SWARM: A Fleet of Microsatellites to Explore the Magnetosphere

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Abstract. To begin to understand the dynamic, global, and multiscale solar terrestrial interaction, the UK has begun planning for SWARM, a fleet of 30 or more microsatellites launched in groups of 6 and covering a range of local times and inclinations. The scientific payload is restricted to a DC magnetometer and electrostatic charged particle (ion and electron) analyzer, providing both high time resolution and characterization of collisionless plasma processes. New technologies, including GPS receivers and mobile phone communications, may be required to provide autonomous satellite operation. Combined electronics and new launch capabilities make the mission practical as well as timely.

1. Introduction

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 as well as remote, astrophysical plasmas. 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.

The above approaches have afforded us the knowledge that many of the key processes, such as reconnection and particle acceleration, are affected by localized, sporadic events and/or responses to temporal variability of the upstream solar wind, to spatial variations, and to other more global dynamic influences. At present, analyzing the sequence of events in such varying conditions requires the serendipitous conjunction of several space missions, and is complicated by disparate instrumentation and calibration issues. 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.

Plans within the UK for such a global, multiscale mission began in earnest early in 1997 through building upon national and international informal interest spanning a decade or more. Expertise in satellite technology and space physics, together with enabling technology, provided the natural motivation in the UK. Thus, the SWARM concept was born. SWARM now forms the third tier in a UK microsatellite program. The program, together with complementary UK activities is described in *"Solar Terrestrial Physics in the UK: Scientific Goals and Projects for the Next Millennium, a report by the UK community to its funding body"* and available at http://www.space-plasma.qmw.ac.uk/UK_STP/.

This paper describes briefly the mission objectives, strategy, payload, and operations.

2. Objectives

The SWARM project will employ a large number (30 or more) of minimally-instrumented very small, inexpensive satellites to study the 3-D, 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 3-D 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.

The mission complements that of Cluster II, which will be launched in mid-2000. Cluster II will employ 4 identical highly equipped spacecraft to unravel the detailed, local micro-processes which mediate the transport through key regions and boundaries (bowshock, high altitude cusp, geomagnetic 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.

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, at least one of which

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includes both equatorial and highly inclined orbits. Six 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 3-D coverage requires different groups to be launched into orbits with different inclinations and sunward apogees at different seasons. For example, two groups may share a common apogee local time but reside in orbits with inclinations differing by 90 degrees. The three remaining groups (making 5 groups or 30 satellites in total) would be spaced in local time to give good coverage. This configuration, sketched in Figure 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. Polar coverage would be improved by the addition of further groups at highly inclined orbits, especially ones with high elevations as well.

4. Payload

The spacecraft and payloads will be identical, based on design and proof of concept trials involving one or two prototype spacecraft prior to mass production. A simple spin-stabilized microsatellite bus provides central services and subsystems.

4.1 Scientific Instruments

The approach is a minimal payload with emphasis on large numbers of spacecraft. The DC magnetic field, sampled at 32 vectors per second, 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 characterization of the particle populations. Additionally, collision-free particles also provide tracers of connectivity and intervening phenomena between locations. Thus the scientific payload includes a combined ion/electron electromagnetic plasma analyzer. The analyzer counts ions in energy per charge bins. Partial moments up to and including the heat flux vector for both electrons and ions (26 moments or phase space densities) sampled 8 times per second would describe the plasma population with maximal precision.

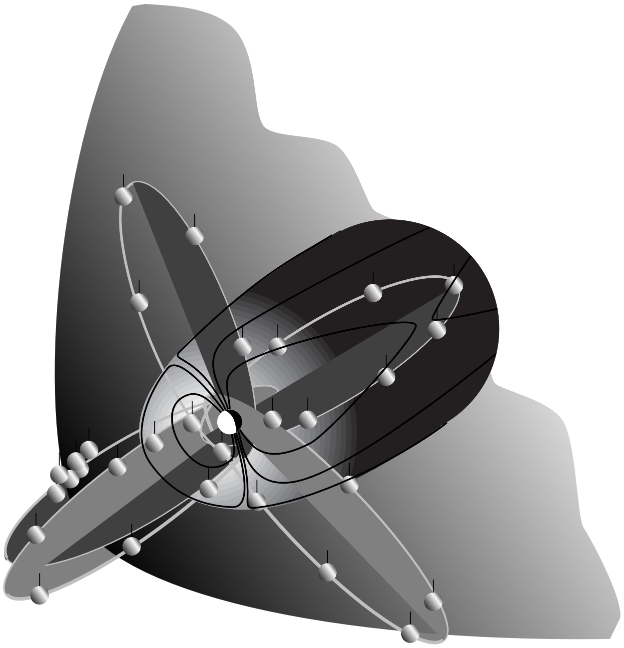

Figure 1. Sketch of the full SWARM in flight, showing the coverage in local time of the different orbital planes, and a duplication at one local time but with different inclinations.

Table 1. Payload Resources

Instrument	Mass Kg	Power W	Data[a] words	Telemetry[b] kbps
Magnetometer	1.5	2.0	96	0.31
Boom	2.0	-	-	-
E/q Analyzer	1.7	2.0	208	0.67
Electronics	1.5	2.5	-	-
Total	6.7	6.5	304	0.98

[a] Science words per second, excluding time tags and housekeeping

[b] Assuming 4 byte science words and factor 10 compression

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, both the particle analyzer and the common electronics for the entire scientific payload require substantial design work. Selective preflight calibration together with in-flight cross-calibration procedures will be required as extensive ground tests are impractical and costly for so many units.

The target payload requirements are summarized in Table 1. Masses are based on present generation instruments and may be pessimistic; compression ratios may be optimistic.

4.2 Spacecraft Subsystems

In any multi-satellite mission, knowing the spacecraft position is absolutely vital. The SWARM spacecraft design includes a GPS receiver to provide autonomously the necessary accuracy (at least for part of each orbit for reconstruction purposes) to better than a km.

Attitude control is not critical, although attitude reconstruction to a degree or so is required for the magnetic field measurements. This may involve a star tracking system of some kind, although simpler solutions requiring less mass and power may prove adequate. Orbital maneuvers after initial orbit insertion are not envisaged for cost reasons. Some small thrusters to establish and maintain an appropriate spin rate may be necessary.

Other components include mobile phone components for communications via commercial satellites in MEO, a simple on-board data handling system (mass memory), and power system.

5. Operations

5.1 Launch

Launch(es) could be piggyback with other payloads to minimize launch costs. Satellites would be launched in groups of 6 to form individual local 3-D mini-clusters until they drift apart. The scientific objectives require orbits with apogees in the range 15-20 R_E. Perigee is determined primarily by the need to provide adequate and variable drag on the spacecraft to spread the initial mini-cluster into roughly equal (in time) along-track separations within the first few months after launch. Other factors impacting on perigee include radiation doses, eclipses, communications, and the launch itself.

One launch scenario involves utilizing the Ariane Structure for Auxiliary Payloads to lift an entire group of six, together with a kick motor for raising the apogee of the group prior to separation. Dedicated launchers are also possible, but increase significantly the launch costs.

The entire fleet should be launched within a window of 2-3 years, depending on individual spacecraft lifetimes, to ensure the multi-satellite technique can be well-exploited in a further year of mission operations.

5.2 Communications and Ground Segment

With so many spacecraft and so much data, communications becomes a central issue. Near autonomy in both spacecraft operation and data handling are required. Very restricted commanding is anticipated. Duty cycles for data taking may be limited by telemetry considerations, but should not be allowed to fall below 50% or so. Data taking must occur simultaneously on all spacecraft, so that duty cycles will be fixed UT intervals.

We are actively exploring the possibility of providing both uplink and downlink capabilities by use of mobile phone technology. Phones on each spacecraft would "ring" the SWARM Operation Centre through existing or planned commercial communications satellites and their ground network. Such communications would only be possible for some fraction of the orbit, although using an MEO-based system would ease the visibility problems between SWARM spacecraft and the telecommunications network of spacecraft. Similarly, commands would be uplinked through the commercial system.

This novel approach simplifies and streamlines the ground segment, although the final cost in telephone time may be comparable to more traditional communications systems. An added problem, however, is the Doppler shift induced by the relative SWARM spacecraft/communication satellite motion. This could be corrected on-board the SWARM spacecraft if ways can be found to determine which single communications satellite in the network would provide the initial link.

An alternative approach involves conventional space-borne communications hardware and a set of small, autonomous PC-controlled ground stations which would feed data over computer networks directly to the SWARM Operation Centre. These stations could be located nearly anywhere, including schools and other public establishments, thereby providing a focal point for public understanding and outreach programs. Overcrowding of limited frequency bands may pose severe restraints on the number of satellites and/or ground stations actively communicating at any one time.

5.3 Data Handling

The key to the success of SWARM lies ultimately in our ability to readily combine, process and visualize data from a large number of spacecraft. New tools and displays will be vital. In this regard, Cluster II may provide the opportunity to explore novel techniques. Cross-calibration of instruments amongst the SWARM fleet will be required, and algorithms need to be developed to accomplish this routinely with minimal human interaction. Rapid data dissemination via the Internet to the scientific community and the public will be a priority.

6. Overall Mission Costs

At present only national mission costs are available. Based on typical microsatellite architecture (~$30kg total weight) and multiple procurement, the total unit cost, including scientific instruments and launch but excluding ground support, is in the range of £1.5million, leading to a total mission cost for the SWARM, including ground segment, of approximately £50-60 million. It is anticipated that further study should reduce this figure by a substantial fraction. The lower quality assurance made possible by redundancy should lead to significant savings which have not yet been quantified. Major areas of uncertainty include mini-cluster launch costs, communications issues, and the trade-off between specialized integrated electronics/ development and off-the-shelf (more massive) instruments.

7. Conclusion

SWARM represents a practical step in our understanding of the solar-terrestrial interaction. Although the emphasis is clearly on multiple, simultaneous sampling of transient processes throughout the magnetosphere, the scientific payload includes sufficient resolution in time and in particle velocity space to relate the key local, collisionless processes to the global response. Most of the components are based on existing designs (magnetometer, spacecraft bus), although developments in a combined E/q ion and electron sensor, in combined payload electronics, in GPS hardware, and in communications solutions are required to reduce spacecraft mass and power requirements, and overall mission costs. Despite these open areas, the mission can be done within a modest cost envelope provided Ariane ASAP or other cost-efficient piggyback launch opportunities are available.

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