult for conventional missions due to the annual rotation of the Sun-Earth line and the inertially fixed nature of conventional orbits. The capability to achieve long residence times significantly enhances the scientific return, providing the means to expand our understanding of processes within the magnetosphere [6]. Multi-satellite observations using WIND and GEOTAIL, of bursty bulk flow (BBF) events, indicate that flux transport in the magnetotail is highly localised and that total magnetotail flux transport is due to the action of several localised activations [7].

The primary scientific goals of GeoSail are:

- Understand how spontaneous magnetic reconnection occurs in a magnetic current sheet.
- Understand the mechanisms behind reconnection mode destabilisation and saturation in the magnetotail.
- Analyse the plasma structure at the sub-second resolution.
- Understand reconnection and particle dynamics at the day/dawn side low-latitude boundary layer along the Earth's magnetopause.

3. INSTRUMENTS

The GeoSail instrument suite is designed to investigate each of the science goals outlined. The instrument suite is based on heritage and ongoing developments, rather than depending on future capabilities, which would require significant funding to realise. However, we note that development of existing instruments may be required in order to successfully incorporate them into a solar sail mission, due to either visibility requirements or environmental factors.

The instrument suite is divided into two mission options, a core and an enhanced mission option. Both options consist of plasma and field instruments designed to measure the local environment in-situ, as detailed in Table 1.

Table 1. GEOSAIL MINIMUM & CORE INSTRUMENT SUITE. DATA1 IS ROUTINE TELEMETRY RATE; DATA2 IS PARTICLE BURST TELEMETRY RATE; DATA3 IS WAVE BURST TELEMETRY RATE.

Instrument	Mass (kg)	Power (W)	Data1 (bit s^{-1})	Data2 (bit s^{-1})	Data3 (bit s^{-1})
Fluxgate Magnetometer	0.26	0.60	256	2048	8192
Electrostatic Analyser	2.22	2.60	608	4395	4395
Solid State Telescope	1.00	1.00	512	1707	4096
Search-Coil Magnetometer	2.04	2.17	555	5120	16384
Total Core Mission	**5.52**	**6.37**	**1931**	**13270**	**33067**
3-axis Electric Field Instrument	5.24	2.10	555	5120	16384
Total Enhanced Mission	**10.76**	**8.47**	**2486**	**18390**	**49451**

Topological changes in the magnetic field are measured by the fluxgate magnetometer, which measures the 3D magnetic field in the DC range up to 64 Hz. Meanwhile the electrostatic analyser measures 3D particle distribution of ions and electrons at energies from 50 eV to 10 keV. The solid-state telescope allows the measurement of energetic particle mass and distribution functions, particularly superthermal 3D ions and electrons at energies from 10-300 keV. The final instrument in the core payload is a search-coil magnetometer, measuring the 3D magnetic field in the range of 10 Hz to 10 kHz. A potential enhanced mission instrument suite is also considered, including a 3-axis electric field instrument, allowing analysis of the electric field in three orthogonal directions.

Payload integration is a key issue. Several options are currently under consideration in order to ensure that the instruments are provided with the environment required enabling the science goals can be attained, such as a magnetically sterile environment for the magnetometers. It is worth noting that during the Geostorm [8] design process a brief internal NASA study concluded that a metallised 7.5 μm Kapton® sail would not experience significant charging. However, the placement of the magnetometers was based primarily on "best engineering practice". Thus, while this was a concern it was not felt to be a mission critical issue, and indeed one of the goals of Geostorm was to investigate this very interaction. Similarly, a technology goal of GeoSail will be the study of the interaction between the sail and the space environment.

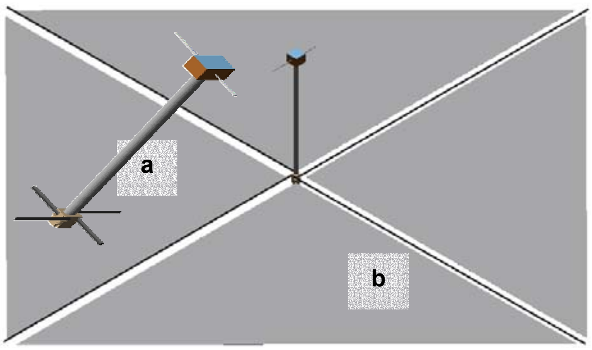

Fig. 1. CENTRAL MAST AND INSTRUMENT BOOMS DEPLOYED, WITH SAIL BOOMS PART DEPLOYED (a); SAIL BOOMS AND FILM FULLY DEPLOYED (b) (TO SCALE).

Furthermore, as shown in Fig. 1, the DLR-ESA sail concept (discussed later and in [5]) utilises a deployable central boom for centre-of-pressure/centre-of-mass offset as yaw and pitch control. Thus, the SailBus with magnetometers mounted on rigid deployable booms attached to it, is approximately 10m from the sail film. The central deployable boom may therefore remove the instruments a sufficient distance that any charging that occurs on the sail would have negligible effect on the instrumentation. Further study is required, particularly when the sail leads the instrumentation as to the wake effect of the sail and when the instrumentation leads the sail as to the bow effect of the sail.

4. TRAJECTORY ANALYSIS

The GeoSail orbit designed to achieve the science goals has a perigee located above the planetary dayside at approximately 11 Earth radii (R_E), corresponding to alignment with the magnetopause. Apogee is aligned with the geomagnetic tail reconnection region on the night-side of Earth, which occurs between 22-30 R_E. However, due to the orbit plane being coincident with the ecliptic plane, the spacecraft will have a shadow event every apogee and as such an immediate trade is required between engineering requirements and science data. Due to uncertainties in the exact region of interest, an apogee of 23 Re was selected in order to reduce shadow duration and sail performance requirements. A key feature of the GeoSail orbit is the ability to investigate the 22-30 R_E downstream region over an extended period. Conventional missions have achieved extended observation times only in the deep tail by executing double-Lunar flybys to precess the orbit apse-line [9]. The utilisation of a small solar sail allows orbit apse-line precession without the requirement of going as far as the Moon, at approximately 60 R_E, hence enabling extended study of this key region of geospace. The GeoSail orbit is illustrated in Fig. 2, where we see the orientation of the orbit with respect to the mean magnetosphere location.

4.1 Solar Sail Performance Requirements

The level of sail acceleration required to match the apse-line precession and the Sun-Earth line rotation can be easily calculated by consideration of the required orbit size. A more advanced analysis has also been undertaken where the required sail acceleration is calculated with account taken for the long shadow periods incurred every orbit. It has also been shown that as the Sun-Earth distance varies, due to the Earth's orbit eccentricity, the sail acceleration correspondingly varies, hence matching the varying rate of rotation of the Sun-Earth line [2].

In this study we assume the sail has 85 % reflective efficiency and 94 % specular reflective efficiency, along with Aluminium front and Chromium rear coatings on the sail film, utilising an optical solar sail force model [10].

We can calculate the ideal sail characteristic acceleration required for the GeoSail orbit to be 0.1127 mm s^{-2} (at 85 % efficiency). The solar sail is orientated at all times such that it is pitched at zero degrees from the Sun-Sail line, hence effectively directing the sail force vector parallel to the orbit major axis. This simple steering law provides the required precession of the orbit apse-line.

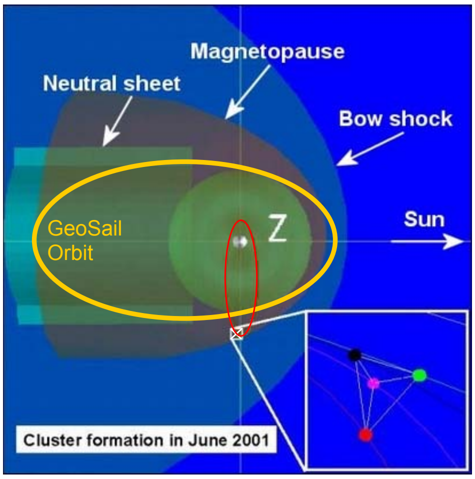

Fig. 2. GEOSAIL ORBIT DIAGRAM, LOOKING DOWN ONTO ECLIPTIC PLANE, WITH CLUSTER ORBIT FOR REFERENCE.

4.2 GeoSail Orbit Evolution

A trade-off was performed between active sail manoeuvring and direct orbit insertion to the mission orbit. Due to the excessively long transfer time from geostationary transfer orbit, we assume direct orbit insertion by a dedicated kick-stage [11].

A simulation of the mission orbit evolution over the core mission duration of two years is presented in Fig. 3. The trajectory model includes Lunar and Solar gravity perturbations as point masses and models the Earth's gravity as a non-spherical body up to the 18th order. Terrestrial and Lunar shadow is modelled, differentiating between penumbra and umbra. The solar sail is modelled using an optical force model, while also correcting for the true Sun-sail distance. The Earth and Moon positions are true-to-date, while the Sun is modelled as a uniformly bright finite disk. The GeoSail trajectory is shown in Fixed-Sun-line coordinates in Fig. 3, where we see that the major axis has rotated to maintain alignment with the Sun-Earth line.

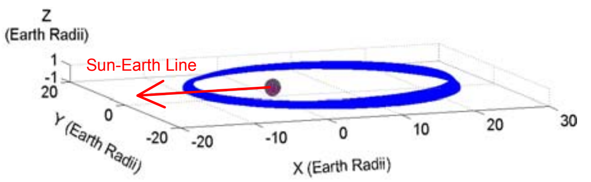

Fig. 3. 2-YEAR GEOSAIL TRAJECTORY IN FIXED-SUN-LINE COORDINATES (SUN-LINE INDICATED).

Closer examination of the variation of the orbital elements is shown in Fig. 4, where we see that the perigee and apogee radii vary by up to 1 R_E. We note that start epoch for the trajectory analysis was 03 January 2010, however if we delay the start epoch until nearer the July solstice we find that the radius of perigee varies from 11 R_E up to 12 R_E, rather than decreasing down to 10 R_E. Apogee varies correspondingly, that is, in the opposite sense to that shown in Fig. 4. Similarly, the variation of orbit inclination, while consistently varying over approximately one degree is dependent on both initial start epoch, throughout the Earth year, and initial position of the Moon, which acts as the primary source of orbit perturbations.

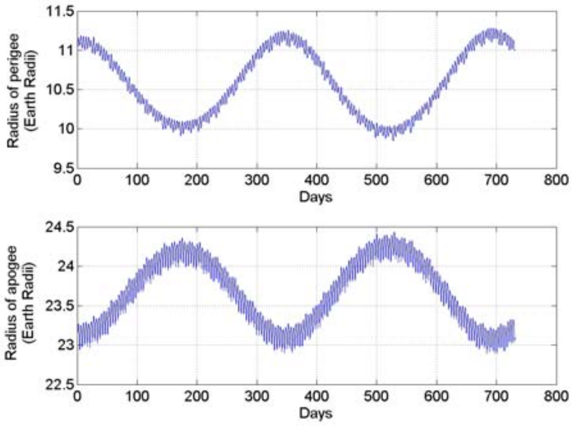

Fig. 4. PERIGEE & APOGEE EVOLUTION.

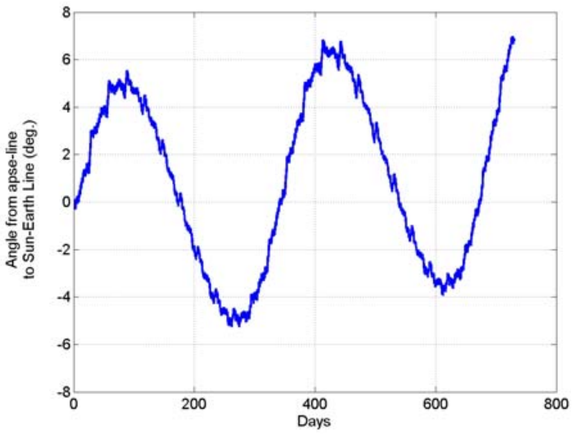

Fig. 5. VARIATION OF ANGLE BETWEEN EARTH-SUN LINE AND ORBIT MAJOR AXIS.

The variation of the angle between the orbit major axis and Earth-Sun line is shown in Fig. 5. We see that while the angle remains small, typically within six degrees, it does show a slow drift of the orbit ahead of the Sun-Earth line. However, a variation in start epoch has been seen to alter this and can reverse the global drift to behind the Sun-Earth line. None of the orbit variations seen present a significant impact on science returns and may enhance the mission due the dynamic nature of the magnetosphere.

5. SPACECRAFT DESIGN

The spacecraft design methodology assumed that while this is a near-term mission, it is likely that the mission would be conducted under the SMART framework. As such it would be expected to demonstrate multiple new technologies while simultaneously providing new and useful scientific data. Thus, while existing hardware is used for the science payload, restricting innovation to the integration of the payload with the solar sail, we expect to be able to demonstrate new, innovative spacecraft bus technologies of the type that would be required for future missions. Hence, if for example we suffer a catastrophic sail deployment failure, we can jettison the sail and continue to gather science data, acting simply as a conventional magnetosphere mission. This reduces the overall mission risk, while simultaneously gaining flight heritage for the spacecraft bus technologies that are required for future missions.

5.1 SailBus Overview

The spacecraft is 3-axis stabilised, driven primarily by current solar sail design concepts and not by science, which may prefer spin stabilisation in certain scenarios. The SailBus should be highly autonomous and fully integrated with the solar sail systems, although they are presented as separate systems in this paper for clarity. The solar sail design will be discussed later. The SailBus overview is presented in Table 2, where we see the difference between flying the core payload versus the enhanced payload.

The attitude and orbit control system (AOCS), contains an IMU, three star sensors, two Sun sensors suites and three coarse Sun sensors, along with two sets of reaction wheels, used for roll control, assuming a gimballed boom for pitch and yaw control. We note that the Sun and star trackers selected for mission analysis are low mass and power and would constitute a technology goal for the mission. Such sensors are available from multiple sources within Europe, but have no flight heritage to date, only laboratory demonstration. An AOCS cold gas propulsion system is used to hold initial Sun acquisition and provide momentum dumps for the reaction wheels. The cold gas system uses Nitrogen, with a specific impulse of 72 seconds. Due to different total masses, the required propulsion mass of the core and enhanced payloads vary and are shown in Table 2. The Δv requirements for AOCS are currently being investigated (estimated as 50 ms^{-1}). SailBus mechanisms include deployable, rigid booms for instrument mounting, allowing the instruments to be deployed in a magnetically sterile environment, although once again this issue is still under examination. The primary spacecraft structure is composed of carbon fibre, due to mass considerations and is expected to save over 50% from a conventional Aluminium structure.

Table 2. SAILBUS OVERVIEW, *ITALIC* REPRESENTS ENHANCED PAYLOAD MISSION DESIGN.

Core <u>Mission</u> ***Enhanced Mission***	**CBE Mass (kg)**	**Margin (%)**	**Mass with Margin (kg)**	**Peak Power (W)**	**Average Power (W)**
Science Instruments	5.52 *10.76*	23.33 *22.67*	6.87 *13.16*	6.37 *8.47*	6.37 *8.47*
Payload Mass	**5.52** ***10.76***	**23.33** ***22.67***	**6.87** ***13.16***	**6.37** ***8.47***	**6.37** ***8.47***
AOCS	6.69	20.00	8.03	62.50	36.50
AOCS Propulsion	12.10 *12.46*	20.00	14.52 *14.96*	10.00	4.50
OBDH and TT&C	11.36	20.00	13.63	12.00	6.50
Power	6.15 *6.28*	20.00	7.38 *7.54*	13.00	8.00
Mechanisms	2.00	30.00	2.60	1.00	1.00
Thermal & Radiation	2.15	15.00	2.47	11.58	8.10
Structure	3.26	10.00	3.59	0.00	0.00
Total	**43.71** ***44.20***	**-**	**52.22** ***52.81***	**110.08**	**64.60**
SailBus & Instruments	-	-	59.09 *65.97*	116.45 *118.55*	70.97 *73.07*
System Contingency	0.89 *0.99*	1.50	-		
Grand Total	**-**	**-**	**59.97** ***66.96***	**116.45** ***118.55***	**70.97** ***73.07***

5.2 <u>SailBus Modes</u>

The spacecraft has five primary modes of operation. During launch and kick-stage firing the SailBus is in Stand-by mode, where all systems draw minimal power provided by a primary battery within the kick-stage. Following insertion to the GeoSail orbit the kick-stage performs Sun acquisition and nulls the body rates prior to being jettisoned, triggering the Initialisation mode, which then charges the secondary batteries. Accurate attitude determination by star sensors follows, after which the spacecraft will initiate ground communication via the low-gain antenna (LGA) reporting its initial state and health. Finally on-board systems are brought online one-by-one and a system checkout performed. In general this mode acts as a diagnostic mode, which the SailBus enters on transfer from one mode to another.

During the Science mode data is collected from the instruments, running simultaneously if necessary, and stored in the on-board memory. The data collected is downlinked whenever possible using the medium-gain antenna. In sunlight there is sufficient power to downlink data and continue to collect new data, hence providing a continuous data stream. During shadow passage, power is severely limited. However, it is critical that the science payload continue to operate, thus the SailBus enters Science in Shadow mode. We continue to collect science data, however no attempt is made to downlink data or correct spacecraft attitude. The inertial measurement unit and star sensors, however, accurately track the spacecraft attitude for data reconstruction post downlink. Furthermore, the LGA transmits a 4 bps health signal, indicating spacecraft status such as attitude rates. If the health becomes critical science data collection can be terminated and power diverted to attitude control systems. The Safe Mode places the science payload in stand-by, along with all other non-essential systems. The LGA attempts to initiate ground communication and on successful contact transfers communication to the MGA. The sail remains in its zero pitch attitude with respect to the Sun and hence also places the solar array at zero pitch to the Sun. In this mode the spacecraft can survive shadow passage on only two of the three secondary batteries. SailBus modes and their relationships are visualised in Fig. 6.

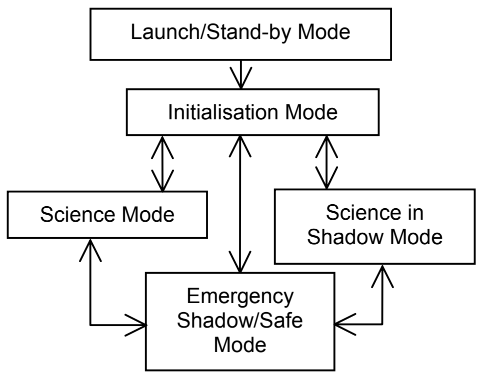

Fig. 6. SAILBUS MODES

5.3 <u>On-Board Data Handling and Telemetry Tracking & Command (OBDH and TT&C)</u>

The OBDH and TT&C systems are part of an integrated avionics bundle, including a power control card and I/O card, as well as an integrated S-Band radio and PC based on-board computer. The goal of the avionics bundle is to provide a standard, low mass base unit for future European missions, hence it should provide standard bus components common across all near-Earth missions, such as power regulation and distribution, communications, command and telemetry handling, data processing and storage. Sub-systems such as power generation and attitude determination are considered separate sub-systems and not included in this core avionics bundle. Mass and power analysis uses the AeroAstro NanoCore Bundle for reference values, which is expected to be flight validated in 2004. However, it is felt that a similar European system should be flight validated for future low mass missions. This avionics system would be a technology goal for the mission.

The communications system is entirely S-Band, 2.5 GHz downlink and 2.65 Ghz uplink, operating over two LGA and two helix MGA. A communications analysis was performed for the ESA ground stations at Kourou and Villafranco, using the trajectory results presented. The communications analysis assumes a non-spherical, non-flat Earth. It was decided to consider Kourou due to its low latitude, which would provide optimal communication conditions for GeoSail, with the results shown in Fig. 7. We see that the visible time from Kourou is more constant through the Earth year, while a clear variation is visible for Villafranco, which tends to provide slightly shorter communications windows, approximately 600 minutes versus 700 minutes.

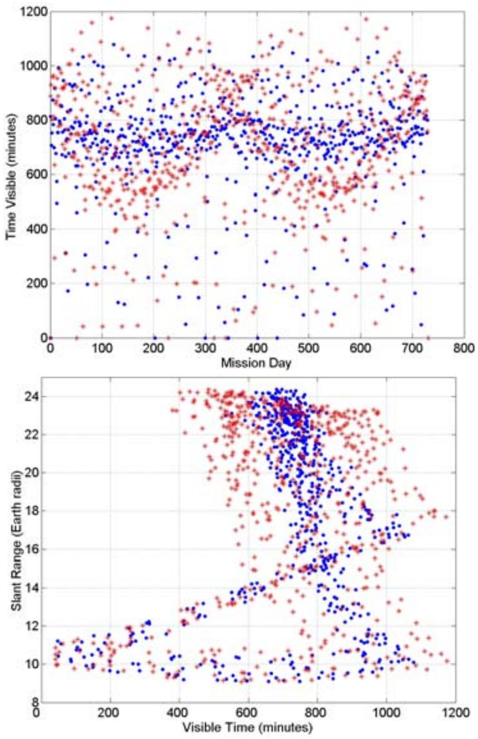

Fig. 7. COMMUNICATIONS ANALYSIS, TOP IS GEOSAIL VISIBLE TIME FROM GROUND STATION AND BOTTOM IS SLANT RANGE, WHEN VISIBLE; ASTERISKS (RED) REPRESENT VILLAFRANCO; DOTS (BLUE) REPRESENT KOUROU.

We also see from Fig. 7 that the slant range and visible time are similar for both ground sites at perigee, however a much wider variation is seen at apogee for Villafranco. Thus, while the Villafranco ground station is the de-facto choice for a European GeoSail mission, further consideration should be given to utilisation of Kourou, which would not require any new hardware and may provide a better communication option.

The communications system was sized for a slant range of 20 Earth radii, while it was assumed communication was not possible if the sail was within 10^{o} of the Sun or in shadow. It was found that we could typically downlink approximately 2.25 Gbit to Kourou per. orbit and 1.95 Gbit to Villafranco assuming less than 25% ground station availability, i.e. one downlink per. orbit, although a downlink opportunity typically arises every 28 hours, 627 opportunities in two years. Hence while both sites provide sufficient link margin, the selection of Kourou may allow better analysis of the plasma structure at the sub-second resolution due to the increased data return capability it offers.

5.4 Power

The power system is configured as a standard science mission bus. The supply is comprised of a single silicon solar array (15% efficient), mounted on the Sun-side of the payload structure. The array covers the full side and does not need to be deployed or actuated, since it is expected that the payload will maintain a fixed orientation with respect to the Sun due to the sail-pointing requirement of always maintaining zero pitch angle. The highest power requirements are during Science Mode, when it is anticipated that the SailBus will draw 71 W (73 W for enhanced payload). We note that the power values (peak and average) in Table 2 represent the unrealistic scenario where all systems are running simultaneously and are hence not used for the design case. Designing for a worst-case Sun angle of 2^{o}, based on the payload-pointing requirement of 1^{o}, we find a required array size of 0.97 m^2 (1.00 m^2 for enhanced payload).

The power system also contains 0.5 kg of Silver-Zinc primary batteries, used for mechanism deployment and for SailBus stand-by power requirements during launch/Stand-by mode. Secondary cells are three Lithium-Ion batteries, with associated charge and discharge regulators. The nominal mission duration of two years results in 174 charge-discharge cycles due to Earth shadow, designed as 250 minutes (0.4 % of perigee-perigee orbit period), though typical shadow duration is nearer 200 minutes. It has been found that by delaying the mission start date by a few days lunar shadow can be eliminated for the core mission duration, however for the scenario presented here three lunar events of 60-90 minutes were recorded, but found not to impact mission operations, although the spacecraft would enter the Science in Shadow mode. It was found for a depth-of-discharge of 50% and a battery to load transmission efficiency of 90%, a total secondary battery mass of 2.2 kg is required (2.3 kg for enhanced mission).

5.5 Thermal, Radiation & Environmental Analysis

The mean sail film temperature, in sunlight, varies from 271.5 K at Earth perihelion down to 266.8 K at Earth aphelion. These bounds present no thermal issues at this stage of sail design, assuming Kapton® is selected as the sail substrate.

Due to the extended Earth shadow durations the spacecraft thermal environment is relatively severe. The thermal subsystem includes heater and thermostat, fifteen separate temperature sensors and approximately 12 layers of Multi-Layer Insulation (MLI). This corresponds to maintaining a minimum SailBus temperature of 5°C and a maximum of just over 31°C. We note that heater power requirements are approximately 11.5 W. While temperature requirements could be relaxed in a future review, it was felt that at this stage of design a stringent set of requirements was preferred.

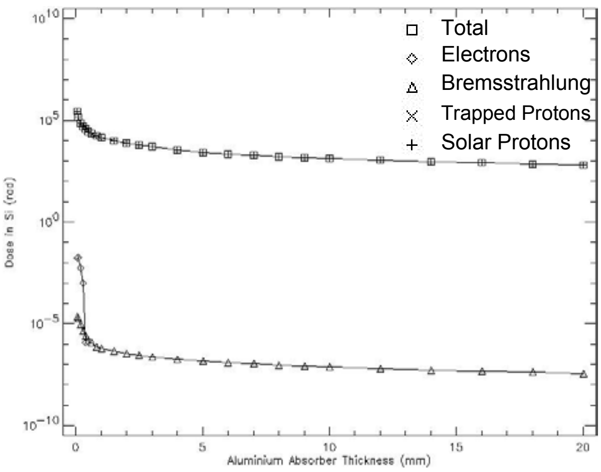

Fig. 8. TID VERSES ABSORBER THICKNESS, PROTON RESULTS WITHOUT NUCLEAR ATTENUATION.

An assessment of cumulative radiation dose was undertaken using ESA's spacecraft environment software, SPENVIS. This assumed an early 2010 launch direct to the GeoSail orbit, for a mission duration of 2 years. The total ionising dose (TID) due to different sources for increasing absorber thickness is seen in Fig. 8, where we see that for a total shielding of 4 mm the TID over the core mission duration is 3.5 krad (Si). We note however, that typical soft COTS technology fails near the 5-10 krad dose, thus little or no additional structure will be required for radiation shielding.

A brief meteoroid analysis using the Grun Meteoroid Model suggests that we can expect impacts with objects no greater than approximately 0.16 mm diameter over the core mission duration of two years, presenting minimal risk to sail systems.

6. SOLAR SAIL REQUIREMENTS

The solar sail design is based on the DLR-ESA solar sail concept, as this is currently the most advanced sail design within Europe. The solar sail is square, 3-axis stabilised, with a 10m deployable central mast, which houses the SailBus and payload instruments. Sail pitch and yaw control is by centre-of-pressure (CP), centre-of-mass (CM) offset, generating a torque to act on the spacecraft. A more advanced, preferable sail design would employ sail-tip vanes for attitude control, since it has been shown that this type of configuration is required for many advanced solar sail missions and would hence provide a more 'future-proof' design [4]. Furthermore, a significant design issue for all sail missions is the requirement for sensors and antennae to be placed on both sides of the sail. This would present much less of an issue if a centrally located SailBus was selected, with sail tip-vanes, in place of the deployed boom concept, which significantly increase design complexity.

Fig. 9 shows the GeoSail solar sail design chart for the core and enhanced payload options. We also see only minimal impact on sail size by implementation of a 30% mass and power margin, opposed to the more realistic approach of setting margin at the sub-system level by consideration of heritage and hardware maturity.

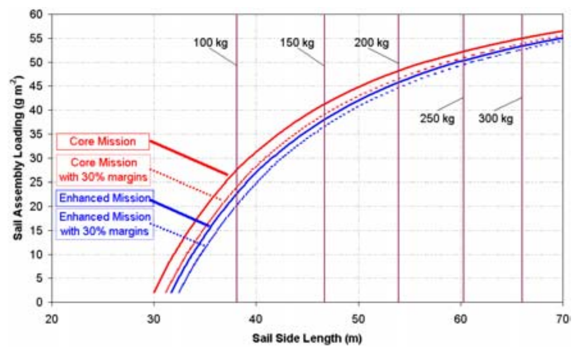

Fig. 9. GEOSAIL SOLAR SAIL DESIGN CHART, WITH TOTAL SYSTEM MASS INDICATED AS VERTICAL CONTOURS.

We see from Fig. 9 that even for a very poor performance sail of 50 g m^{-2}, the enhanced mission payload requires a square solar sail of only 59.7 m per. side, giving a sail and payload total of 245 kg. The DLR-ESA solar sail concept has a current benchmark of 17.9 g m^{-2}, for a 60 m per. side sail [5]. Using Fig. 9 we can define the required solar sail mass breakdown, for a range of possible sail designs.

Assuming the DLR designed CFRP booms (28 m boom length at 101 g m^{-1} up to 120 g m^{-1} for a 42 m boom) and a fixed mass of 25 kg of mechanisms that cannot be jettisoned, we find that for commercially available 7.5 µm Kapton® the minimum sail size is 41.2 meters for core payload and 42.8 meters for the enhanced payload. This includes a 0.1 µm aluminium front coating, 0.01 µm chromium rear coating, as considered during trajectory analysis and a bonding mass at 10% of the coated film mass. If we switch to Mylar film, which is commercially available down to 0.9 µm, we find we can reduce the sail size by up to 3.7 meters. However, Mylar has very poor radiation properties in comparison to Kapton® and would probably not be suitable for a mission such as GeoSail.

Fig. 10 shows the effect of decreasing Kapton® thickness and sail boom linear density on the size of the required sail. We see that a significant reduction in film thickness to 2 µm and a boom density of 50 g m^{-1} results in a required sail size of 37.1 m, only a 4-metre reduction from the current DLR-ESA sail design, but a sail system mass reduction of 6.74 kg, a 12 % mass reduction. Note, Kapton®, Mylar and Polyethylene Terephthalate (PET) have similar density and thus Fig. 10 shows that selection of any of these alternative materials would give similar mass benefits at constant film thickness.

7. LAUNCH, ORBIT INSERTION & COST

As previously noted, orbit insertion should be executed by a kick-motor, rather than by active sail manoeuvring, due to the prohibitive duration of such a transfer trajectory. A detailed trade was not performed in this study, instead a Vega launch was assumed. However, the consideration of other launch vehicles should be considered as a matter of course in future studies. It was found that a Vega launch into a 23.4^{o} inclination, circular 1500 km altitude orbit, could deliver both the core and enhanced payload options with significant launch mass margin. The transfer Δv to the 11x23 R_E orbit is approximately 3.5 km s^{-1}, giving a total propellant mass of 527 kg, assuming an Isp of 318 s for a bi-propellant system. A launch mass breakdown is presented in Table 3, where we see a Vega launch mass margin of approximately 42 % and 40 % (core and enhanced payloads respectively) for a Vega launch into a 23.4^{o} circular 1500 km orbit, followed by orbit transfer by a bi-propellant system. No staging of the kick-motor was considered but should be in future studies. A launch configuration is seen in Fig. 11, although this has not been optimised for structural loading it is clear that the stack fits into the required fairing volume.

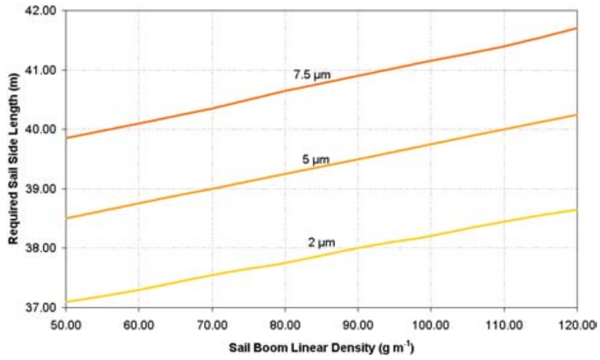

Fig. 10. REQUIRED SAIL SIZE FOR DIFFERENT KAPTON® THICKNESS AND BOOM DENSITY, FOR CORE MISSION.

Current ROM estimate of the GeoSail cost is approximately 103.2 M€, or 117.6M US$ (FY 2003), including 30% margins, which compares well with the SMART-1 mission cost of approximately 100 M€ (FY 2002). ROM cost includes launch, ground segment, integration, assembly and testing, and software and represents a very conservative high-end cost estimate. This cost places GeoSail firmly within the potential SMART mission range.

Table 3. LAUNCH MASS BREAKDOWN, *ITALIC* REPRESENTS ENHANCED PAYLOAD.

Component	Value	Unit	Mass Fraction
SailBus	60.0 *67.0*	kg	9.9 % *10.5 %*
Solar Sail (Assembly loading 33.43 g m^{-2} and 32.12 g m^{-2})	56.7 *58.2*	kg	9.3 % *9.1 %*
Jettisoned Sail Deployment Mass	25.0	kg	4.1 % 3.9 %
Total Mass Delivered by Kick-stage	**141.7** ***150.1***	kg	**23.3 %** ***23.6 %***
Bi-prop. kick-motor Dry Mass	57.4 *59.3*	kg	9.4 % *9.3 %*
Bi-prop. kick-motor Wet Mass	467.1 *485.9*	kg	76.7 % *76.4 %*
Launch Mass	**608.8** ***636.0***	**kg**	**-**

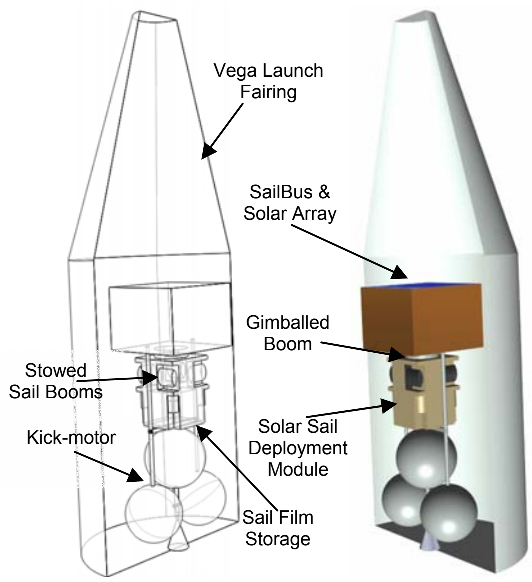

Fig. 11. A GEOSAIL LAUNCH CONFIGURATION

8. CONCLUSIONS

The GeoSail mission is a unique opportunity to demonstrate solar sail technology under the framework of a SMART mission, providing a demonstration of several new technologies that will be required across a wide range of future European missions, not only for solar sailing. GeoSail provides unique science opportunities, due to the long residence times in the key regions of geospace and the potentially massive amounts of data which can be returned, allowing sub-second resolution measurements of the plasma fields.

While key issues remain to be investigated and the current payload reviewed, it is clear that the GeoSail mission concept is strong and is also expandable to a constellation which would enable multiple rotating orbits, reducing the required constellation size by perhaps an order of magnitude. The required sail performance level is compatible with current European capabilities and the rotation of the orbit major axis showcases the mission enabling capabilities of solar sailing. GeoSail is a logical choice for a first operational European solar sail mission and is currently the only concept that is truly enabled by solar sail propulsion.

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