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FRISBEE – A PLATFORM FOR A SMALL SATELLITE SCIENCE SWARMS

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ABSTRACT

The FRISBEE multi-mission platform is presented, alongside the mission concept for SWARM (Space Weather Advanced Research Mission), a fleet of 30 or more microsatellites launched in groups of 5 and covering a range of local times and inclinations. The aim of this mission is to develop an understanding of the dynamic, global, and multiscale solar terrestrial interactions. The scientific payload is restricted to a dc magnetometer and electrostatic charged particle (ion and electron) analyser, providing both high time resolution and characterisation of collisionless plasma processes.

The baseline satellite swarm can be launched in a variety of configurations and be augmented by future launches of identical satellites to provide greater coverage and density of measurement. The satellites require only loose formation control to ensure equal separation throughout the set of orbits defined in this document. The individual satellites are spin stabilized and each have a mass < 25 kg.

This mission represents the next step in understanding the solar terrestrial interaction and the potential results will be of great interest to the space science community at large. This mission has a true requirement for a swarm such that it can sample the magnetosphere in three dimensions and with sufficient density of measurements.

The spacecraft required for this proposed mission could be designed and built within 24 months as most of the platform and payload technologies are re-used from previous missions. The mission has the potential for international collaboration, with provision of spacecraft platforms and world-leading scientific research.

A demonstration of this mission has been down-selected by the Particle Physics and Astronomy Research Council (PPARC) for potential funding in the UK National MOSAIC small satellite programme.

1 INTRODUCTION

Missions dedicated to the understanding of the Sun-Earth connections have explored a range of phenomena that can be explored with single spacecraft. Furthermore, missions such as Cluster have started to explore specific time and space varying characteristics of the magnetosphere. SWARM is a mission comprising a large number of spacecraft to explore the large-scale magnetosphere.

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The spacecraft required for this proposed mission could be designed and built within 24 months as most of the platform and payload technologies are re-used from previous missions. The mission has the potential for international collaboration, with provision of spacecraft platforms and world-leading scientific research.

A demonstration of this mission, termed “FRISBEE”, has been downselected by the Particle Physics and Astronomy Research Council (PPARC) for potential funding in the UK National MOSAIC programme second round, which is expected to be announced and initiated in early 2004. The demonstration is for a single spacecraft, and this mission would benefit by having additional spacecraft alongside to enhance the science of this early demonstration of the larger scale swarm.

As an additional step, a science mission concept based on 8 FRISBEE spacecraft can be employed in the study of specific time-varying elements of the magnetosphere beyond those that have so far been possible with Cluster.

1.1 Background

Solar terrestrial physics has made great advances over the past 20 years due to the wealth of detailed data taken by numerous spacecraft. Our present understanding is concentrated in two diametrically opposed perspectives. At the microscopic level, high resolution particle and fields measurements have elucidated the variety of collisionless processes which influence and control the exchange of mass, momentum, and energy between the solar wind and the Earth's magnetosphere. Such processes, including collisionless shocks, particle acceleration, and magnetic reconnection, have far-reaching implications for terrestrial plasmas on the one hand, and more remote, astrophysical plasmas on the other. At the other extreme, the global shape of the magnetosphere, and the various layers and boundaries within it, have been determined essentially on a statistical basis by collecting and averaging the results of many spacecraft traversals over an extended period of time.

However, we know that many of the key processes, such as reconnection and particle acceleration, are affected by localised, sporadic events and/or responses to temporal variability of the upstream solar wind, to spatial variations, and to other more global dynamic influences. To date, analysing the sequence of events in such varying conditions required the serendipitous conjunction of several space missions, and was complicated by disparate instrumentation and calibration issues.

Thus, the time has come to take the next leap in understanding the solar terrestrial interaction. The growing reliance on space-born technology by society at large adds a degree of urgency and applicability to the basic scientific questions, which need to be addressed.

1.2 Objectives

This swarm project will employ a large number (30 as a minimum) of minimally-instrumented very small, inexpensive satellites to study the 3D, time-dependent magnetosphere of the Earth. Specific objectives include:

1. Mapping magnetic field configurations throughout a substorm
2. Mapping the shape and response to varying solar wind input parameter regimes and transients of key boundary layers (bow shock, dayside magnetopause, cusp, tail current sheet) which mediate the Solar-Terrestrial Interaction
3. Simultaneous study of 3D time dependence over many scales, ranging from micro/gyroscales to global scales
4. Studies of naturally occurring turbulence (e.g., magnetosheath, foreshock, and auroral acceleration regions) including study of planarity, coherence, propagation directions and mode identification
5. Testing and validating geospace and magnetospheric models

Cluster II employs 4 identical highly equipped spacecraft to unravel the detailed local micro-processes, which mediate the transport through key regions and boundaries (bow shock, high altitude cusp, geo-magnetic tail). By contrast, SWARM is a minimal payload to map and follow large-scale, global processes and transients. By analogy with meteorology, Cluster II will unravel the structure and physics of a hurricane, while SWARM will establish the global weather configurations under which hurricanes form and how they move.

1.3 Strategy

To meet these scientific objectives requires spacecraft covering a wide range of local times. Additionally, some combination of equatorial and polar coverage is needed to separate latitudinal and longitudinal variations and to examine the key polar regions. SWARM will investigate the terrestrial response to solar wind conditions, and thus must extend to radial distances throughout the outer magnetosphere and upstream/foreshock regions.

The proposal is to occupy 4 local time zones (with a duplication in one local time at a different apogee) and one polar orbit. Five spacecraft per orbit ensures a reasonable spread, and provides a small level of redundancy. A certain failure rate is expected and acceptable. Satellite orbits will drift apart, confined to their orbital plane. Thus 3D coverage requires different groups to be launched into orbits with different inclinations and sunward apogees at different seasons. This configuration, sketched in Figure 1with details in Table 1, rotates in local time with the seasons, but ensures that there is nearly always an upstream monitor and a range of radial distances. Such orbits sample all of the magnetosphere including the solar wind and bow shock, magnetosheath and magnetopause, cusp/auroral regions, dawn and dusk flanks, and near geomagnetic tail.

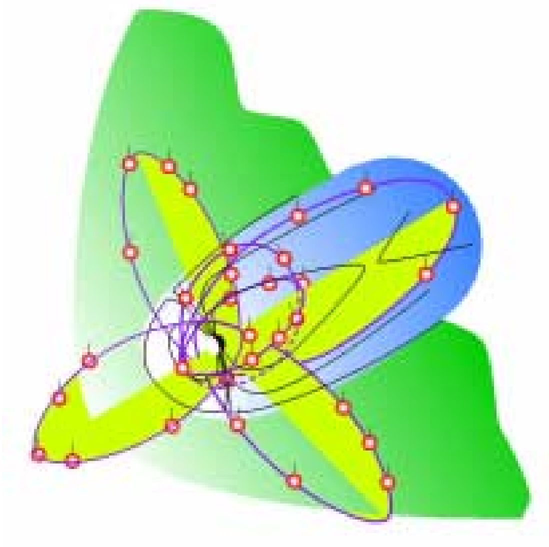

Figure 1 Sketch of the full SWARM in flight

Group	LT	Incl.	GSE lat. @ apo.	Apogee	Perigee
1	1200	0º	0º	$20R_e$	$2.5R_e$
2	1800	0º	0º	$20R_e$	$2.5R_e$
3	0600	0º	0º	$20R_e$	$2.5R_e$
4	0000	0º	0º	$12R_e$	$2.5R_e$
5	0000	0º	0º	$30R_e$	$2.5R_e$
6	0000	~90º	~60º	$15R_e$	$2.5R_e$

Table 1. Orbit Parameters – 5 Satellites in each group

2 PAYLOAD

In this swarm, the spacecraft and payloads will be identical, however, the flexible payload interface allows for different instruments to replace the standard set as required. These could include solid-state energetic particle detectors, radio experiments etc. A simple spin-stabilised microsatellite bus provides central services and subsystems.

2.1 Scientific Instruments

The approach is a minimal payload with emphasis on large numbers of spacecraft. The dc magnetic field, sampled at 128 vectors per spin period, provides a good road map of the solar-terrestrial system and local variability.

However, measuring and following the collisionless processes, which lie at the heart of the solar terrestrial interaction, requires at least some characterisation of the particle populations. Additionally, collision-free particles also provide tracers of connectivity and intervening phenomena between locations. Thus the scientific payload includes particle (ions and electrons) detectors.

These two instruments would share an integrated data processing unit, spacecraft interface, and power supply. Although the magnetometer would be based on a standard fluxgate instrument, the particle detectors are based on a common unit incorporating a miniaturised electrostatic analyser based on Cluster PEACE and Cassini ELS heritage. A prototype is currently under construction for which the baseline resolution is 60 Energy x 16 Azimuthal x 8 Polar bins.

The detectors are corner mounted with a full 360° field of view in a plane parallel to the spin axis. Thus full 4π steradian coverage by a single sensor is accomplished in half a spin period. The ion sensor and electron sensor are mounted on the corners of the spacecraft. The baseline spin period for this mission is 4 seconds.

The target payload requirements are summarised in Table 2.

Instrument	Mass Kg	Power W	Data Words [a]	Telemetry kbps [b]
Magnetometer (head/boom/ electronics)	1.95	0.8	96	0.75
Ion Sensor	0.9	1.5	3840	30
Electron Sensor	0.9	1.5	3840	30
Electronics	0.6	5.0	-	-
Total	**4.35**	**8.8**	**7776**	**60.75**

Table 2. Payload Resources

[a] Science words per second, excluding time tags and housekeeping (expected housekeeping data rate is 32 words/sec = 0.25 kbps)

[b]Assuming 2 byte science words and factor 2 compression

3 LAUNCH, DEPLOYMENT, CONTROL AND DISPOSAL OF THE SWARM

3.1 Launch and Deployment Strategy

3.1.1 Launch Vehicle

Three alternatives for the launch and deployment of the constellation will be studied as follows. Separate and independent Ariane ASAP launches into GTO are the baseline for this swarm mission. A certain spread out in time – up to 18 to 24 month - of the ASAP opportunities is acceptable for this mission. It would also be possible to launch all SWARM groups at once by some capable launcher into a rapidly precessing transfer orbit and then perform independent boosts for each group as the transfer orbit precessed to the appropriate local time. This could be accomplished within ~ a year depending on the initial transfer orbit. In this alternative we have e.g. Sealaunch and the new European Vega launcher. The three Russian alternatives will also be studied for the high inclination group - group 6, Start-1, Eurorockot, Dnepr. Independent ASAP launches remain the baseline SWARM strategy. This minimises risk and increases flexibility.

3.1.2 Getting the swarm S/Cs into the intended orbits

The spread in required Local Time of the different SWARM groups is easiest to achieve with separate launches into GTO. It is expected that the detailed ”worker” and “hive” concepts described below are compatible with the Ariane V ASAP configuration.

The high inclination group (group 6) requires two hives carrying at most 3 workers each to obtain their orbit within the ASAP constraints. Each ASAP launch of one Hive is followed by either a direct insertion or delayed insertion into the intended SWARM orbit for that specific group. The purpose of a delayed orbit insertion is to utilize the node drift of the Ariane GTO – about 150 deg/year – to achieve the required LT, and thus allow smaller boosters for the shaping of the SWARM orbits. The raising of the apogee and perigee is done using the hive boost motors. A design concept is shown below.

Figure 2. Multiple spacecraft adaptor and dispenser

3.1.3 Getting the five in the hive spread out uniformly in time

After the insertion of the Hive into the intended Swarm orbit, the workers are separated from the hive by a simple mechanical spring/release separation system. The workers are spun up, the spin vectors individually precessed into attitudes suited for the subsequent mean anomaly adjustment phase. A series of constant burns with the cold gas system are applied, tangentially in the orbital plane. The resulting deltaV will adjust the individual orbital periods for the five. Over time – from three to six months – the five in the hive will have reached the required spread in Mean anomaly. During this adjustment phase, two of the workers will have their periods shortened, two will get longer periods, one will be untouched. When the Mean anomalies have reached the required targets, a finalizing series of cold gas burn will halt the relative mean anomaly drift and adjust the period back to the nominal period for that SWARM group, the separation in time is now frozen. The cold gas burns are most effectively done at the apogee, the resulting deltaPeriod for a constant deltaV is between 5 and 12 times more efficient at apogee than at perigee, depending on which of the six groups. A more detailed elaboration on this will be done in the study.

SWARM Worker - The payload, described more fully in subsequent sections, will fit comfortably on a spacecraft bus of microsatellite class. These individual SWARM “Workers” in science flight are spin-stabilised,

SWARM Hive - Five SWARM workers are attached around the perimeter of the SWARM Hive, which is a cylindrical assembly containing two oppositely directed solid booster motors. These boosters provide individual burns to raise apogee and perigee from GTO. One Worker is designated the “Queen” for the Hive and provides control during the transfer phase. In the baseline alternative with separate GTO ASAPs, Group 6 destined for a high inclination, requires additional thrust to change the orbit. This group is split into sub-groups of two each with three Workers. Each sub-group is launched on a separate Hive.

Figure 3. SWARM hive concept

3.1.4 Flexible Launch Window

There is considerable tolerance in the placement of the groups 1-3 in LT. The midnight groups 4 and 5 need to be more carefully inserted to ensure simultaneous and broad cover of the near and far geomagnetic tail. The two sub-groups of the high inclination orbit (group 6) need to be phased to provide the required polar coverage, which need not imply identical local times at apogee. Manufacturing constraints and launch availability, together with operational considerations, need further study. The actual epoch for SWARM launch and science is flexible, although a science mission period near the maximum in the solar cycle, with frequent transients - especially large scale energetic ones, would be beneficial.

3.2 Swarm control strategy

The principles for controlling the Swarm during the different mission phases is described schematically below:

HIVE and QUEEN phase

Activity	Type of Control	Comment
Launch of Hive	OFF	
Hive separation from upper stage	OFF	
Power up of Hive basic functions	Autonomous	Time-tagged from separation signal
IOT Health Check of Hive	Autonomous/	Go Ahead

	Ground	Cmds
Drift of Hive orbit into desired LT for the intended SWARM orbit for that specific group	Autonomous	
Wait,	Autonomous	
Configure for Lean science	Autonomous/ Ground	Go Ahead Cmds
Preparation of Hive for Orbit insertion	Ground	Enabling Cmds
Apogee and Perigee boosts manoeuvres, into desired shape for the intended SWARM orbit for that specific group	Autonomous	

WORKER phase

Activity	Type of Control	Comment
Worker separation	Autonomous/ Ground	Go Ahead Cmds
Worker spin up	Autonomous/ Ground	Go Ahead Cmds
Mean anomaly adjustment phase		
Prepare for cold-gas deltaV	Ground	Enabling Cmds
Individual spin vector precession	Autonomous	
Acquire apogee burn attitude	Autonomous	
Initiating series of apogee cold gas burns	Autonomous /Ground	Enabling Cmds
Relative drift in the mean anomaly	Autonomous	
Wait	Autonomous	
Configure for Lean science	Autonomous/Ground	Go Ahead Cmds

Current estimates of the all-in spacecraft mass suggest that each vehicle will have a mass of < 25kg. This will lead to 125 kg per group of 5 spacecraft and 750 kg for the swarm not including the hive booster stage. To stay inside the 1200 kg mass limit specified by ESA, a variety of launch options have been assessed alongside reductions in the spacecraft mass.

4.2 Platform Description

4.2.1 Radiation Environment

The total radiation dose over the mission lifetime will be on the order of 50-100 kRad. A major concern will be the high-energy electrons found in the outer radiation belt, which will be traversed once per orbit. In order to meet these requirements using traditional low cost microsatellite subsystems, more careful component selection and testing will be necessary, but also shielding can be successfully applied in most cases.

4.2.2 Power

Primary power to the satellite is supplied via multi-junction GaAs cells mounted on a set of solar panels. An 8 A-Hr Li-Ion battery back will provide power during the eclipse periods. The 28V supply to the platform subsystems and the 5V supply to the payload is via a Direct Energy Transfer power system, which

Finalizing series of apogee cold gas burns	Autonomous /Ground	Enabling Cmds
Individual S/Cs are now spread out uniformly in time	Autonomous /Ground	Enabling Cmds
Spin down to "science" rate	Autonomous /Ground	Enabling Cmds
Individual spin vector precession into "science" attitude	Autonomous	

SWARM phase

Activity	Type of Control	Comment
Commissioning of Constellation	Ground	
Science Routine Operations	Autonomous	

3.3 Disposal of the swarm

Disposal of the swarm at end of life is an outstanding issue to be studied, and complicated by the high-energy requirement. This may be seen to be essential as the perigees of the swarm orbits all lay at MEO altitudes and 25 of the 30 spacecraft will intersect the GEO ring.

4 PLATFORM DESCRIPTION

4.1 Payload Requirements

The payload requires 8.8 W of power and has a mass of 4.35 kg. The data rate from the payload is 60.75 kbps.

is based on the SSTL/ESA/QinetiQ designed STRV-1c/d system designed for operation in GTO.

4.2.3 AOCS

The platform will be spin stabilized and will use fan beam Earth & Sun Sensors for attitude determination and spin rate information. A cold gas system is baselined for attitude and orbit control (thrusters required: spin-up, spin-down, precession and orbit control). Rhumb line precessional manoeuvres can be phased off the sun sensor. Due to the close initial proximity of the swarm vehicles, the cold gas will be selected to avoid contamination of neighbouring vehicles.

A GPS system augmented with NORAD Two Line Elements should meet the orbit determination requirement. PRN ranging methods have also been considered.

4.2.4 Payload Interface and OBDH

The payload interfaces point-to-point into the dedicated data processing unit. This will be based on the radiation hard OBC 695 which employs a single chip implementation of the ERC32 processor. 16Gbits of radiation hard RAM is provided for payload data storage.

A second processor performs the platform processing functions and is also an OBC 695. The data bus is based on the CAN bus system which both SSTL and SSC have a great deal of experience with. The OBC695 and a radiation hard implementation of the CAN bus will be flown on the platform SSTL is developing this for ESA's GSTB-v2 mission.

Figure 4. OBC695 Prototype

The key parameters of the OBC695 are listed below.

OBC695 specification	
Parameter	**Value**
Processor	Atmel TSC695F SPARC V7 RISC Architecture
Performance	20 MIPS/5 Mflops @ SYSCLK 25MHz (Timing analysis indicates SYSCLK @ 20MHz preferred)
Memory	4 Mbytes (expandable to 8 Mbytes) with cyclic EDAC as standard (2 bit detection, 2 bit correction per byte)
Non-volatile storage	32Kbyte Boot PROM
Communications	Four Full Duplex HDLC Links, up-to 10Mbits/sec (HDLC Links modified to support CCSDS) Two Full Duplex RS422 Asynchronous Links
Spacecraft Bus	Controller-Area-Network (CAN)
Radiation Tolerance	>100 KRad (Si)
Single Event	Latch Up Immune
Power	5W peak
Mass	3kg

Table 3

4.2.5 Communications

The baseline for communications is via an S-band link. The technologies and strategies for communications to multiple spacecraft need development in conjunction with an operations concept. This would include frequencies, protocols and multiple access schemes. The selection of suitable ground stations and the possibility of running the payload in a lower resolution mode to reduce data rates are being considered, alongside X-band downlink solutions.

4.2.6 Technology Developments Required

In summary, the technology developments required for this platform are:

- Radiation hardening of traditional LEO microsat subsystems
- Communications - technologies and strategies
- Development of an intelligent booster / dispenser for the SWARM
- SWARM disposal at end of life
- Dynamics and collision avoidance
- Time determination and synchronisation across a SWARM

Figure 5. Impression of vehicle during science flight with magnetometer boom deployed.

5 SUPERCLUSTER - STEPPING STONE MISSION

As a stepping stone to a full-blown mission, it is possible to employ the same platform design in the SuperCluster mission concept. A swarm of 8-10 microsatellites launched into an orbit, which will take them through key plasma regions of the solar wind - magnetosphere system. The swarm configuration will allow for measurements to be made at a number of different scales (from the very small electron process scales up to the much larger ion process scales), which will illuminate the different collisionless space plasma processes taking place.

Figure 6. SuperCluster artist impression

SuperCluster provides the next step after the ESA Cluster mission in understanding the solar wind - magnetosphere system and the potential results will also be of great interest to the space science community at large. This mission has a true requirement for a swarm such that it can make simultaneous measurements at a number of different scales. Like SWARM, the mission also has the potential for international collaboration, with provision of spacecraft platforms and world-leading scientific research.

5.1 Scientific Background

Electron processes within current layers undergoing magnetic reconnection control the exchange of mass and energy which is manifested at ion and magneto-hydrodynamics scales. In order that these multiscale processes be better understood this swarm will attempt simultaneous measurements at scales ranging from < 1 km (never before attempted) up to many 1000s of km.

This mission acts as a follow on from the single scale observations made by Cluster. The scientific payload is restricted to a dc magnetometer and electrostatic charged particle (ion and electron) analyser, providing both high time resolution and characterisation of collisionless plasma processes.

To meet these scientific objectives requires two concentric and differently sized 'polyhedrons' (spacecraft located at the vertices) of spacecraft traversing an orbit, which passes through regions of interest in the solar wind – magnetosphere system. The 'polyhedrons' will inevitably change shape and evolve throughout the orbit and mission lifetime, which has a baseline of two years. The evolution of the 'polyhedrons' will be controlled such that they are in a desirable configuration as they pass through the regions of interest. The payload will only be on as the spacecraft pass through these regions to reduce the amount of data storage required and to minimise the communications link requirements. The desired orbit and control of the spacecraft will be determined in the study.

It is intended that the separations in the smaller 'polyhedron' will be of the order of < 1 km whereas the larger 'polyhedron' will have separations of > 1000 km. Determining and maintaining the spacecraft separations in the smaller 'polyhedron' will be extremely challenging and will require detailed study.

In this swarm, the spacecraft and payloads will be identical, however, the flexible payload interface allows for different instruments to replace the standard set as required. These could include solid-state energetic particle detectors, radio experiments etc. A simple spin-stabilised microsatellite bus provides central services and subsystems.

The approach is a minimal payload with emphasis on large numbers of spacecraft. The dc magnetic field, sampled at 128 vectors per spin period, provides a good road map of the solar-terrestrial system and local variability.

However, measuring and following the collisionless processes, which lie at the heart of the solar terrestrial interaction, requires at least some characterisation of the particle populations. Additionally, collision-free particles also provide tracers of connectivity and intervening phenomena between locations. Thus the scientific payload includes particle (ions and electrons) detectors.

These two instruments would share an integrated data processing unit, spacecraft interface, and power supply. Although the magnetometer would be based on a standard fluxgate instrument, the particle detectors are based on a common unit incorporating a minituarised electrostatic analyzer based on Cluster PEACE and Cassini ELS heritage. A prototype is currently under construction for which the baseline resolution is 60 Energy x 16 Azimuthal x 8 Polar bins. The detectors are corner mounted with a full 360° field of view in a plane parallel to the spin axis. Thus full 4p-steradian coverage by a single sensor is accomplished in half a spin period. The two ion sensors are mounted on adjacent corners so that their fields of view are 90° with respect to each other; thus their combined data have a resolution of a quarter of a spin period. The electron sensor has a similar design and is mounted on a third corner of the spacecraft.

The target payload requirements are summarised in Table 4

Instrument	Mass Kg	Power W	Data Words [a]	Telemetry kbps [b]
Magnetometer (head/boom/ electronics)	1.95	0.8	768	6
Ion Sensor	1.8	3.0	61440	480
Electron Sensor	0.9	1.5	30720	240
Electronics	0.6	5.0	-	-
Total	**5.25**	**10.3**	**92928**	**726**

Table 4. SuperCluster Payload Reseources

[a] Science words per second, excluding time tags and housekeeping (expected housekeeping data rate is 32 words/sec = 0.25 kbps)
[b] Assuming 2 byte science words and factor 2 compression.

6 CONCLUSION

The multi-mission FRISBEE platform has been described, alongside two science missions, SuperCluster and SWARM, which it can address. Very low cost science platforms, capable of surviving the harsh environment of the Earth's magnetosphere will enable more large-scale missions to be flown to aid in the detailed understanding of Sun-Earth interactions. Better understanding of the space weather will bring significant benefit to commercial space applications, as well as terrestrial applications.