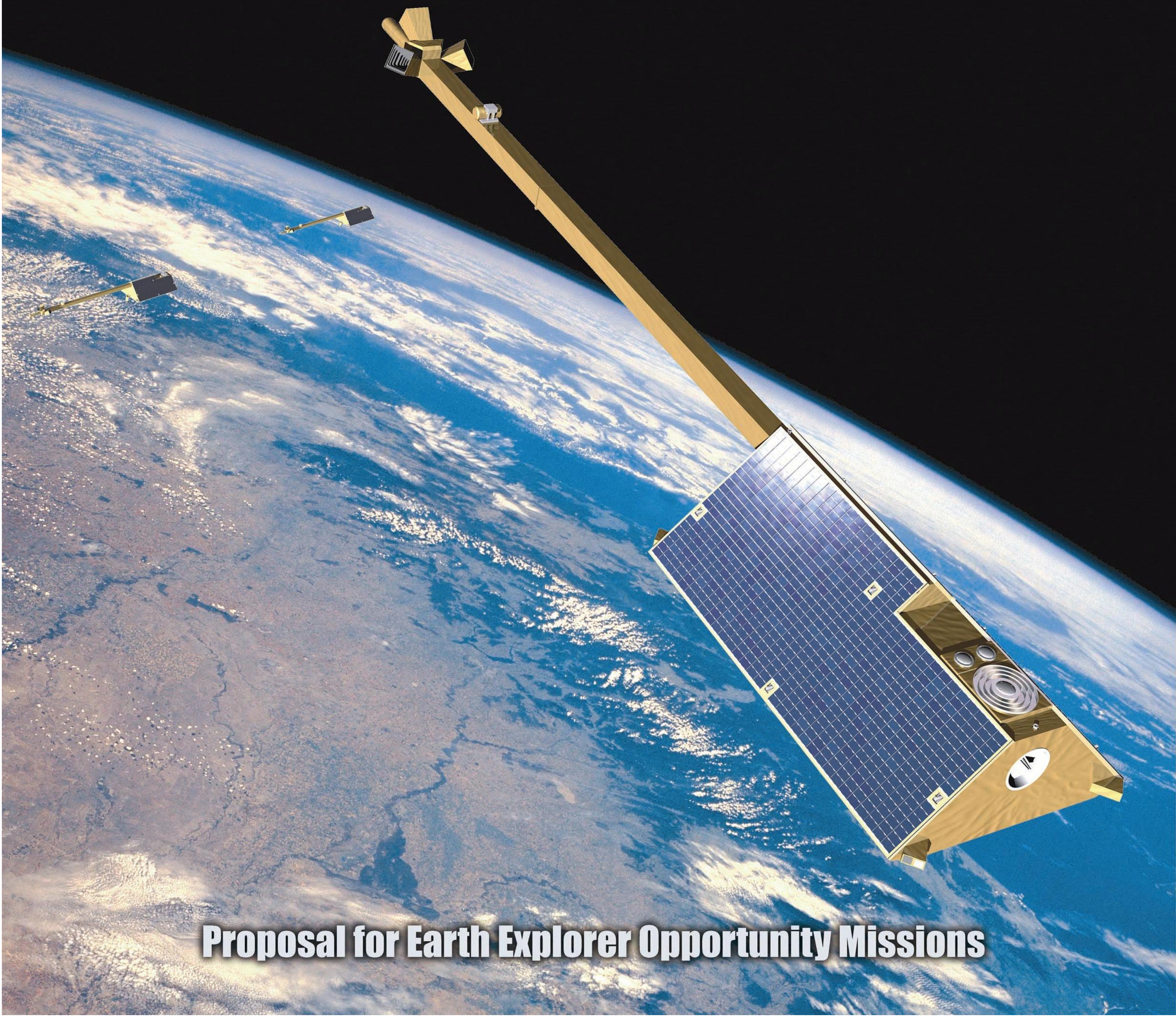
swarm

a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System



Proposal for Earth Explorer Opportunity Missions

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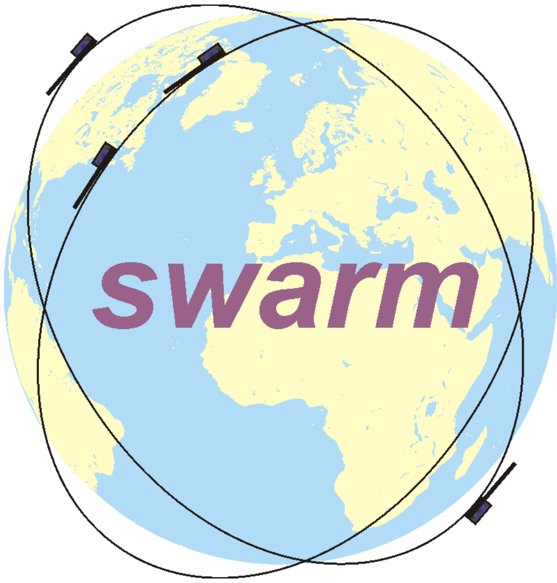

a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System

Proposal for Earth Explorer Opportunity Mission

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Executive Summary

Over the last 150 years, the axial dipole component of the Earth's magnetic field has decayed by nearly 10%. This is ten times faster than if the dynamo that generates the field were switched off completely. The current decay rate is characteristic of magnetic reversals, which paleomagnetic data sets have shown occur on average about once every half million years. The objective of the *swarm* mission is to provide the best survey ever of the geomagnetic field and its temporal evolution, enabling a better look at the global dynamics of the fluid core.

Magnetic fields play an important role in physical processes throughout the Universe. In our own solar system the planetary magnetic fields are surprisingly different, even for planets of similar composition. In addition to being evidence of the evolution of the planet the magnetic field exerts a very direct control of the electrodynamic environment, on thermospheric dynamics, and possibly even on the evolution of the lower atmosphere.

The magnetic field measured at or near the surface of the Earth is the superposition of contributions from a variety of sources: the fluid core, the magnetisation of rocks in the Earth's crust, electric currents flowing in the ionosphere and magnetosphere, currents induced in the Earth by the time-variations of the field, and electric currents induced by the oceanic circulation. The scientific challenge is the sophisticated separation of these various sources and the accurate determination of the spatial and temporal structure of them all.

In spite of the recent advances in instrument performance the currently operating geomagnetic missions, Ørsted, Ørsted-2/SAC-C, and CHAMP, are not able to accomplish this with the required accuracy. The main reason for this is that they are all designed as single satellite missions. This introduces a significant time-space ambiguity in the determination of the dynamical behaviour of the sources. Dedicated multi-point measurements are required for this. Furthermore, the duration of the existing missions is not sufficiently long to investigate the secular variation and solar cycle effects.

The *swarm* concept consists of a constellation of four satellites in two different polar orbits between 400 and 550 km altitude. Each satellite will provide high-precision and high-resolution measurements of the vector magnetic field. In combination, they provide the necessary observations for the global high-precision survey of the geomagnetic field that is needed to model the various sources of the geomagnetic field. A few additional instruments like GPS receivers, an accelerometer, and an electric field instrument provide supplementary information for studying the interaction of the magnetic field with other physical quantities describing the Earth system.

The mission will enable investigations of the global dynamics of the fluid core. It will also provide details of the conductivity structure of the mantle, and its contained subduction zones, via a better knowledge of the temporal and spatial distribution of the inducing currents. The geometric configuration of the lower pair of satellites allows for the lithospheric magnetic field to be characterized unambiguously in the polar regions for the first time.

In addition to its crucial contribution to Solid Earth Science, the mission will provide important new knowledge of the expanding and deepening South Atlantic Anomaly, with its serious implications for low-Earth orbit satellite operations. Geographically, the recent decay of the dipole is largely due to changes in the field in that region. The geomagnetic field models flowing from this mission have practical applications in many different areas such as Space Weather and radiation hazards and the understanding of atmospheric processes related to climate and weather.

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1. Scientific Justification

1.1 Introduction

Magnetic fields play an important role in many of the physical processes throughout the Universe. In particular, the Earth has a large and complicated magnetic field, the major part of which is produced by a self-sustaining dynamo operating in the fluid outer core.

What is measured at or near the surface of the Earth, however, is the superposition of the core field and fields caused by magnetised rocks in the Earth's crust, by electric currents flowing in the ionosphere, magnetosphere and oceans, and by currents induced in the Earth by time-varying external fields. The benefit and the challenge of the *swarm* mission is related to the sophisticated separation of all these various sources, each of which have their specific characteristics in terms of spatial and temporal variations. Furthermore, a few additional and dedicated instruments like an accelerometer (for measuring air density), an ion-driftmeter (for measuring the electric field) and an advanced GPS receiver (for occultation studies of the ionosphere and atmosphere) will serve the purpose of studying the effects of the geomagnetic field on the Earth's environment. Although field changes of internal as well as external origin occur at all time scales, a common practice in separating them relies on their different temporal variations. Over the last 150 years, the axial dipole component of the Earth's magnetic field has decayed by nearly 10%. This is ten times faster than the natural decay, in case the dynamo was switched off. The current decay rate is characteristic of magnetic reversals, which – as paleomagnetic data have shown – occur on average about once every half million years. Geographically, the recent dipole decay is largely due to changes in the field beneath the South Atlantic Ocean, connected to the growth of the South Atlantic anomaly. The core field and, in particular, its temporal changes, known as secular variation, are among the very few means that are available for **probing the properties of the outer core**. The secular variation directly reflects the **fluid flow** in the outermost core and provides a unique experimental constraint on **geodynamo theory**. However, only the part of the core field that varies on time scales longer than, say, one year is observable at the Earth's surface, shorter fluctuations are heavily attenuated due to the non-vanishing conductivity of the mantle. Hence variations with time scales longer than 4 years are usually attributed to processes in the core, whereas those with periods shorter than 1 year are attributed to external field contributions. Yet interesting features occur at intermediate time scales. The physical mechanism giving rise to **oscillations of the Earth's core** on time scales of months is a hot topic. An improved determination of the **core's contribution to the Earth's angular momentum** budget will allow for a better estimation of interannual and longer changes in mean atmospheric/oceanic zonal circulation patterns from **variations in the length of day**. Such studies of the electromagnetic **core-mantle coupling** require a better knowledge of the electrical conductivity of the lowermost mantle, which, for instance, can be obtained by the analysis of **jerks** – sudden changes in the secular variation that last for 1 to 2 years. A serious limitation regarding the investigation of internal processes at time-scales of months to years is the effect of geomagnetic variations of external origin, since they contribute significantly on time scales up to that of the 11-year solar cycle. All this clearly demonstrates the need for a **comprehensive separation and understanding of external and internal processes**.

The *swarm* constellation will also allow for new and exciting studies of the **lithospheric field** that are beyond the possibility of the existing missions. Another topic is **3D imaging of mantle conductivity**. The *swarm* constellation is excellently suited for providing the required

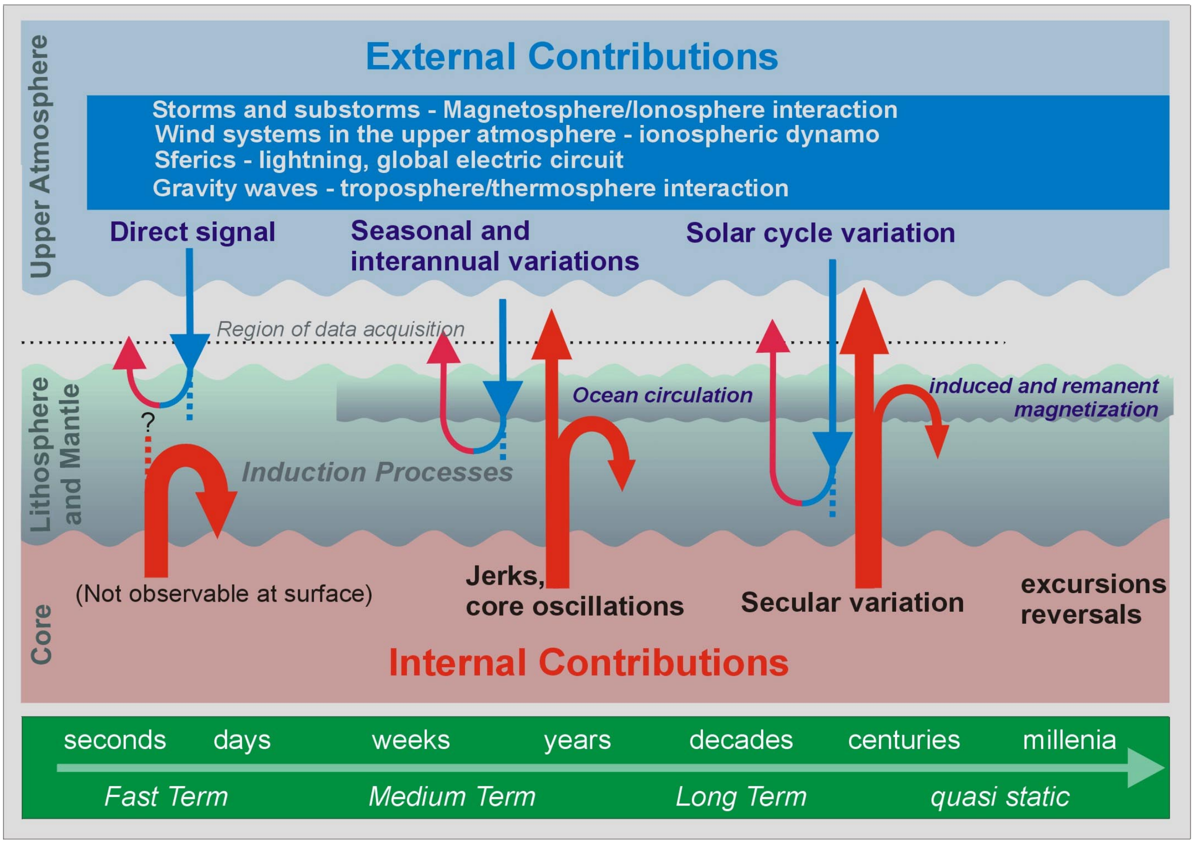


Figure 1.1: *The objective of swarm is to separate the various sources and processes that contribute to the geomagnetic field at different time-scales*

determination of the time-space structure of the geomagnetic field over different regions of the Earth.

Model simulations have demonstrated that the movement of seawater through the geomagnetic field produces large-scale electric current systems in the ocean. The resulting magnetic field perturbations at satellite altitude amount to a few nT. The *swarm* constellation may be able to separate these signals, allowing for an independent **determination of ocean circulation.**

But the magnetic field is not only an issue related to scientific research regarding its origin in the core and the evolution of our planet Earth. The magnetic field is of primary importance for the **external environment** of the Earth. While it is well-known that the air density in the thermosphere is statistically related to geomagnetic activity, recent results from the CHAMP mission have indicated that the **air density** is locally affected by the **geomagnetic activity** in a very specific way that is still to be explored and understood. Furthermore, the magnetic field acts as a shield against high-energy particles from the Sun and from outer Space. It controls the location of **the radiation belts**, and also the trajectories of incoming **cosmic-ray particles**. For example, the **South Atlantic Anomaly** (SAA), a region of low magnetic field intensity, has a significant effect on the distribution of high-energy particles in the near-Earth part of the radiation belts. The development of regions such as the SAA and hence the high radiation environment is a direct consequence of the secular variation of the geomagnetic field. Magnetic field models derived from Ørsted and CHAMP have shown that the SAA has grown by 10% during the last 20 years. The deeper penetration of energetic particles cause radiation damage to spacecraft and enhanced radiation exposure to humans in space.

Continuous space-borne monitoring of the magnetic field at low Earth orbit, and the derivation of field models, play an important role in predicting radiation hazards within the space environment. The magnetic field also controls the **transport of energy and momentum from the solar wind to the Earth** including near-Earth effects like **induced surges in long power lines** and, more generally, the **position of the auroral zone**.

In summary, few other measurements, if any, of a single physical parameter may be used for such a variety of studies related to the Earth, its formation, its dynamic and its environment, stretching all the way from the Earth's core to the ultimate source of life on Earth, the Sun.

Geomagnetic Research with Ørsted, CHAMP and Ørsted-2/SAC-C
A new era in geomagnetic research began with the launch of the Ørsted satellite in February 1999. Ørsted is the first of a series of geomagnetic mapping missions during the *International Decade of Geopotential Research*. CHAMP (launched in July 2000) and the Ørsted-2 experiment on board the SAC-C satellite (launched in November 2000) will continue to deliver high-precision geomagnetic data during the first years of the new millennium.

However, these three satellites have been conceived as single-satellite missions. Recent progress in geomagnetic research indicates that the limiting factor in the accuracy of present geomagnetic field models is the dynamic behaviour of the external current configuration. Single satellite missions are not able to describe this. Models derived from data of single satellites can therefore be obtained with accuracy no better than a few nT, which is far less than the accuracy of the current magnetometers (better than 0.5 nT). Hence, single satellite missions are not able to take advantage of the impressive instrument improvement, which has been achieved during the last couple of years. Multiple satellite missions measuring simultaneously over different regions of the Earth offer the only way to take full advantage of this new generation of instruments. It enables a **monitoring** of the time-variability of the geomagnetic field, which is a great advancement over the extrapolation based on statistics and on ground observations at selected sites that is currently used. At the same time magnetic field monitoring has important **space weather applications**. Preliminary results of combining simultaneous data from Ørsted, CHAMP and Ørsted-2/SAC-C (see Example 1) indicate the great potential of a constellation, but more extensive analyses are hampered by the fact that the orbital parameters of the various missions do not allow an optimal constellation for geomagnetic research.

Another limiting factor regarding the advance of geomagnetic research concerns the requirement for long-term measurements. The current missions hopefully will provide continual measurements for 1999 to 2006. *swarm*, in addition to the improved model capabilities, will stand a very good chance to continue this beyond 2010. This would allow a **full solar cycle coverage,** which is urgently needed to properly distinguish between solar activity and secular variation effects.

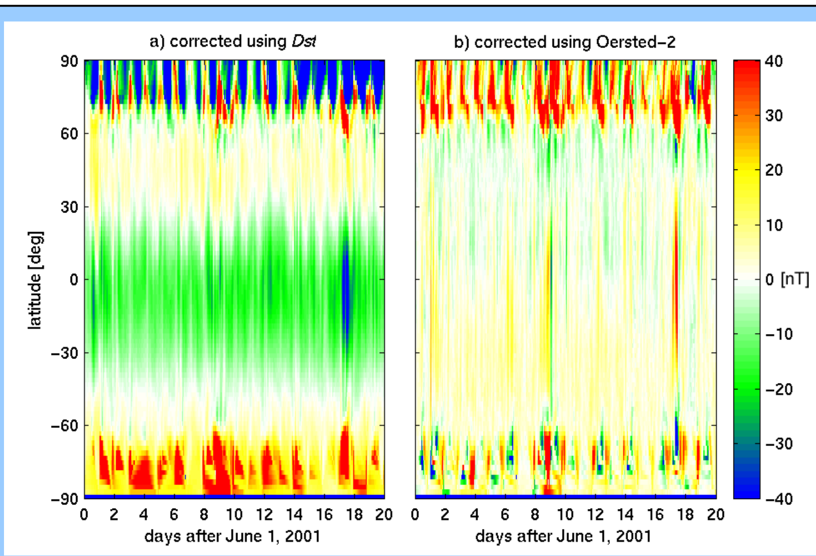
1.2 Science Case

1.2.1 Science Objectives, Earth Interior

Data from the *swarm* mission will provide models of the near-Earth magnetic field of much increased accuracy compared to single satellite missions. This may facilitate investigation of hitherto undetected features of the Earth's interior, especially concerning processes in the core and the mantle.

Improving Geomagnetic Models by Reducing the Noise from External Sources

For studies of the Earth's interior, it is essential that the field models used be contaminated as little as possible by fields originating in the Earth's crust or in the upper atmosphere. The separation problem is further complicated by the fact that, as seen from a satellite, the ionospheric field, the sources of which are located at 110 kilometres altitude, behaves as an "internal" part. Recent investigations have shown the great advantage of modelling Earth's main field and its secular variation simultaneously with ionospheric and magnetospheric contributions in a comprehensive approach by means of a joint inversion of ground-based and satellite magnetic field measurements[1]. The ability of *swarm* to obtain simultaneous measurements at different places in space will allow a better separation of internal and external sources, thereby improving geomagnetic field models.



Example 1: *The joint interpretation of data from more than one satellite yields an improved correction for magnetospheric fields. Correcting Ørsted data using the Dst-index yields residuals of 10 nT rms at non-polar latitudes (left panel), whereas using simultaneous Ørsted-2/SAC-C observations reduces the rms to below 5 nT rms at non-polar latitudes (right panel).*

Core Dynamics (Core Flow, Earth Rotation and Core-Mantle Coupling)

Strong electric currents are driven in the core by a self-sustaining dynamo process: fluid flowing across magnetic lines of force generates electromagnetic forces, which drive electric currents and thereby maintain the prevailing magnetic field. On time scales shorter than a century the core may be considered as a perfect conductor. The main consequence is that the magnetic field appears as frozen in the material of the core. Thus, **the fluid flow in the core** causes an advection of the lines of force of the magnetic field. Consequently, temporal variation of the main geomagnetic field observed at the surface of the Earth, namely secular variation, directly reflect fluid flows in the outermost layer of the core[2]. These flows, which can only be recovered from observations of the magnetic field and its secular variation, have been shown to reflect short-term MHD phenomena such as torsional oscillations and display characteristics seen in numerical simulations of the Geodynamo[3]. Hence, secular variation

[1] Sabaka, T. J., N. Olsen and R. A. Langel, A Comprehensive Model of the Near-Earth Magnetic Field: Phase 3, NASA/TM-2000-209894, April 2000 (in review for *Geophys. J. Int.*)

[2] Bloxham, J. and A. Jackson, Fluid flow near the surface of Earth's outer core, *Rev. Geophys.*, **29**, 97-120, 1991

[3] Pais, A. and G. Hulot, Length of day decade variations, torsional oscillations and inner core superrotation: evidence from recovered core surface zonal flows, *Phys. Earth. Planet. Inter.* **118**, 291-316, 2000

provides a unique experimental constraint on dynamo theory and the geodynamo mechanism. Ørsted has recently demonstrated the capacity of satellite missions to greatly enhance the resolution with which secular variation can be imaged[4]. By ensuring the continuity of space observations with an even better spatial resolution, *swarm* will thus contribute to our better understanding of core dynamics.

The **Earth's rotation** presents irregularities of different time scales: fluctuations of the length of day (lod) with periods ranging from days to decades are superimposed on a quasilinearly increasing trend. The low frequency variation is successfully attributed to the exchange of angular momentum between the mantle and the core[2]; no other angular momentum sink is anyway big enough to account for it. Estimates of the interannual and longer changes in mean atmospheric circulation from observations of the length of day require knowledge of the core circulation. Although the **coupling mechanism between the core and the mantle** has been addressed for forty years this is still a timely and controversial question[5]. In addition, the very mechanism of core-mantle coupling is not yet a matter of consensus: is the torque coupling the mantle and core electromagnetic, topographic, gravitational, or a combination of all three? The discussion of electromagnetic coupling raises the question of electrical conductivity of the mantle, whereas topographic coupling raises the question of core-mantle boundary topography, a subject to which seismologists have recently devoted much work. To tackle this problem, one needs an accurate determination of the flow of the fluid in the core for which geomagnetic studies are the only source.

Fluid flow patterns derived from the core field models will be used to study how the core and mantle are coupled. In particular, an attempt will be made to discriminate between the three most likely mechanisms. Correlation of computed momentum transfer with changes in length of day will also be further investigated.

Although the secular variation usually represents smooth time changes of the main field, episodes of much more abrupt change have occurred in the past. These are known as **geomagnetic jerks**. There has been some discussion on the global character of jerks[6]. The availability of well-distributed global data from *swarm* will enable a more definitive answer to be given on this question. By performing spherical harmonic analyses at intervals during a jerk it will be possible to separate the parts of internal and external origin, and to study the possible recurrence of about 10 years found by some investigators[7]. The two last jerks occurred around 1991 and 1999[8]. We may thus reasonably expect another jerk to occur sometime during this decade.

A typical jerk occurs rapidly and the conducting mantle alters the amplitude and frequency content of what is observed at or above the Earth's surface. It is possible to apply mantle filter theory to the sparsely distributed data that are currently available from the network of magnetic observatories but, as with all global phenomena, it is far better to have a data set that is as uniform and dense as possible in covering the Earth. A combination of ground-based

[4] Hulot, G., C. Eymin, B. Langlais, M. Mandea and N. Olsen, Small-scale structure of the Geodynamo inferred from Ørsted and Magsat satellite data, in review for *Nature*, 2002

[5] Holme, R., Electromagnetic core-mantle coupling – I. Explaining decadal changes in the length of day, *Geophys. J. Int.,* **132**, 167-180, 1998

[6] Alexandrescu, M., D. Gibert, G. Hulot, J. L. Le Mouël, G. Saracco, Worldwide wavelet analysis of geomagnetic jerks, *J. Geophys. Res.,* **101**, 21975-21994, 1996

[7] De Michelis, P., L. Cafarella, and A. Meloni, Worldwide character of the 1991 geomagnetic jerk, *Geophys. Res. Lett.*, **25**, 377-380, 1998

[8] Mandea, M., Bellanger E. and J.L. Le Mouël, A geomagnetic jerk for the end of the 20th century?, *Earth Planet. Sci. Lett.*, **183**, 369-373, 2000

observatory data plus data from *swarm* is an ideal setup and the improvement of our knowledge on the time scales involved will help to refine our estimates of the electrical conductivity of the lower mantle.

A careful search will be made to detect any jerk that may occur during the mission. If any are found, satellite and ground-based data will be analysed to discover when the jerk happened and how it evolves in space and time on global scale. Attempts will be made, using recently developed techniques such as wavelet transform analysis, to elucidate the precise nature of any jerks, for example whether they represent a discontinuity in the second time derivative of the geomagnetic field or something more complex. The global nature of the satellite data set should help to decide definitively whether a jerk is a local or a global phenomenon. The problem of whether jerks originate within the Earth or above its surface will also be studied. If it is verified that the source is internal, and therefore most probably originating in the outer core, the implications for lower mantle electrical conductivity will be investigated.

3D Imaging of the Mantle

Electromagnetic induction in the heterogeneous mantle by external sources allows determining the distribution of the electrical conductivity. This parameter is temperature driven and very sensitive to small changes in the fluids content and partial melting in the mantle and, to a lesser extent, to changes in mineralogy.

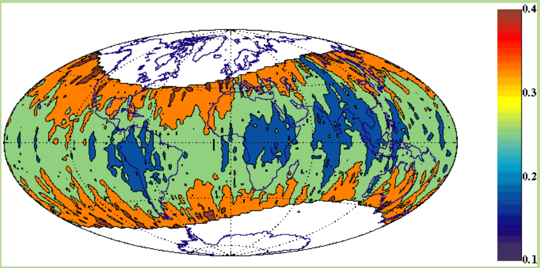
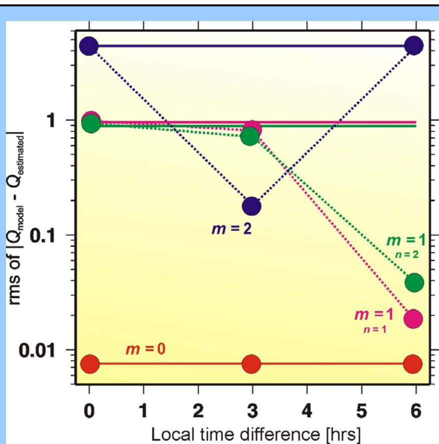


Figure 1.2: *Induced magnetic field, expressed as a fraction of the inducing field (assumed to be of magnetospheric origin and describable by a time-varying uniform field), as found by analysing individual MAGSAT passes between ±50° magnetic latitude. There is a strong correlation between smaller induced fields (blue) and equatorial landmasses, implying lower conductivity under the continents than in the oceans, as one would expect. The bands of large, high latitude fields (orange) are probably the result of failure to fit higher-order structure in the inducing fields. The swarm constellation will greatly enhance the possibility to study these features.*



Example 2*: Recovery of the ratios Q of induced over inducing magnetic fields in the period range 0.8-10 days and for different external source geometry (spherical harmonic degree/order up to 2). For one single satellite (full lines) only the ratios for m=0 are well recovered. Satellites in orbits at two local time (i.e. longitude) allow to recover also the non-zonal ratios (m=1,2). A local time difference of 3-6 hours is therefore optimal for induction studies. This condition is met for months 18-36 of the mission.*

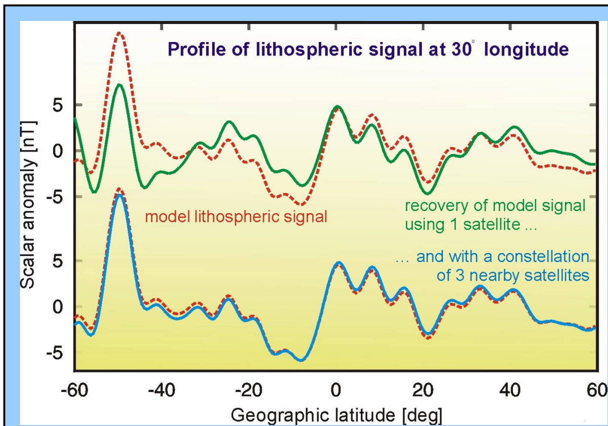
There are two ways of determining the conductivity of the mantle. It can be probed "from below" using signals originating in the core and observed at the surface. This method requires a precise determination of the field during rapid and isolated events such as geomagnetic jerks as well as some *a-priori* assumptions about the kinematics of fluid motion at the top of the core[9]. Mantle conductivity can also be probed "from the top" by the analysis of natural

[9] Mandea Alexandrescu, M., D. Gibert, J. L. Le Mouël, G. Hulot, G. Saracco, An estimate of average lower mantle conductivity by wavelet analysis of geomagnetic jerks, *J. Geophys. Res*, **104**, 17735-17745, 1999

geomagnetic variations at various frequencies. This method requires a good knowledge of the space-time dependence of the magnetic field of external origin. Using magnetic observations from previous missions, the possibility to probe mantle conductivity from space has been demonstrated[10]. Also lateral variation of conductivity can be resolved by satellite data[11]. However, the necessity of having simultaneous observations over different regions hampers induction studies with single satellites (see Example 2). The *swarm* constellation will greatly improve the situation and offers a unique opportunity to get a detailed coverage of electromagnetic transfer functions and hence 3D models of the mantle electrical conductivity. In addition, these studies will provide better models of the transient external field to be removed from the observations prior to other studies of the core and lithosphere.

Studies of the Lithospheric Field

In crustal field studies a first and very important step is the removal of an accurate estimate of the field from the core since this represents, typically, over 90% of the observed signal at the surface of the Earth. The crustal signal is an even smaller proportion of the measured values when satellite data are used, and the need for accurate main-field and external field information that will be provided by *swarm* is even greater. Some of the crustal field contribution is due to magnetisation of crustal rocks induced by the present-day main field and an accurate knowledge of the main field is essential for the correct processing and interpretation of such data. Other contributions are due to permanent (remanent) magnetisation, which may be stable (hard remanent) over geologic time or slowly varying



Example 3: *A constellation of three satellites within 2000 km separation allows for a much better separation of external contributions and hence better recovery of the lithospheric signal. A time-varying magnetospheric source (up to degree/order 2) has been added to the lithospheric signal (red line) of the CM3 model. Recovery of the lithospheric signal with a constellation of 3 nearby satellites (blue line) yields a much better result compared to using a single satellite (green line).*

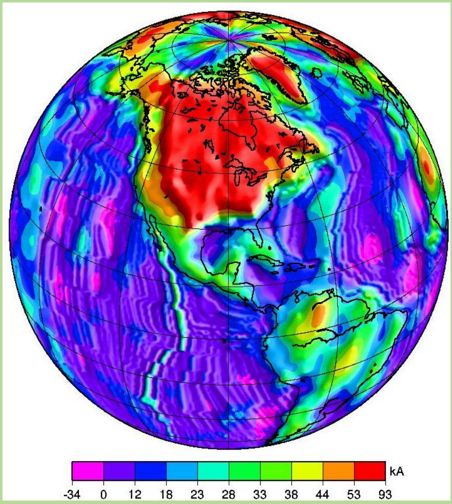


Figure 1.3: *A vertically-integrated magnetisation model of induced and remanent magnetization that explains magnetic field observations from Magsat and Ørsted. The model also incorporates information from near-surface magnetic field observations[12].*

[10] Olsen, N., Induction Studies with Satellite Data, *Surveys of Geophysics*, **20**, 309-340, 1999

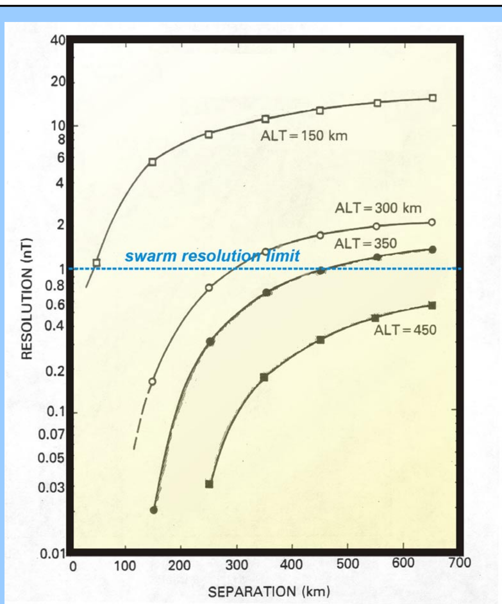
[11] Tarits P. and Grammatika N., Electromagnetic induction effects by Sq at MAGSAT altitude, *Geophys. Res. Lett.*, **27**, 4009-4012, 2000
Grammatika N. and Tarits P., Contribution at satellite altitude of electromagnetically induced anomalies arising from a 3-D heterogeneously conducting earth, using Sq as an inducing field, *Geophys. J. Int.*, submitted, 2001
Constable S. and Constable C., Observing geomagnetic induction in magnetic satellite measurements and associated implications for mantle conductivity, *G[3]*, submitted, 2001

(viscous remanent) in response to the changing main field. The discovery of an extensive hard remanent magnetisation in the old southern hemisphere of Mars that is an order of magnitude larger than terrestrial magnetisation has reignited the debate over the proportions of induced, hard remanent, and viscous remanent magnetisation in the terrestrial crust and upper mantle.

Knowledge of the crustal field is important not only scientifically in its own right, but also for the insights it can give to the exploration geophysicist in the search for mineral and hydrocarbon deposits. With previous satellite missions an impressive number of results have been obtained about the magnetisation of the crust and uppermost mantle and its geodynamic implications. However, the resolution of previous satellite magnetic field data was such that researchers were largely confirming results already known from other lines of evidence. Going to lower altitudes will provide the ability to break new scientific ground. Fundamental unresolved questions include:

- the origin of some of the anomalies that cannot be explained by the induced or remanent magnetisation of known structures either in the crust or the mantle,
- the proportions of induced, viscous remanent, and hard remanent magnetisation within the crust and upper mantle.
- the systematic mismatch of magnetic anomaly amplitudes between the existing large scale land and aeromagnetic anomaly maps and the satellite magnetic anomaly maps,
- the difficulty of extracting north-south magnetic anomalies at all wavelengths, because of the systematic use of polar orbits and along-track filtering of external field effects,
- more generally, the bias introduced by the external field and its induced part,
- and finally the bias introduced by the insufficient accuracy of main field models.

There are significant advantages for lithospheric studies in having two magnetometers closely following one another in space and time. The measured horizontal gradient does a better job of outlining the edges of magnetic bodies than do measurements of the total field. Although the horizontal gradient can also be calculated as the difference between nearby measurements made using the same magnetometer, two magnetometers allow for the removal of rapidly varying external field signals. The optimum separation between magnetometers is determined by maximizing the gradiometer sensitivity while stipulating that the spacing between sensors should be small with respect to the distance to the sources in the lithosphere. For the proposed *swarm* configuration, the optimum horizontal separation of two magnetometers searching for magnetic edges in a relatively quiet external field environment would be about 500 km. At higher external



***Example 4**: Resolvability of two nearby bodies in the lithosphere as a function of their separation and satellite altitude. The lowering of one satellite during the third mission year to altitudes below 250 km may greatly enhance the ability of resolving small-scale lithospheric features.*

[12] Purucker, M., B. Langlais, N. Olsen, G. Hulot, and M. Mandea, The southern edge of cratonic North America: Evidence from new magnetic satellite observations, *Geophys. Res. Lett.*, 2002, in press

field levels such as characterize the polar regions or the dayside ionosphere, a gradiometer will allow for the effective separation of the total field lithospheric signal, something not possible with present or past missions. *swarm* will also contribute indirectly to crustal field studies through better models of the core field and external field, which will enable a re-analysis of data from previous satellites at low altitude.

Sensing Ocean Circulation
The motion of the electrically conducting seawater through the geomagnetic field generates electric currents and associated magnetic fields of a few nT at satellite altitude. The opportunity of remote sensing of ocean variability using magnetic observations[13] is attractive because the ocean-generated signals largely describe the baroclinic component of the ocean flow. Furthermore, these signals have the advantage that they readily pass through sea ice. An oceanic signal has been identified in ground-based magnetic data[14], and model simulations have demonstrated that depending on the time-scale of the flow, the magnetic signal at 500 km altitude is between 1 and 10 nT. With the improved separation capabilities of *swarm*, and using statistical methods it should be possible to recover this signal, since the frequencies of the processes are very well known.

1.2.2 Science Objectives, Earth Environment

The measured magnetic field and its temporal variation provide crucial information about the various sources of external and internal origin and hence about the origin of the physical processes that contribute to form the Earth's system.

In addition to elucidating fundamental information about system Earth that is not perceivable by any other means, the geomagnetic field itself also plays an important role in controlling many of the physical processes in the Earth's environment that directly affect our daily life, in particular those that are related to our increasing utilisation of highly technological systems in space.

The *swarm* mission will not only measure the magnetic field itself. In order to maximise the interpretation of those measurements and in order to measure some of the most direct effects on the Earth's system, a few supplementary but very dedicated instruments have been added to the payload.

Configuration and Dynamics of the External Current Systems
A mission like *swarm* is a suitable tool to monitor the current systems in the ionosphere, since electric currents always produce magnetic fields. Due to the anisotropic conductivity of the ionosphere there are two important current configurations in this region, the horizontal currents in the *E* region and the field-aligned currents connecting ionosphere and the magnetosphere, thereby mainly linking between the outer part of the geospace and the auroral latitudes. These currents are responsible for the major part of energy transported from the solar wind to the upper atmosphere during times of enhanced magnetic activity. Field-aligned currents are virtually invisible from ground-based observation, and due to high variability single spacecraft observations suffer severely from the space/time ambiguity. A constellation of four non-coplanar satellites allows determining the current flowing through the

[13] Tyler, R. H., J. M. Oberhuber, and T. B. Sanford, The Potential for Using Ocean Generated Electromagnetic Fields to Remotely Sense Ocean Variability, *Phys. Chem. Earth (A)*, **24**, 429-432, 1999
[14] McKnight, J. D., Lunar daily variations in New Zealand, *Geophys. J. Int.*, **122**, 889-898, 1995

constellation uniquely by applying the curl-B technique[15] developed for instance for the Cluster mission. It will be possible with *swarm* to resolve the full space-time characteristic of this important current element. By measuring simultaneously the electric field it is possible to calculate the Poynting vector which describes the amount of energy flowing into or out of the

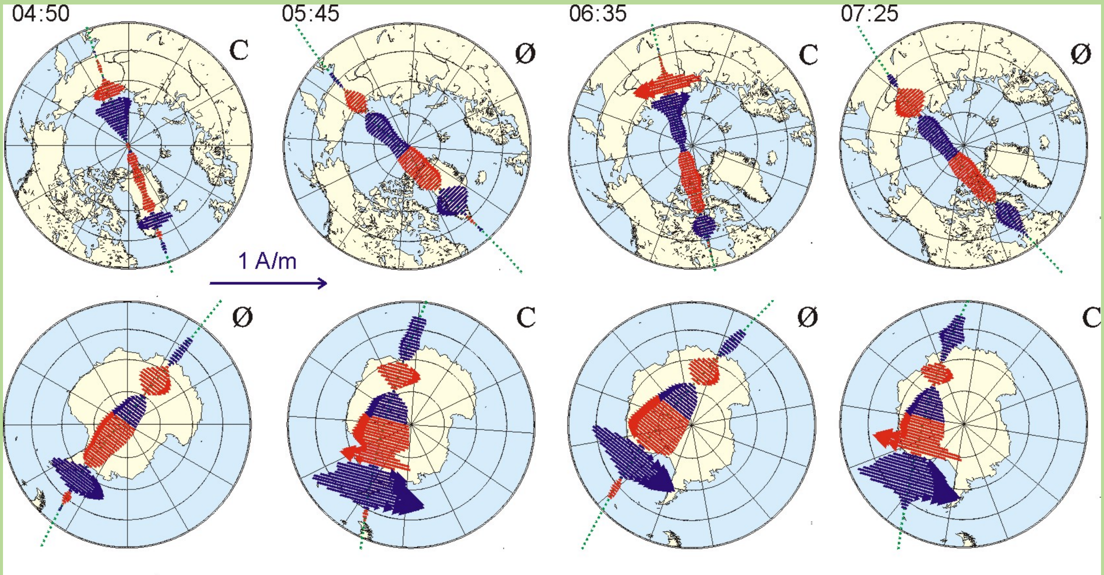


Figure 1.4: *Maps of horizontal ionospheric currents for a sequence of orbits for which Ørsted and CHAMP passed opposite poles nearly simultaneously in the morning of April 22, 2001. There is a considerable asymmetry of the currents between northern and southern polar cap, despite of the fact that the data are for equinoctial conditions. Eastward dominated currents are shown in **red**; westward dominated curents are shown in **blue**[16].*

atmosphere. The effect of this energy dump on the atmospheric density will be observed by other instruments (see next section).

Another important mechanism responsible for energy input to the atmosphere is the generation of geomagnetic pulsations. These quasi-harmonic variations of the geomagnetic field cover a frequency range from a few mHz to a few Hz. Pulsations can be caused by different wave modes and show various propagation characteristics. The efficiency of energy transfer depends on these features. We plan to apply the wave telescope technique developed for Cluster to magnetic field measurements obtained by *swarm* in order to find out the wave properties.

Horizontal ionospheric currents are particularly strong in the auroral *E* region. Around the magnetic poles and inside the so-called auroral regions extending to say 30 degrees from the poles there exist two basic vortices, which, however, are highly variable in time and space depending on the solar wind input. There is no way of directly measuring the current density by spacecraft. Instead, the magnetic effect of the horizontal currents has to be separated from the contributions of all the other internal sources and then properly interpreted. Measuring the electric field at the same time helps considerably to perform this task, since the electric and magnetic field variations related to the currents have a fixed phase relation. Intense electric currents are observed in both the northern and southern polar region. As part of the *swarm* mission, it is planned to have a certain time period with one pair of satellites crossing the

[15] Robert, P., M. W. Dunlop, A. Roux, G. Chanteur, Accuracy of current density determination, *in Analysis Methods for Multi-Spacecraft Data*, G. Paschmann and P. Daly (Eds.), ISSI Science Report, SR-001, 1998

North Pole while the other is sampling the region around the South Pole. It will be the first time to get a detailed view of the response to activity at conjugate locations in space. Until now such investigations have been based on occasional constellations of the existing satellites[16], and on statistical studies. Having truly simultaneous observations will allow studying the influence of environmental factors like solar illumination, air density or main field configuration. The ionospheric currents induce as a secondary effect considerable currents in the upper part of the Earth. Related effects will be addressed below.

Another intense ionospheric current system is the Equatorial Electrojet (EEJ). The EEJ is a narrow current ribbon flowing along the dip equator generally from west to east on the dayside. Until now the complete current system and the relation to other systems like the Sq-currents is not well understood. Data from the Magsat satellite have confirmed the existence of a 3-D meridional current system, which forms in the evening sector and routes the prime current to the return currents north and south of the equator back to the morning side. Here again the curl-B technique can be applied to data from a set of 3 or 4 satellites separated less than about thousand kilometres to determine the current configuration. The current intensity has a direct effect on the plasma dynamics in the *F* region after sunset. This is the time when plasma instabilities like spread *F* or plasma bubbles occur at low latitudes[17]. For the investigation of the relationship between the Electrojet intensity and the plasma dynamics it is important to have sensors on board for measuring the plasma density and the electric field.

The EEJ signature varies with longitude. It is particularly intense over South America and Indonesia, with a minimum over Africa. *swarm*, having two pairs of satellites passing the EEJ at longitudes preferably separated by 3 to 6 hours in local time, allows to find out how such a system is kept divergence-free. The EEJ is believed to be driven primarily by neutral winds in the *E* region that are modulated by atmospheric waves. The above-mentioned constellation can also be used to manifest the relationship between the structure of the EEJ and the neutral wind field.

Closely related to the EEJ, although less intense, is the large-scale “Solar quiet"(Sq) current system. It consists of two current vortices, one in each hemisphere, covering more or less the whole sunlit part of the ionosphere. The main driver of these currents is the system of thermal winds, which moves the ions across the geomagnetic field. Sq currents show a fair amount of variability, which could so far not be resolved adequately on global scale. The *swarm* mission with two pairs of satellites passing the current vortices at longitudes separated by 3 to 6 hours in local time will be able to resolve the space-time structure of the system. This structure is of importance for the understanding of the dynamics of the upper atmospheric wind fields, the neutral/ion interaction and the effect of the geomagnetic field configuration on the current intensity. The Sq currents are also an important source for induction studies.

Monitoring of the Ionosphere and Thermosphere

Reliable now- and forecasting of space weather phenomena needs an improved understanding of the behaviour of the ionosphere and its coupling to the magnetosphere and thermosphere. *swarm* will in particular contribute to the study of ionospheric climatology, ionospheric and geomagnetic storms, Travelling Ionospheric Disturbances (TIDs) and small-scale ionospheric irregularities. In particular the latter cause severe degradation of position information from

[16] Moretto, T., N. Olsen, P. Ritter, and G. Lu, Monitoring the auroral electrojets with low altitude polar orbiting satellites, *Ann. Geophysicae*, 2002, in review.

[17] Lühr, H., S. Maus, M. Rother and D. Cooke, First in-situ observation of night-time *F* region currents with the CHAMP satellite, *Geophys. Res. Lett.*, **29**, 2002, in press

satellite-based navigation systems (GPS) and a better understanding of these phenomena may improve GPS positioning.

Dual frequency GPS measurements on board the *swarm* satellites provide a unique chance of providing a comprehensive monitoring of the global ionosphere and thermosphere. In general, the GPS-LEO radio occultation technique yields the integrated electron density (TEC- total electron content) along the occultation ray path as a basic data product[18]. TEC can precisely be derived by computing the differential phases of the coherent L-band signals (L1, L2) of GPS satellites[19].

The proposed constellation of two separation-controlled satellite pairs enables a simultaneous sampling of the vertical electron density structure and is particularly powerful at characteristic scale

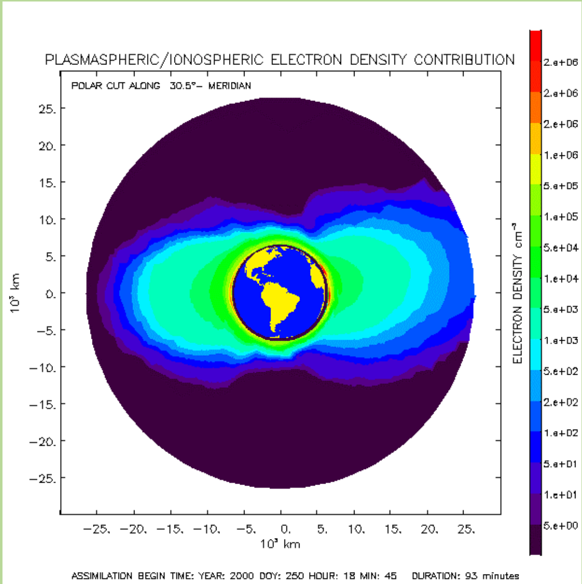


***Figure 1.5**: Electron density distribution of the topside ionosphere/plasmasphere above the CHAMP orbit in the 30.5°E plane on Sep. 6, 2000, 18:45 - 20:18 UT after data assimilation[20].*

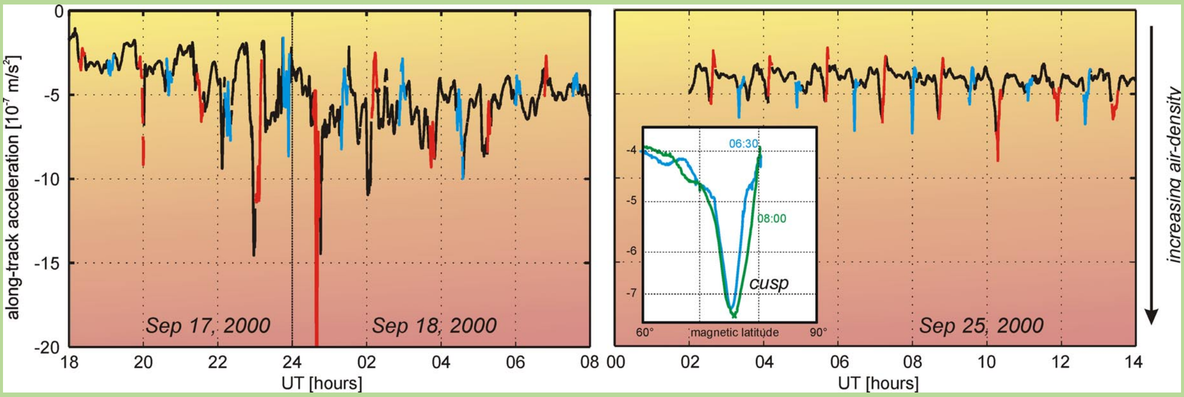


***Figure 1.6:** Air drag in units of 10^{-7} m/s^2 at 450 km altitude, as measured by CHAMP, during geomagnetically disturbed (left) and quiet periods (right), respectively. Crossings of the northern (southern) polar region are indicated by **blue** (**red**) line segments, accordingly.*

*Shortly after the onset of the geomagnetic storm on September 17, 2000 at 21:00 UT, the density of the upper atmosphere is increased on average, resulting in enhanced air-drag (more negative acceleration). Particularly striking is the high degree of variability especially in the southern auroral region (**red** segments). Also during magnetically quiet periods the air-density is strongly structured by the geomagnetic field, as indicated in the right panel. Localized features of increased air density coinside with the polar cusp. They probably mark regions of uprising air parcels driven by energy dissipation from ionospheric currents.*

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[18] E.g., Schreiner, W.S., S.V. Sokolovsky, C. Rocken, Analysis and validation of GPS/MET radio occultation data in the ionosphere, *Radio Sci.*, **34**, 949-966, 1999
Jakowski, N., S. Heise, A. Wehrenpfennig, S. Schlüter TEC Monitoring by GPS: A possible Contribution to Space Weather Monitoring, *Phys. Chem. Earth (C)*, **26**, 609-613, 2001

[19] E.g., Jakowski, N., TEC Monitoring by Using Satellite Positioning Systems, Modern Ionospheric Science, (Eds. H.Kohl, R. Rüster, K. Schlegel), EGS, Katlenburg-Lindau, ProduServ GmbH Verlagsservice, Berlin, 371-390, 1996

lengths matching ionospheric phenomena such as the mid-latitude trough or the low-latitude Appleton anomaly. Since those are closely related to the electrodynamics of the ionosphere and magnetosphere, the *swarm* concept allows for the first time a comprehensive view on the complexity of coupling processes.

The upward looking *swarm* GPS navigation antenna, in analogy to ground-based GPS measurements, will be used to map the plasma density distribution of the topside ionosphere/plasmasphere. After calibration of TEC data by comparing thousands of different radio links the simultaneous measurements of the four *swarm* satellites allow for a tomographic reconstruction of the plasmasphere density distribution[20]. Figure 1.5 shows a unique picture of the actual electron density of the plasmasphere, derived from CHAMP navigation data that have been assimilated into an ionosphere/plasmasphere model[21]. Combining all ground- and space-based GPS data that will be available during the *swarm* mission can be used to provide a now-cast of the 3D electron density distribution of the ionosphere and plasmasphere.

Another quantity highly relevant for space applications is the thermospheric density. It has strong influence on the dynamics of satellites in Low Earth Orbits (LEO). Present atmospheric models like MSIS do not account properly for the high variability of the upper atmosphere with geomagnetic field variations, especially during magnetically active periods. Only recently the full range of variation could be detected with the help of a sensitive accelerometer on board the CHAMP satellite by converting the experienced drag into air density. At altitudes around 400 km the density can be enhanced up to a factor of 10 during severely disturbed periods. The rise in density is also far from being spatially uniform. Besides the day/night asymmetry the auroral region often exhibits local density maxima. In particular, the ionospheric cusp region seems to be a preferred location for an uprising atmosphere. Figure 1.6 shows examples of density fluctuations encountered by the CHAMP satellite for a number of consecutive orbits during magnetic active and quiet periods. There is a clear asymmetry in air density between the northern and southern cusp region. An important question that has to be addressed by the *swarm* mission is the roll of the electrodynamics in lifting up the air parcels. Is it primarily the Joule heating in the ionospheric *E* region? What makes the cusp so special for the air transport? Are there effective interactions taking place between charged and neutral particles at greater altitudes? Measurements at two heights, as provided by *swarm*, will help answering these questions. The investigation of the wave-like propagation of the thermospheric bulges towards the equator that has been found with CHAMP, and in particular the identification of the driving forces, requires multi-point measurements preferably at equally-spaced points some thousand kilometres apart. *swarm* measurements provide the basis for new atmospheric models with a much-improved parameterisation of controlling indices. In an operational space weather system the data of *swarm* could be available for a now-cast reporting of the thermospheric density.

The intense and highly variable ionospheric currents in the auroral and sub-auroral regions induce large currents in the Earth's interior during magnetic storms. These induction effects can cause damages in technical systems such as power grids, communication lines and

[20] Heise, S., N. Jakowski, A. Wehrenpfennig, Ch. Reigber and R. König, Preliminary Results on Ionosphere/Plasmasphere Imaging Based on GPS data Obtained Onboard CHAMP, *Proc. International Beacon Satellite Symposium*, Boston, June 2-6, 2001

[21] Daniell, Jr., R. E., L. D. Brown, D. N. Anderson, M. W. Fox, P. H. Doherty, D. T. Decker, J. J. Sojka, and R.W. Schunk, Parameterized ionospheric model: A global ionospheric parameterization based on first principles models, *Radio Sci.*, **30**, 1499-1510, 1995

pipelines. With a *swarm* of satellites in orbit both the spatial and temporal development of hazardous current configurations can be tracked.

Various global and local geomagnetic indices based on ground magnetic measurements have proven useful for the specification, monitoring, and prediction of space weather conditions. One important indicator of space weather storm conditions is the position and strength of electrical currents in the auroral zones. While difficult to obtain from ground a direct measure of this is provided twice (north and south polar region) in each 90 minutes orbit by each of the four satellites of the *swarm* constellation (cf. Figure 1.6). The potential of this for space weather monitoring and forecasting is obvious, and so too is the potential for the derivation of other global geomagnetic indices based on *swarm* measurements and the use of them for testing and refinement of the ground based proxies.

Modelling of the Geomagnetic Field and Radiation Damage in Space
Radiation damage to spacecraft and radiation exposure to humans in space is a matter of increasing concern. For low earth orbit spacecraft, such as Hubble, Topex, CHAMP, and others in the 300-1000 km altitude range damage has frequently occurred and will continue, in particular, over the South Atlantic Anomaly (SAA). The low magnetic field strength allows high energetic particles from the radiation belts to penetrate deep into the upper atmosphere and create intense radiation. The SAA is an important example of a region where the magnetic field cannot be monitored well by the net of observatories alone (since they are confined to the land areas). Recent instrument failures on some low Earth orbiting spacecraft have suggested that the SAA has shifted to the Northwest, which has been confirmed by the magnetic measurements taken by Ørsted and CHAMP. Accurate and timely geomagnetic field models clearly play a pivotal role for space operations[22] as do good estimates of the rate and form of changes of the field to know what is to be expected in the coming years. The *swarm* mission will continue the efforts of the geomagnetic missions already in orbit to provide improved models and predictions of the identification of the problem regions, their position, strength and evolution in time. Amongst other, the operation of the International Space Station makes this issue highly relevant.

1.3 Relevance to the Objectives of the Earth Explorer Program

The *swarm* mission would contribute to the Earth Explorer program mainly within the two themes, Earth Interior and Physical Climate, as summarised in Table 1.1.

Earth Interior
Accurate models of the magnetic field from the Earth's core and its evolution provide one of the few means to gain insight into the properties of the outer core, in particular concerning its dynamics. Similarly, investigations of the geomagnetic field variations can be used to perform 3D imaging of mantle conductivity describing properties of the mantle, and to study the lithospheric field. All topics, which are central to the Earth Interior theme.

The gravity field is another source of information and is the objective of the "Gravity Field and Steady State Ocean Circulation" of the "Earth Explorer Core Mission" program. The *swarm* mission would be an important supplement to this mission.

[22] E.J Daly, J. Lemaire, D. Heynderickx, and D.J. Rodgers, Problems with Models of the Radiation Belts, *IEEE: Transactions on Nuclear Science*, **43**, 403-415, 1996

Component	Objectives	Relation to Earth Explorer Programme
Core	• Map the core flow • Determine core dynamics • Investigate jerks: their time-space structure and recurrence • Understand core-mantle coupling and its implication for Earth rotation	Theme 1, Earth Interior • "origin, evolution, and composition of core, mantle, and crust and their roles in determining the internal dynamics of the Earth"
Mantle and Crust	• Perform 3D imaging of mantle conductivity • Determine remanent and induced magnetisation of the lithosphere	
Earth's Environment	• Determine the position and development of the radiation belts and their near-Earth effects • Investigate the time-space structure of the magnetospheric and ionospheric current systems on all time scales • Monitor the solar wind energy input into the upper atmosphere (Poynting flux) and sense its effect on the thermospheric density • Sound the electron density of the ionosphere/plasmasphere and determine its relation to the magnetic activity • Study the modulation of the cosmic ray flux and its effect on tropospheric conductivity and associated processes related to weather and climate	Theme 2, Physical Climate • "understand the internal variability of the various components of the climate system … study past and present changes in the global environment"

Table 1.1: *Main science objectives and their relevance to the Earth Observation Programme*

Physical Climate

The physical climate is the result of a number of complex processes involving the atmosphere, the oceans, and the land surface. Many of these processes are poorly understood. The potential danger of the enhanced greenhouse effect caused by human activity is broadly recognised but the size of the problem is only poorly determined, mainly because the effects on climate are imbedded in natural climatic changes that have existed through all times and which we do not fully understand.

Many of the past climatic changes have been reported to be well correlated with changes in solar activity. Such changes may be due to changes in solar luminosity, in the UV spectral bands, or, as has recently been suggested, by changes in the cosmic ray flux penetrating deep into the atmosphere. These particles constitute the prime cause of ionisation in the lower atmosphere, particularly over the oceans. Statistical studies of global cloud cover demonstrate a significant correlation with the cosmic ray flux[23] and recent computer simulations[24] indicate

[23] Marsh N. and H. Svensmark, Low cloud properties influenced by cosmic rays, *Phys. Rev. Lett.*, **85**, 5004-5007, 2000

[24] Yu, F. and R. P. Turco, Ultrafine aerosol formation via ion-mediated nucleation, *Geophys. Res. Lett.*, **27**, 883-886, 2000

that the presence of ions may significantly enhance the creation of ultra-fine aerosols that constitute the basis for the formation of cloud condensation nuclei.

The geomagnetic field and its interaction with the solar wind play an important role in forming the external environment of the Earth. The solar wind modulates the flux of incoming cosmic ray particles whereas the Earth's magnetic field controls the geographical distribution of the cosmic ray flux as well as the location of the radiation belts. The *swarm* mission is aiming at advancing our understanding of these processes and their effect both on the upper atmosphere and at the surface of the Earth. This all constitutes a variable background, the importance of which must be realised in benefiting fully from the research and missions concerned with climate change. As such this issue lies at the heart of the objectives of the Physical Climate theme that aims at the scientific understanding of the variability of the various components of the climate system.

1.4 Science Interest

The large and widespread scientific interest for the *swarm* mission is documented in two ways. The team of co-investigators of the Ørsted and CHAMP projects counts more than 60 groups from 16 countries both in Europe and overseas. Many of these groups and some additional ones have united in the large team of co-investigators, which put forward this proposal. It seems clear that the *swarm* mission would consolidate the European lead in geomagnetic mapping missions demonstrated by the Ørsted and CHAMP missions.

The swarm Science Team
The team of co-investigators on the proposal includes 19 groups from 8 European countries, and 5 groups from the US. This demonstrates the large interest in the idea behind *swarm* and the potential for this team to be enlarged even further. The team will constitute a core science team under the leadership of the project office at DSRI for which it will be an important source of support during the phase A/B of the project.

Interdisciplinary Gain
A unique feature of the Ørsted and CHAMP science teams is that they join scientists from communities engaged in research in the internal as well as in the external sources of the geomagnetic field, and both research areas have benefited from this interaction. The multi-point aspect of *swarm* and its dedicated objective to investigate the influence of the magnetic field on the Earth system will further strengthen this cross-field collaboration.

Relation to Other Programmes
The mission will act as a geomagnetic contribution to the *International Decade of Geopotential Research* announced by the International Union of Geophysics and Geodesy (IUGG). The objectives of *swarm* are very similar to those outlined in the Solid Earth science working group report of NASA (http://solidearth.jpl.nasa.gov). In addition, the various instruments of the *swarm* constellation will contribute to the European Space Weather Program (ESWP).

Looking beyond the objectives of the Earth Explorer programme, the *swarm* mission will serve as an important near-Earth component of the International Solar Terrestrial Physics (ISTP) programme.

2. General Mission Characteristics

2.1 Scientific and Technical Requirements

Prime mission requirement imposed by the science objectives is the precise measurement of the vector components of the geomagnetic field with a global and continuous coverage.

Single satellite magnetic missions do not allow taking full advantage of present day instrument precision for science interpretation due to the time-space ambiguity, which results in an inadequate separation of contributions from the various sources. In principle, field modelling requires a global data set that has been taken instantaneously, or that temporal variations have been accounted for properly. One satellite cannot provide a good global coverage in less than two to three months.

At satellite altitude the contributions from the variable ionospheric currents appear as internal sources, and a single satellite mission can not separate these contributions from the contributions originating in the core and lithosphere. However, a multi-satellite mission will be able to identify ionospheric contributions due to their specific time dependent features much more effectively. Having four satellites in two suitably located polar orbits furthermore reduces the time necessary to acquire sufficient data for recovering the main field to about a week during a quiet period.

A configuration of four satellites can be regarded as an optimum in a cost/benefit trade-off. Any core signal varying at time scales less than a month cannot reach the Earth's surface due to the electrical conductivity of the mantle. On the other hand, it is known that the geometry of the external field can become extremely complex when considering time scales of less than a day. Deriving global external field models during geomagnetic active periods is difficult, even with a much larger number of satellites. The *swarm* configuration will sample the same region on ground four times a day. A whole range of time scales can be checked for variability when taking into account all possible combinations. This will help significantly to sort out ionospheric contributions from internal field data sets.

From science considerations it follows that the orbit inclination shall be near polar, primarily to obtain a good global coverage. Furthermore, the latest dynamo simulations suggest specific signals of internal origin near the poles in the "shadow of the inner core". Also the ionospheric current systems exhibit complex structures at high latitudes demanding a dense coverage at polar regions. It should be noted that previous missions except CHAMP left substantial areas around the poles unsampled.

2.1.1 High-Precision Vector Magnetic Field Measurements

The key requirement for the acquisition of magnetic data results from the signal strength belonging to features with sizes comparable to the satellite altitude. This constitutes to first order the resolution of the mission. The absolute accuracy of the vector magnetic field measurements must be better than 1 nT per component. In present missions the limitation regarding the accuracy of the vector measurements is related to the uncertainty of the attitude determination. An improvement up to the required arcsecond attitude precision can only be achieved using a multi-head star tracker. An absolute scalar magnetometer providing an accuracy of 0.5 nT is needed to check the validity of the vector data. This puts tight limits on the magnetic disturbance level from the satellite system that can be tolerated at the sensor. An accuracy of 1 nT for the magnetic components translates into an additional requirement for the position to be better than 20 m, which can be obtained with current GPS receivers. The whole constellation has to be regarded as one system, and maintaining the stated precision across the satellites requires a time synchronisation of better than 10 ms.

2.1.2 Orbit and Mission Characteristics

A launch in 2007 is optimal for several reasons. It will make the *swarm* mission a direct continuation of the CHAMP mission. Together with the Ørsted and SAC-C missions, chances are very good that satellite measurements of the geomagnetic field can be obtained for a full solar cycle (1999 – 2010+).

The scientific objectives put some constraint on the orbit parameters. The altitude should be as low as possible to allow for a high resolution of lithospheric features. At the same time an active mission lifetime of more than three years shall be maintained. The required distribution of the satellites in space calls for two circular orbits with different altitudes. All these needs are satisfied with a constellation in 2 different orbits, one at 400-450 km altitude and another at 550 km altitude. The inclination shall be close to 90°, but the two orbits shall have slightly different inclinations to obtain different precession rates leading to a separation of the two orbit planes of at least 6 hours in local time after three years. The following scenario fulfils these requirements:

- Two satellites are launched into an orbit at 550 km altitude with an inclination of 86°. The orbital drift rate w.r.t the sun is ω_1 = -1.506°/day, i.e. the satellites cover all local times in 120 days.
- The other two satellites will fly in an orbit at initially 450 km altitude with an inclination of 85.4°; the drift rate is ω_2 = -1.615°/day.
- The local time difference of the two satellite pairs will change by 0.44 min/day, corresponding to a 90° separation (6 hours in local time) after 27 months.

Optionally, the altitude of one of the lower satellites can be decreased forcing a re-entry during the third year, to get low-altitude (<250 km) magnetic data, for improved lithospheric studies. This scenario requires an initial altitude of the lower satellite pair of 410 km. Depending on solar activity and orbit decay the altitude of the satellites is decreased or increased after 1-2 years (cf. the green curves of Figure 2.2). This is an excellent situation for lithospheric studies, since it allows, for the first time, to measure the magnetic field from low-altitude (<250 km) while simultaneously observing the larger scale features of the magnetic field with the other satellites at higher altitude.

2.1.3 The Constellation Concept

The science goals rely on the possibility to obtain multi-point measurements of the near-Earth magnetic field on a global as well as on a regional scale. The scientific return of many of the objectives can be enhanced considerably when optimised spacecraft constellations are available. Since different spacecraft constellations are optimal for the various science objectives, a possibility to change or maintain a desired separation of the two satellites in the same orbit is required.

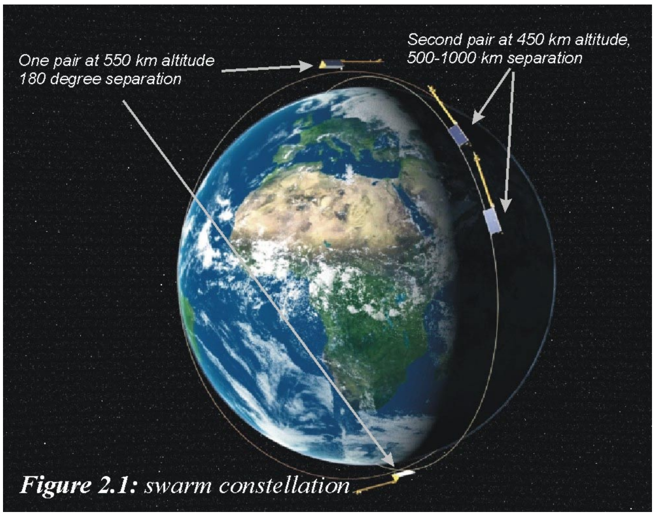

Figure 2.1: *swarm constellation*

The different science objectives will be addressed during times when the constellation of satellites is favourable for the actual task to be performed. A close constellation with spacecraft distances up to a few thousand kilometres is preferred, for example, for lithospheric studies, which will be the case during the first year. Induction studies benefit from local time separations of the two orbital planes between 3 and 6 hours, which is encountered during the second year of operation. For the recognition of large-scale external contributions in geomagnetic field modelling a local time separation of about 6 hours is optimal. This occurs during the third year. In that case the satellites of the lower pair will be separated by a distance of the order of 1000 km, which is optimal for extracting information about small-scale variations like ionospheric fields. The satellites of the upper pair are separated by 180 degrees, which is optimal for studying global-scale variations and for conjugate point studies (e.g. simultaneous observations over Northern and Southern polar region). Three of the four satellites will be within 2000 km separation for more than 15% of the time during the first 6 months, and for almost 50% of the nominal mission duration, three satellites will be within 4000 km.

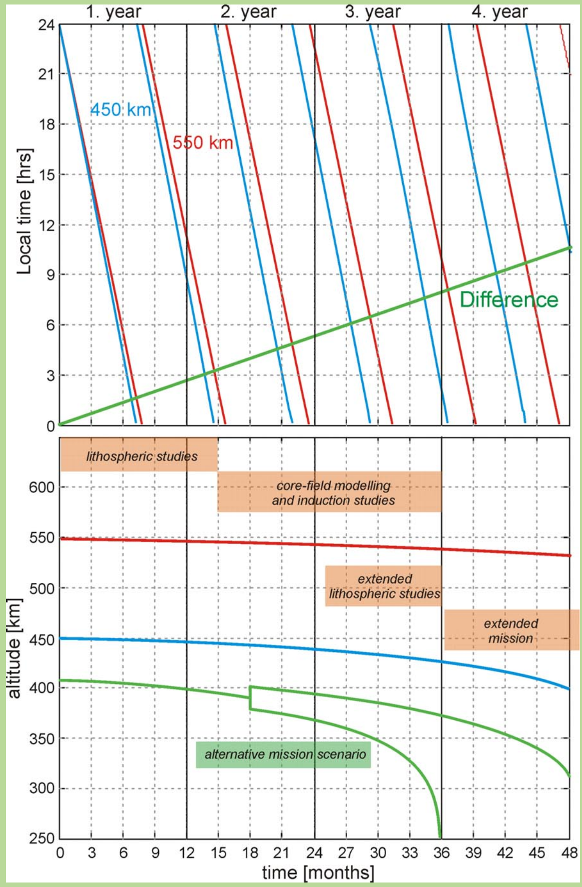

Figure 2.2: *swarm mission scenario. Top: evolution of local time for the two satellite pairs, assuming an (arbitrary) initial local time of 0 hrs. Bottom: change in altitude vs. time.*

Three satellites (one pair at 450 km altitude with 500-1000 km separation, and one satellite at 550 km altitude) is the minimum number to fulfil the basic science requirements. Having a fourth satellite at 550 km altitude with a 180 degree separation doubles the amount of data with the required nearby constellation. The fourth satellite will further enhance the chance of continued geomagnetic measurements beyond 2010, at least with one satellite. This will be of great significance regarding research related to secular variation and solar cycle variability.

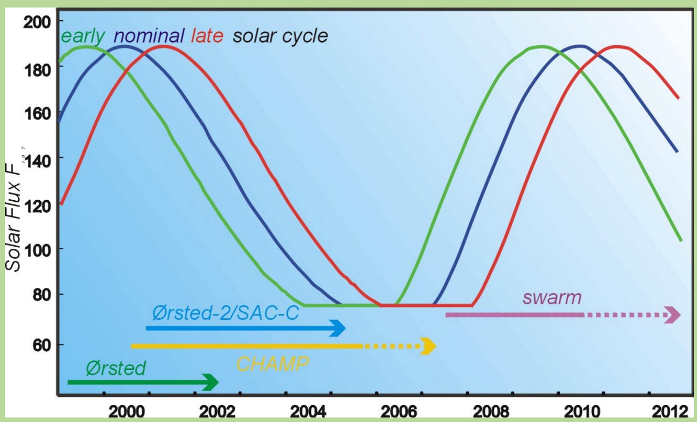

Figure 2.3: *swarm will continue present geomagnetic missions*

2.1.4 Requirements due to GPS radio occultation

Regarding the important issue of the interaction of the magnetic field with the Earth's environment, additional instruments sensing the properties of the atmosphere/ionosphere are required. A very effective and powerful tool for this purpose is the GPS radio occultation technique. In the *swarm* mission it is foreseen to utilise this for probing the electron density of the ionosphere and plasmasphere. The advantage of this technique is that existing hardware, GPS receivers, can be used for that purpose. Derived mission requirements include a 3-axes stabilised attitude having the occultation antenna always pointing in the desired direction.

At a little extra expense in software development the same GPS receiver can also be employed for atmospheric sounding, allowing estimating vertical temperature and humidity profiles. Although this is outside the scientific scope of the present proposal, it could be offered to be implemented as an added service for other science groups interested in studies of these parameters. Performing the needed occultation measurements is a rather straightforward task with the envisaged payload and platform. The proper interpretation of the data, however, requires significant auxiliary information. This includes:

- High precision orbit determination to 30 cm position and 0.1 mm/s velocity
- Precision orbit determination for GPS satellites
- Determination of clock drifts of GPS and constellation satellites
- Global network of GPS ground stations for double differencing

The infrastructure for deriving all these parameters is presently only available at NASA/JPL and GFZ Potsdam. It is presently used for the CHAMP and SAC-C occultation measurements and will be available for *swarm*, if required.

2.2 Relation to Other Missions

The *swarm* mission should be seen as a natural extension of the three missions, Ørsted, CHAMP and the Ørsted-2 experiment on SAC-C, all of which provide high-precision measurements of the near-Earth geomagnetic field. It is aimed directly at overcoming the inherent limitations of single satellite missions and will significantly improve their results. It will furthermore extend these geomagnetic research efforts to cover a full solar cycle. The improved understanding and modelling capabilities of the near-Earth magnetic field to result from the *swarm* mission will therefore also enhance the value of data from preceding missions.

In several ways, the *swarm* mission can be seen as a direct and relevant supplement to the missions chosen as candidates for the "core missions" of the Earth Explorer element of the Earth Observation program. Accurate measurements of the geomagnetic field provide one of the few means to gain insight into the properties of the outer core and mantle which is also addressed in the GOCE mission. The geomagnetic field and its interaction with the solar wind play an important role in forming the external environment of the Earth. It constitutes a variable background, the importance of which must be understood, if one is to fully benefit from other missions concerned with changes of the Earth system.

Ampère
In 1997, several French geomagnetic research institutions (UBO, IPGP, CETP and CEA) proposed the Ampère project to CNES in the framework of a call for opportunities for microsatellites as secondary payload of Ariane 5. The main scientific objectives in solid Earth sciences are the core dynamics and the global electrical conductivity imaging of the Earth mantle. These objectives require long time series of geomagnetic data. As a result, it is

proposed that Ampère be launched in the 2005-2007 time frame prior to *swarm* to maintain a continuous recording of the geomagnetic field. Ampère will be launched into a polar orbit at 550 km altitude or less. The payload consists of an absolute vector magnetometer, a triaxial fluxgate magnetometer, a triple-head star imager, and a GPS receiver. Ampère is the priority of the Earth Science panel of the CNES Earth environment scientific committee (TAOB) and is currently under review for a possible phase-A selection in 2002.

ST-5 Follow-On
In 1999, NASA selected the ST-5 mission as a component of the New Millennium program, to test new technologies as part of its Sun-Earth connection program. The goal is to launch three nanosatellites, each weighing about 20 kg, that would make observations of the earth's magnetic field. The spacecrafts would fly in a constellation much like *swarm*, performing coordinated scientific observations as if they were a single larger spacecraft. ST-5 is scheduled to fly in 2004, with a primary mission duration of 3 months. ST-5 would be in a low-inclination geosynchronous transfer orbit with a perigee at 200 km. Although it will make vector observations of the Earth's magnetic field from a boom-mounted magnetometer, those measurements will not be in the same class as *swarm* because of the lack of a star camera and a scalar magnetometer. The U.S. Co-investigators in the *swarm* team propose to take the ST-5 concept (a full-service nanosatellite capable of formation flying) and bring the magnetic field and GPS measurement components to the accuracy of *swarm*. In order to overlap with the *swarm* mission and take advantage of the lessons learned during ST-5, they intend to propose the mission in 2003 as either an Earth System Science Pathfinder (ESSP) or as a Sun-Earth Connection mission. Based on current NASA development times, this would lead to a mission in 2009. As outlined in the Solid Earth science working group report of NASA (http://solidearth.jpl.nasa.gov), the objectives of the mission would be very similar to those outlined for *swarm* in this proposal. The proposed NASA mission would incorporate an integrated GPS/Star camera being developed for the upcoming Grace mission. This hardware may also be made available to the *swarm* project for incorporation within its satellites.

Looking beyond the objectives of the Earth Explorer programme, the *swarm* mission will serve as an important near-Earth component of the International Solar Terrestrial Physics programme (http://www-istp.gsfc.nasa.gov), including the ESA Cluster-II mission.

3. Technical Concept

3.1 Science Payload Concept

The basic requirement that has to be fulfilled by the selected payload concept is to provide high quality measurements of the Earth's magnetic field and related quantities. Particularly demanding is the precise determination of the magnetic field vector. This requires a low noise, highly stable and ultra linear vector magnetometer. The orientation of the instrument is obtained by a dedicated star tracker system with respect to inertial stellar coordinates. Both these critical instruments are mounted on an optical bench which is placed at the end of a 4 m boom, in order to relieve the constrains on magnetic cleanliness of the spacecraft. An additional absolute scalar magnetometer on the boom is foreseen for calibration purposes.

Among the devices monitoring phenomena that are related to the geomagnetic field is the electric field instrument. For this mission it is foreseen to measure the ion drift vector and deduce from it the electric field. Variations of the ambient air density are sensed by an accelerometer at the center of gravity of the spacecraft. Finally a dual-frequency GPS receiver is needed for the precise orbit determination and for an absolute timing of the measurements. This instrument will also be used for limb sounding studies of the ionosphere and atmosphere.

3.1.1 Science Payload Elements

The payload elements proposed for this mission resemble in many respects the successful complement flown on CHAMP. Modifications are planned where deficits were observed. In the subsequent sections the individual instruments are briefly introduced.

Absolute Scalar Magnetometer (ASM)

To maintain absolute accuracy in a multi-year geomagnetic field mission the ability of performing an in-flight calibration of the vector magnetometer is needed. For this purpose an Absolute Scalar Magnetometer (ASM) is included in the payload complement acting as the magnetic standard. Best suited for this purpose are magnetometers based on Nuclear Magnetic Resonance (NMR) or optically pumped instruments. Their output frequency is related to the ambient magnetic field solely by atomic constants[25].

For the Ørsted and CHAMP missions an Overhauser effect proton magnetometer has been flown successfully. Unfortunately, this instrument is no longer available. There are, however, promising developments towards an omni-directional Helium vapor scalar magnetometer[26]. Such a magnetometer provides higher resolution and a faster sampling, but it still awaits a space qualification. As a fallback option for this instrument a classical proton precession magnetometer is foreseen. This device has been used on several sounding rocket flights. A caveat is its reduced sampling rate. This does, however, not compromise the in-flight calibration, which is the prime purpose.

The required performance of the ASM is an absolute accuracy of <0.5 nT and a resolution <0.1 nT within a full-scale range of ±65000 nT. Typically requiremented resources are indicated in Table 3.1. Date rate is 0.5 MB/day. There is furthermore a reference frequency needed which should be controlled by the GPS clock.

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[25] Primdahl, F.; "Resonance Magnetometers", in: P. Ripka (ed.) "Magnetic Sensors and Magnetometers", 267, Artech House, Boston-London, 2000

[26] Gravrand, O., A. Khokhlov, J. L. Le Mouël, and J. M. Léger, On the calibration of the 4He pumped magnetometer, *Earth, Planets, Space*, **53**, 949-958, 2001

Compact Spherical Coil (CSC) Vector Feedback Magnetometer (VFM)

The Compact Spherical Coil (CSC) Vector Feedback Magnetometer (VFM) accomplishes high precision, ultra-high linearity and low noise measurements of the Earth's magnetic field vector components. The VFM is regarded as the prime instrument of the *swarm* mission. This magnetometer uses the fluxgate principle that is simple and reliable. A dedicated development led to the vector fluxgate magnetometers for Ørsted, CHAMP and Ørsted-2/SAC-C drawing heavily from former mission heritage (Figure 3.1 shows the 82 mm diameter sensor). The CSC is a tri-axial spherical sensor offering the smallest external dimensions for the largest internal homogeneous field volume, which gives rise to the extraordinary omni-directional linearity.

Figure 3.1: *Ørsted FM CSC Sensor*

All 3 sensor components are placed in the common null field inside the homogeneous volume of the spherical coil. Each fluxgate element acts as a null field indicator and controls the feedback current of the corresponding outer coil. The coil current is an exact measure of the corresponding ambient magnetic field component. The instrument highlights can be summarised as:

- Compact spherical coil vector feedback
- Stress-annealed, low noise amorphous magnetic metal ring core fluxgates
- Low-impedance preamplifier for the fluxgate element output current
- All-even harmonics output signal detection

The CSC sensor is placed on the boom at the end of the optical bench (Figure 3.2), while the satellite hosts the interface electronics. The VFM samples the magnetic field at a rate of 50 vectors/sec. The full-scale range of ±65000 nT in each component is digitised by a 24 bit converter. Power requirement and mass are outlined in Table 3.1.

Advanced Stellar Compass (ASC)

The Advanced Stellar Compass (ASC) is a miniature, fully autonomous, star tracker. The ASC is designed to deliver highly accurate attitude data for the vector magnetic field measurements. Since the ASC was originally designed for magnetic mapping missions like Ørsted and CHAMP, it features a low magnetic moment Data Processing Unit (DPU) and a virtually non-magnetic, Camera Head Unit (CHU).

The principle of operations is, that the CHU acquires an image of the stars in the Field Of View (FOV), with an integration time ranging from 16sec to 1/16sec, selectable by the user according to the slew rate over the sky. The image is subsequently digitized and read into the DPU via a very low noise A/D circuitry. The ASC achieves a remarkable operational robustness that allows for attitude updating very close to the bright Earth limb, close to the Sun and even with the Moon inside the FOV. This feature substantially increases the freedom of attitude maneuvering under full operation.

After the DPU gains access to the image, it is first sifted for star-like objects. This filtering efficiently removes objects such as the Moon, stray light associated ghost images and planets, but more importantly, it also removes radiation induced charges, that otherwise could impair proper operations. The ASC is able to operate under severe radiation fluxes encountered e.g. in the South Atlantic Anomaly.

At start up or after a dropout the ASC automatically switches to the Lost In Space algorithm, which is based on a simple yet robust star triplet comparison with the on-board star database for deriving the initial attitude. The latter step typically takes only 50-60ms. The switch into this algorithm is transparent to the user. Normally, the ASC will know the approximate attitude from a previous measurement, so the matching of the star centroids with the on-board star catalogue is a simple least square fit with an associated outlier rejecter, which assures a highly accurate attitude update with a minimum data-latency.

The DPU is able to deliver 5.5 attitude updates per second, and it supports from one to four Camera Head Units (CHUs). For the *swarm* payload three CHUs are foreseen. Two DPU units will be cross-strapped in a cold redundant configuration, such that either unit can drive the camera heads. Using cross-strapping, a system reliability of 99.99% for a 3 years mission is achieved.

Key values for the ASC system are, Size: 100mm × 100mm × 100mm per DPU and 50mm × 50mm × 50mm per CHU; power and mass are indicated in Table 3.1. The accuracy per CHU is better than 2" perpendicular to the boresight and 25" twist about the boresight. Combining the readings from all three CHUs and down-weighting the poor directions provides a sub-arcsec attitude accuracy.

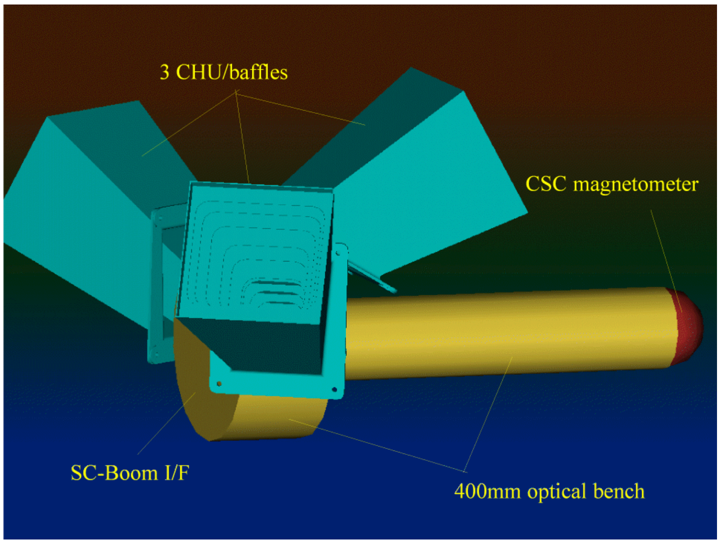


Figure 3.2: *Optical bench mounted with triple CHU and CSC*

The optical outer baffle parts of the star tracker cameras are mounted on the CFRP boom, whereas the inner baffles and the CHUs are mounted directly on the optical bench. Hereby, a stable thermal environment for the 400mm optical bench is ensured. The CSC sensor is mounted at the far end of the boom system in order to avoid disturbances. The CHUs are tilted up 30°, to avoid stray light from the Earth albedo.

Electric Field Instrument (EFI)

The Electric Field Instrument (EFI) on board the *swarm* satellites makes in-situ measurements of the ion distribution and its moments. Key parameters that can be determined by this instrument are the ion density, the drift velocity and the electric field by applying the ($\mathbf{v} \times \mathbf{B}$) relation.

Instead of using a double-probe instrument for sensing the electric field it is intended (and possible due to the 3-axes stabilized spacecraft) to use an ion drift meter in combination with a Retarding Potential Analyzer (RPA). Such instruments have been flown on missions like DE-2 and are in operation on all recent DMSP satellites. In addition a Planar Langmuir Probe (PLP) is added to the complex, which provides readings about the ion density and monitors the spacecraft potential. Prime measurement quantity is the ion velocity vector. This value is heavily biased by the orbital speed of the satellite. Precise orbit and attitude data are needed to retrieve the rest-frame velocity. Together with the magnetic field the electric field can be calculated: $\mathbf{E} = -(\mathbf{v} \times \mathbf{B})$. All the quantities orbital velocity, attitude and magnetic field are measured precisely on *swarm*. For proper operation, the EFI requires its aperture to point into the ram direction within a 5° cone. Furthermore, it has to be made sure that the spacecraft potential with respect to the ambient plasma does not exceed 1 V.

The envisaged instrument is capable of measuring the electric field in a range of 0.3 V/m with a resolution better than 3 mV/m. Acceptable ion densities range from 10^8 to 10^{13} m^{-3}. Sample rates are selectable up to 16 Hz. Power and mass requirements are indicated in Table 3.1.

Accelerometer (ACC)

An electrostatic accelerometer (ACC) shall serve for measuring the non-gravitational accelerations, such as air-drag, Earth albedo and solar radiation pressure acting on the bodies of the *swarm* satellites. The air drag is directly correlated with the air density and its fluctuations at S/C altitude. The basic measurement principle of an electrostatic accelerometer for space applications is the use of a free-floating proof-mass within a cage, which is equipped with electrode pairs that control the motion of the test body both in rotation and translation by electrostatic forces. The accelerometer cage is fixed to the S/C body. By applying a closed-loop control to all electrode pairs it can be achieved to keep the proof-mass motionless at the center of the cage. The electrostatic forces needed to fulfill this task are directly proportional to the forces, which are acting on the body of the satellite. In order to keep the disturbance accelerations from the satellite orbital motion and AOCS action minimum, the proof-mass has to be positioned close to the CoG of the spacecraft.

The ONERA STAR accelerometer sensor uses a parallelepipedic proof-mass within a cage made from ultra-low expansion ceramics in order to minimize effects of thermal expansion and it features the following characteristics:

- Measurement bandwidth — 10^{-4} ... 10^{-1} Hz
- Measurement range — $\pm 10^{-4}$ m/s^2
- Resolution of the two high-sensitive axes — $< 3\cdot10^{-9}$ m/s^2
- Resolution of the less sensitive axis — $< 3\cdot10^{-8}$ m/s^2

It consists both of a sensor and a data processing unit and delivers a total of about 2.5 MB of data per day. Power and mass are indicated in Table 3.1. Care has to be taken to minimize thermal variations of the sensor both over the orbit and the various mission phases in order to keep the thermally driven changes in bias and scale factor as low as possible.

GPS Receiver

The GPS receiver is needed for the autonomous in-orbit navigation and for the precise orbit determination in the course of post-processing. By using the precise timing information contained in each navigation solution in combination with a synchronization pulse delivered every second by the receiver, an absolute time scale (GPS time) can be established for all the *swarm* satellites. The GPS receiver performs Satellite-to-Satellite Tracking (STS) and operates by receiving the coded navigation signals from the satellites of the GPS constellation and transforming them into tracking observables. A state vector of the receiving antenna (the navigation solution) is obtained every 10 seconds from the less precise C/A code on a single frequency while pseudo-range and carrier phase data are derived on both the L1 and L2 frequency which enables the generation of ionospheric-free orbit data with a precision of few centimeters. For radio occultation events, the signal distortion caused by the ionosphere is derived from recording both GPS carrier phases with 1 Hz sampling during the occultation event. Optionally, the receiver can be programmed to support also atmospheric occultation measurements with an update rate of 50 Hz.

NASA's „BlackJack“ GPS receiver is a fully autonomous instrument which allows for automatic signal acquisition, scheduling and tracking. It can serve up to 4 antennas (e.g. 2 for

Precision Orbit Determination [POD], 2 for limb sounding) and 48 receiver channels thus handling up to 16 GPS satellites at a time. Its main performance characteristics are:

- Accuracy of navigation solution — <10 m (Select. Availability off)
- Time calibration accuracy — <1 µs from GPS time
- Dual-frequency POD accuracy (iono-free) — <0.2 cm (phase), < 30 cm (range)
- Limb-sounding observables (carrier phases) — <0.05 cm (L1), <0.15 cm (L2)

The receiver delivers a total of ~6 MB POD and ~20 MB of radio occultation data per day. For the GPS antennas an obstruction-free field of view is required. Power and mass requirements are outlined in Table 3.1.

3.1.2 Instrument Heritage and Development Basis

All the instruments presented in the previous sections are recent developments and represent the cutting edge in performance for the proposed kind of mission. Even though, most of them (VFM, ASC, EFI, ACC, GPS) have demonstrated their performance and reliability in previous missions like Ørsted, CHAMP and SAC-C. The institutions anticipated for building the scalar magnetometer (LETI or DTU) are very experienced in providing space-borne hardware. From that point of view a very mature payload complement is proposed.

Based on the experience of former missions we plan to improve specific instrument characteristics, which turned out to be the limiting factor in system performance. One such point is the employment of the triple-head star tracker. This allows deriving the attitude information from at least two camera head all the time, which provides a reduction in attitude noise by a factor of about 5 over single-head solutions.

3.1.3 Technology Challenges and Critical Issues

As has been outlined in the previous sections, space-proven instruments are foreseen for the science payload. Therefore we see no development risk, which could compromise our scientific aims. The challenging tasks come with the full utilization of the constellation. For this mission the requirements on system performance have to take into account the whole constellation as a single measurement setup. This has to be taken into account in the spacecraft design. The measurements at the individual sites need to be localized precisely both in time and space. It is planned to realize an absolute timing of the payload control and the dating of the readings, based on the GPS time information. Similarly, for the orbit position GPS navigation data will be employed.

Another part of this job has to be achieved by proper calibration of the instruments to make their results directly comparable. A key test to be performed on ground is the determination of the relative orientation of the magnetic field and star tracker measurements. The consistency of the scalar magnetometer results has to be checked and parameters of the electric field instrument calibrated in a dedicated facility. The accelerometers can only be calibrated in orbit due to its limited operational range. An approved strategy is to integrate the readings over a certain time period and compare the result with the orbital development.

3.2 Platform Concept

3.2.1 *swarm* Platform Requirements

There are a few key requirements posed by the mission objectives on the spacecraft bus

- Long orbital life-time: ballistic coefficient >400 kg/m^2
- Cold gas system for attitude and orbit maintenance
- Magnetic cleanliness: perturbation at ASM < 0.5 nT (after correction for torquer field)

- Low SC electrical potential wrt. ambient plasma: < 1 V
- Position of ACC proof-mass: Distance to CoG < 1 cm
- Attitude control: 3 axes stabilized within ±5°
- Absolute timing of on-board control: Uncertainty < 10 ms

All these requirements have been met either in the CHAMP or Grace mission. For this mission we assume the same approach as used there. The gained experience will allow to meet the specifications within reasonable effort just by an appropriate design. In case of the magnetic cleanliness the approach used for CHAMP is proposed which did not require a demanding control program but placed special emphasis on the grounding concept, the layout of solar panel wiring and positioning of magnetically critical items. The low electric potential can be achieved at the given orbit altitude by grounding the plus pole of the solar array strings to SC structure. This has been realized both in CHAMP and Grace. The collocation between the ACC proof-mass and the spacecraft CoG in flight configuration is a requirement, which has to be considered from the beginning of the design. The attitude control has to be performed very smoothly, preferably by magneto torques with a cold gas system as a back up and for orbit maintenance. Momentum wheels are not acceptable due to the noise induced in the accelerometer. The payload instruments VFM, ASC and GPS shall be used as attitude sensors. To improve their reliability they will be equipped with redundant electronics boards. A central timing system based on GPS signals, which directly controls all the activities on board, is required. To a good part this is realised on CHAMP.

3.2.2 Engineering Budgets

Mass and Power Budgets

Table 3.1 (below) summarises the unit mass and power resources of each *swarm* satellite.

Due to the heritage for most of the instrument and bus electronic units the above margins are judged to be comfortable. Only the structure and harness masses are related to higher uncertainty. Further, the available launch mass is currently estimated very conservatively and may increase as more detailed calculations are performed.

Link Budget

A preliminary link analysis has been performed for both the S-band up- and downlinks using the performance parameters listed in Section 3.2.3 Table 3.2. The link analysis demonstrated ample margin for ground stations down to 1.8 m (G/T ≈ 5 dB/K at S-band) and downlink bit rates up to 1 Mbps and 4 kbps uplink rate. ESA/CCSDS compatible encoding and data formats are assumed. This allows even small ground stations like the current Ørsted ground station in Copenhagen to assist in operating the constellation and receiving science data.

Item	Qty.	Total Mass (kg)	Orbit Avg. Power (W)	Remarks	Heritage
Instruments		**28.1**	**37.5**		
Accelerometer system	1	10.0	7.0	ACC + ICU + housing	*CHAMP*
Global pointing system	1	5.0	10.0	Receiver + POD + Occul.	*CHAMP*
Scalar magnetometer	1	3.0	5.0	ASM (CSC sensor + DPU)	
Vector magnetometer	1	2.4	2.0	VFM (sensor + DPU)	*CHAMP*
Star sensors	3	2.5	8.5	ASC (heads + DPUs)	*CHAMP/Grace*
Electric field instrument	1	2.7	5.0	EFI	*CHAMP*
Optical bench	1	2.5	--		*New design*

Item	Qty.	Total Mass (kg)	Orbit Avg. Power (W)	Remarks	Heritage
Structure		**115.0**	**0.0**		
Primary	1	85.0	--		*New design*
Secondary	1	10.0	--		*New design*
Balance mass	1	20.0	--		
Boom	1	**12.0**	**0.0**		*CHAMP*
Thermal		**7.0**	**50.0**		*CHAMP/Grace*
Data handling, OBC	1	**15.3**	**25.0**		*AstroBUS*
Power		**55.9**	**27.1**		
Solar cells		9.4	--	GaAs triple-junction	*AstroBUS*
PCDU	1	8.7	7.0+6.5		*CHAMP*
Battery	1	7.8	12.2	Li-Ion	*TerraSAR-X*
Harness		25.0	1.4		*New design*
Telemetry/telecommand		**7.4**	**8.9**		
RFEA	1	7.0	8.9	8 min TX per orbit	*CHAMP/Grace*
Antenna	3	0.4	--		*CHAMP/Grace*
Attitude & orbit control		**28.8**	**12.5**		
RCS		14.5	--		*Grace*
Cold gas		12.0	--		
Magnet torquers	3	0.9	0.5		*DIVA*
Gyro	1	0.8	12.0		*Grace*
CESS heads	6	0.6	--		*CHAMP/Grace*
Total		**269.5 kg**	**161.0 W**		
Max. allowed		**310.0 ***	**192.5 ****		
Margin		**15.0%**	**19.6%**		

* Rockot into 450/550 km circular orbit with 86° inclination: 1.400 kg / four separation systems, 25 kg each.
** Noon orbit condition with 220 W/m^2 orbit average solar array power and 2.75 m^2 projected area

Table 3.1: *swarm Satellite Budgets and Unit Heritage*

3.2.3 Technical Implementation

The electrical architecture summarised in Figure 3.3 is based on CHAMP and Grace.

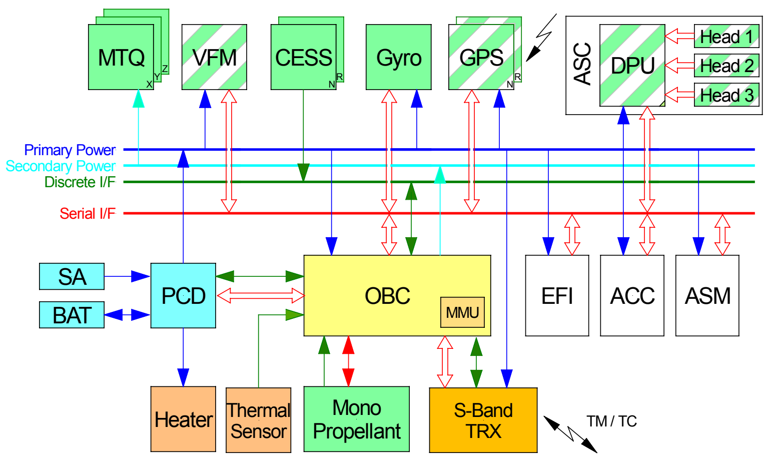


Figure 3.3: *swarm Overall Electrical Architecture*

Structural/Thermal Design

Basic requirements for the *swarm* configuration are

- the accommodation of four identical satellites inside the fairing of the ROCKOT launch vehicle or alternatively inside the fairing of the DNEPR launch vehicle.

- the accommodation of a long boom for the mounting of three star sensors and scalar/vector magnetometer instrumentation
- the accommodation of instrument and bus electronic units (based on the heritage from the CHAMP and Grace project) and
- provision of an adequate solar array area.

Figure 3.4 (next page) indicates the accommodation of *swarm* in the Rockot fairing and also shows the trapezoid structure cross section with the pair of solar array panels at the outside and the accommodation of the electronic units and N_2 tanks on both sides of the central equipment panel. The launcher separation interfaces are located in the edges of the trapezoid end plate at the lower side of the spacecraft.

The structure is made out of aluminium sandwich panels with a box type aluminium backbone structure. The load carrying solar array structure panels are covered with an open cell foam (thermal insulation) and a CFRP facesheet with solar cells (CHAMP/Grace heritage).

Heat dissipation is provided via the nadir orientated radiator foil below the equipment panel. The passive thermal concept is supported by a heater arrangement with software controlled set points.

Command & Data Handling Subsystem (C&DH)

The C&DH system is in charge of the reception of telecommands from the on-board receiver, decoding and distribution to the manifold on-board users as well as the acquisition, intermediate storage of housekeeping and science data and its subsequent transmission to the on-board transmitter during RF ground contact periods. Furthermore the C&DH system provides all necessary processing and memory capacities to support the operation of application (mainly AOC and thermal control), resource management and FDIR software.

The C&DH is physically implemented within the on-board computer (OBC). The OBC contains two permanently powered decoder units, providing the means to decode and issue high priority commands as well as transmit nominal command data to the processor for further distribution involving the software and the C&DH internal I/O facilities. The on-board software is running on an ERC32 processor with the following main characteristics:

Processor Type	ERC32				
On-Board Computer Capacity	Processing Speed	Throughput	Prog RAM	Data RAM	EEPROM
	20 MHz	15 Mips (RISC)	6 MByte	32 MByte	3 MByte
Clock Frequency Drift	< 2 E-04 in temperature range from 0 °C to +40 °C				
Distributed Timing Signals	1 Hz, 4 Hz, 8 Hz, 32 Hz				
External Source Synchronisation	Synchronisation of internal clock by external signal, 1 PPS from GPS Receiver				

Table 3.2: *C&DH main characteristics*

A reconfiguration module within the OBC is in charge to switch from the affected computer chain to the redundant one under maintenance of the old configuration status using an internal safe-guard memory. The internal 8 GBit mass memory is lavishly sufficient to store science and housekeeping data in accordance with the mission requirements. The Memory is internally protected by background memory scrubbing and latch-up mechanisms. The telemetry module transmits data in CCSDS format (real time and playback from memory) to the on-board receiver during ground contact periods. An external Mil Std 1553 bus and a set of I/O modules (discrete digital and analogue, serial UARTs) realise the command and acquisition link to the on-board users, including the necessary interfaces to the cold gas propulsion system.

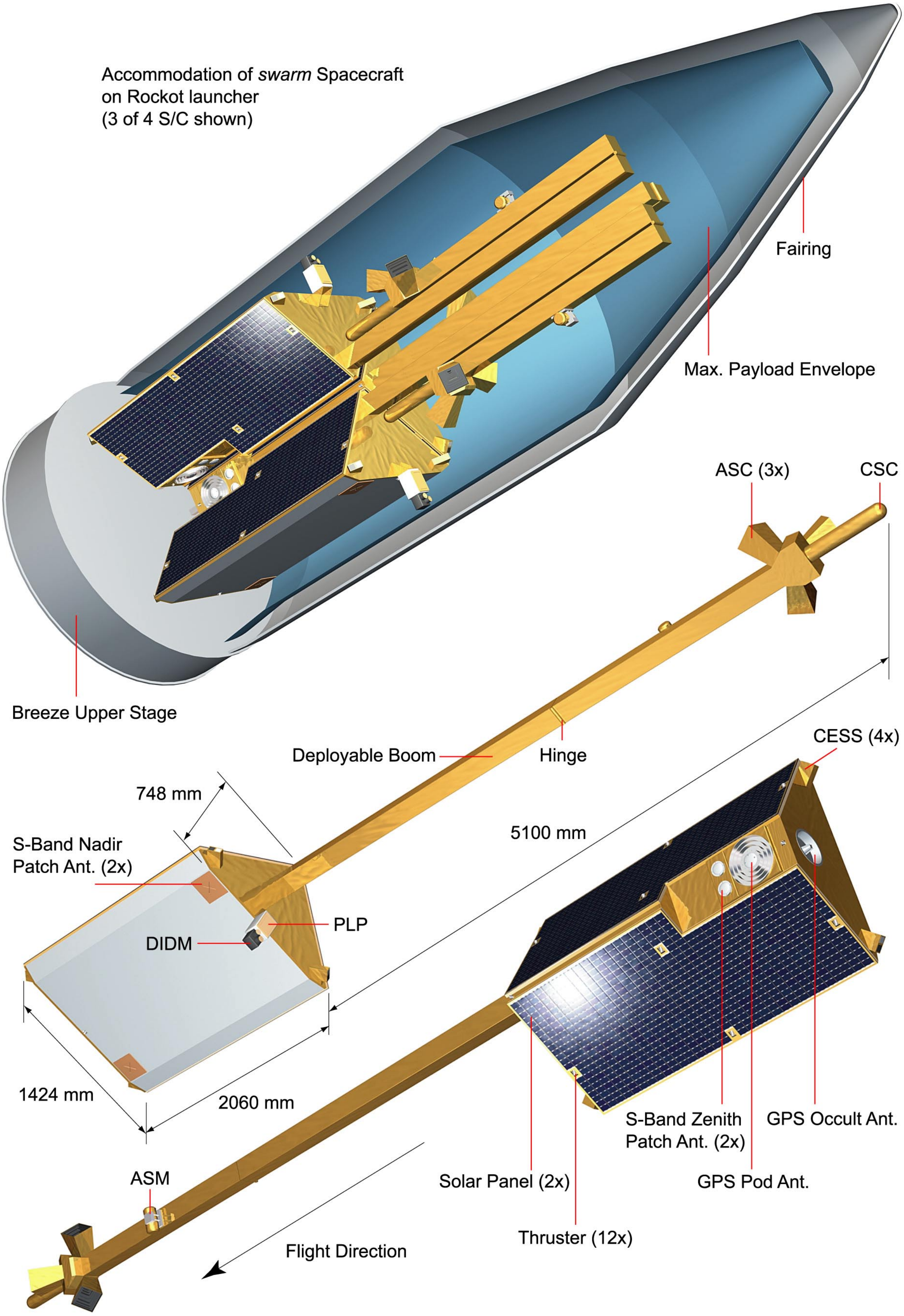


Figure 3.4: *swarm satellite configuration and accommodation in Rockot fairing*

Electrical Power Subsystem (EPS)

The EPS, as roughly outlined in Figure 3.5, is in charge of generation, safe storage (charge control), and distribution of sufficient energy for the bus during all illumination phases. The solar generator consists of approximately 4 m^2 of triple-junction GaAs cells accommodated on the 45° slanted roof panels (Fig.3.4). The power generated during sun phases will be routed into the regulator section of the power control & distribution (PCD) unit. In accordance with the state of charge of the battery and the required regulation rules, the input power of the solar generator will be regulated using a serial analog regulation principle, characterised by a high throughput efficiency and low electromagnetic noise generation. During phases with no or insufficient solar generator power, the bus unit will be supplied with electrical power from the Li-Ion battery with an appropriate energy capacity of 35 Ah.

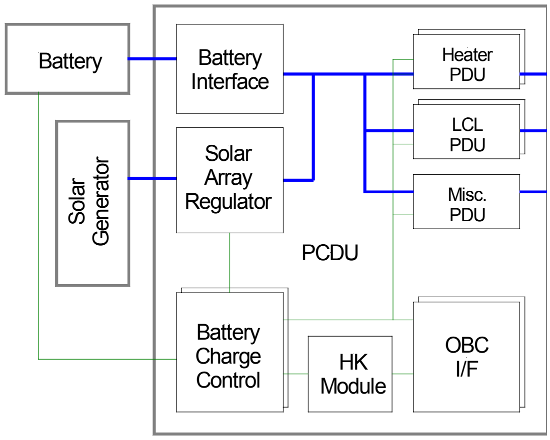


Figure 3.5: *EPS Architecture*

Power to the users (electronic units, heaters) will be distributed on switchable, current protected output lines arranged on PDU blocks within the PCDU. Current driven output lines with specific levels of inhibit are foreseen for the driving of EEDs for the different implemented deployment systems.

Communication Subsystem (COMS)

Communication subsystem (COMS) consists of a transceiver system, an RF distribution unit and three antennas. It is in charge of receiving and demodulating RF command data from ground (to OBC) and modulate and transmit housekeeping data to ground (from OBC). The communication system is transparent with respect to the data handled. The antennas consist of a combined receive / transmit quadrifilar helix antenna, pointing towards earth, as well as a hemispheric patch receive antenna and patch transmit antenna pointing away from earth. The signal of both receive antennas are superposed using a combiner/splitter and routed to the two hot redundant receivers. The signal of the cold redundant active transmitter will be routed to the nadir helix antenna. In case of a failure associated with the active transmitter, the redundant transmitter will be connected to the nadir antenna using the coax transfer switch (CTS). The main characteristics of the communications subsystem are

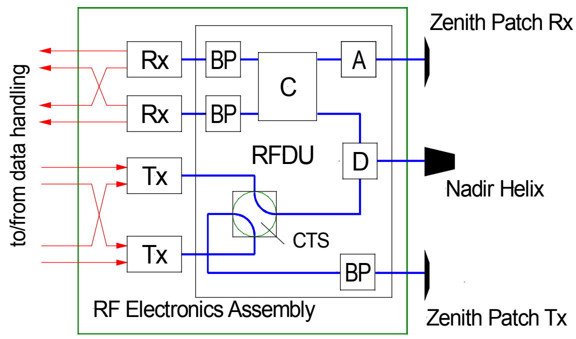


Figure 3.6: *Communication Architecture*

Receiver Characteristics	
Operating Frequency	2025 - 2120 MHz
Data Rate	4 kbps
Modulation	PM / BPSK
Sub-Carrier Frequency:	16 kHz
BER:	10^{-6} at -114 dBm

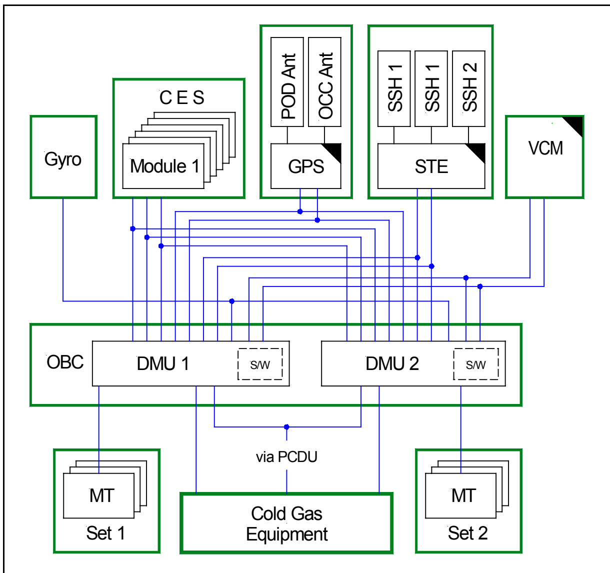
Transmitter Characteristics	
Operating Frequency	2200 - 2290 MHz
Data Rate	64 kbps / 1 Mbps selectable
Modulation	BPSK
Output Power	20 dBm / 29 dBm selectable
Load Mismatch	VSWR < 1.5

Table 3.3: *Communications subsystem characteristics*

Attitude & Orbit Control Subsystem (AOCS)

The AOCS system, as schematically outlined and characterised by its main performance parameters in Figure 3.7, is in charge of providing orbit maintenance capabilities and keep the spacecraft in the required earth pointing attitude during nominal and contingency phases.

During initial acquisition and contingency operations the AOCS relies on the coarse earth & sun sensor (CESS) assembly in conjunction with a gyro as sensors and the cold gas equipment for actuation. During nominal conditions, the utilised position and attitude determination will be realised by using the GPS receiver in conjunction with the star camera, both part of the payload, as sensors and the magnetorquers as actuators, supplemented by cold gas, when necessary. In order to properly use the magnetorquers, the data of the payload vector magnetometer will be used as reference.



Type / Architecture	3Axis Stabilised Earth Pointing (Nominal & Contingency)		
Orbit Knowledge	In-Track	Cross-Track	Altitude
	50 m	50 m	50 m
Jitter Spectrum	Power Spectral Density (PSD) of Angular Acceleration does not exceed: 0.2 ... 5 Hz: 0.005 f mrad/s^2/Hz > 5 Hz:1.0 mrad/s^2/Hz		
Pointing Accuracy	Roll	Pitch	Yaw
	3 deg	3 deg	3 deg
Pointing Knowledge	Roll	Pitch	Yaw
	0.1 deg	0.1 deg	0.1 deg
Maximum Manoeuvre Rates	0.1 deg/sec		
Gyro Measurement Range Limits	15 deg/sec		

Figure 3.7: *swarm AOCS Architecture and Main Performance Data*

3.2.4 Deployable Boom

For *swarm* a 4 m carbon fibre boom is foreseen with a deployable part of 2 m length, which is in principle similar to the design of CHAMP. The 180° deployment is performed by a simple, but robust hinge concept (Astrium patent).

The deployment of the boom is forced by a pair of helical tension springs, which are bent sideways by 180° in stowed condition. After release, a pair of guiding blocks guarantees the in-plane rotation of the boom. These blocks and the tube fitting are formed such that between these parts a low friction rolling (w/o slipping) is achieved.

Figure 3.8: *CHAMP Boom*

Once the boom reached the final position the tube fitting reaches the end stop and the deployment springs are tensioned again. Thus, the braking force restricts the overswing angle (no latching) and the boom is accelerated backwards, starting a free in-plane oscillation swing. After damping of the oscillation the boom rests on the three-point suspension formed by the guiding blocks and the end stop.

3.2.5 Separation Subsystem

The separation system proposed for the *swarm* spacecraft is the Russian Mechanical Lock System (MLS). The MLS is offered for use with spacecraft that are attached to the launch vehicle at discrete points, rather than through a ring (a clamp band system). Such point attachment systems are particularly advantageous when deploying several satellites during a single launch. The MLS fastens the satellites to the Launch Vehicle payload adapter via three or four mechanical feet (locks) at the base of each satellite. The satellites are released two and two via firing of a single pyro-driver located in the payload adapter system. This actuates a mechanical drive to unlock the attachment points. The satellites are then rotated around a hinged joint and then pushed away in opposing directions to avoid collision (spring pushers with a selectable relative velocity between 0.1 to 0.8 m/sec are used for the separation). The two remaining satellites are not released until the launch vehicle upper stage has been re-directed to the second orbital plane. Twenty-three in-flight separations using this MLS/ hinge separation system, have been performed on three Proton launches as well the Rockot Commercial Demonstration flight demonstrating simultaneous spacecraft release.

3.3 Launch Opportunities

There are several launch opportunities for the *swarm* constellation. Two have been investigated during the cause of the proposal writing. DNEPR and *Rockot.* Both opportunities appear to be both viable, affordable and reliable. However, due to the European involvement in the *Rockot* launch vehicle, this is currently considered the primary launch opportunity. Table 3.4 (below) provides a brief summary of the *Rockot* launch system's capabilities versus the major *swarm* mission requirements. The *Rockot* launch system is fully compatible with ALL requirements.

Characteristic	**Value**	**Compliance with *swarm* requirements**	**Status/heritage**
Launch system offered	Rockot launch vehicle from Eurockots state-of-the art facilities in Plesetsk	YES	Rockot family of vehicles has performed over 145 successful launches. The Rockot KM commercial configuration offered for *swarm* is flight-proven and will perform three flights in 2002 into similar orbits to *swarm*. (see 3.3.1)
Total number of spacecraft per launch	Four (4)	YES	Rockot has demonstrated simultaneous release of 2 spacecraft during its CDF mission. In 2002, the LAP mission will demonstrate injection of spacecraft into different orbits with several re-ignitions (see 3.3.1).
Accommodation of spacecraft	To fit within standard Rockot payload fairing (see drawing later)	YES	The fairing offered is a standard Rockot fairing that is flight-proven (see 3.3.2).
Adapter/ separation system	Base mounted system, able to perform simultaneous release of 2 spacecrafts at a time	YES	Simultaneous spacecraft release has been demonstrated with a base-mounted system for 23 separations. See chapter 3.2.6 for a description of the flight qualified system proposed for *swarm*.

Characteristic	Value	Compliance with *swarm* requirements	Status/heritage
Spacecraft mass	Each spacecraft to weigh 310 kg each (adapter separation system is not included in this figure)	YES	See mission profile and performance section later. See section 3.3.3.
Orbits	2 spacecraft in: 450 km x 450 km x 85.4° 2 Spacecraft in: 500 km x 500 km x 86.0°	YES	2 spacecraft in: 450 km x 450 km x 85.4° 2 spacecraft in: 500 km x 500 km x 86.0° (see section 3.3.3)

Table 3.4: *Rockot launch system's capabilities versus major swarm requirements*

3.3.1 Rockot Launch Vehicle Overview

Rockot is a flight-proven, three-stage, liquid propellant Russian launch vehicle for launches into low Earth orbit. It uses for its first two stages the SS-19 /(RS-18) Stiletto ICBM as booster stages. Over 360 SS-19 ICBMs were manufactured during the 1970s and 1980s. The *Rockot* booster stages (SS-19) have successfully flown 141 out of 144 times. Rockot combines the SS-19 booster stages with the re-ignitable *Breeze* upper stage. *Rockot* has so far performed 4 successful flights and have currently four (4) signed contracts for flights in 2002 & 2003. Flight number four with the *Breeze*-KM took place on 16th May 2000 as the Commercial Demonstration Flight (CDF) successfully launching two test payloads. This date marked the operational readiness of the commercial *Rockot* launch system including its dedicated launch facilities at Plesetsk.

3.3.2 Flight Sequence

The *Rockot* vehicle can inject 4 *swarm* spacecraft each with a mass of 310 kg into the required orbits (see table 3.4 above).

The mission profile for the Rockot vehicle is described briefly below, cf. figure 3.9.

- Lift-off to 319s seconds: Rockot booster flight:
  1st, 2nd stage ascent with payload fairing jettison
- L + 319s: 2nd Stage/ 3rd Stage (Breeze) separation
- L + 319s to L + 917 s: Breeze first ignition
- Injection into a 160 km x 450 km x 85.4° orbit
- L + 4800s: Second breeze ignition
- Injection into a 450 km x 450 km x 85.4° orbit
- L + 5700s: Separation of first two spacecrafts
- L + 7600s: Third breeze ignition
- Injection into a 450 km x 550 km x 85.7° orbit
- L + 10400s: Fourth Breeze ignition
- Injection into a 550 km x 550 km x 86° orbit
- L + 11300s: Separation of second set of spacecrafts
- Stage contamination and collision avoidance manoeuvre

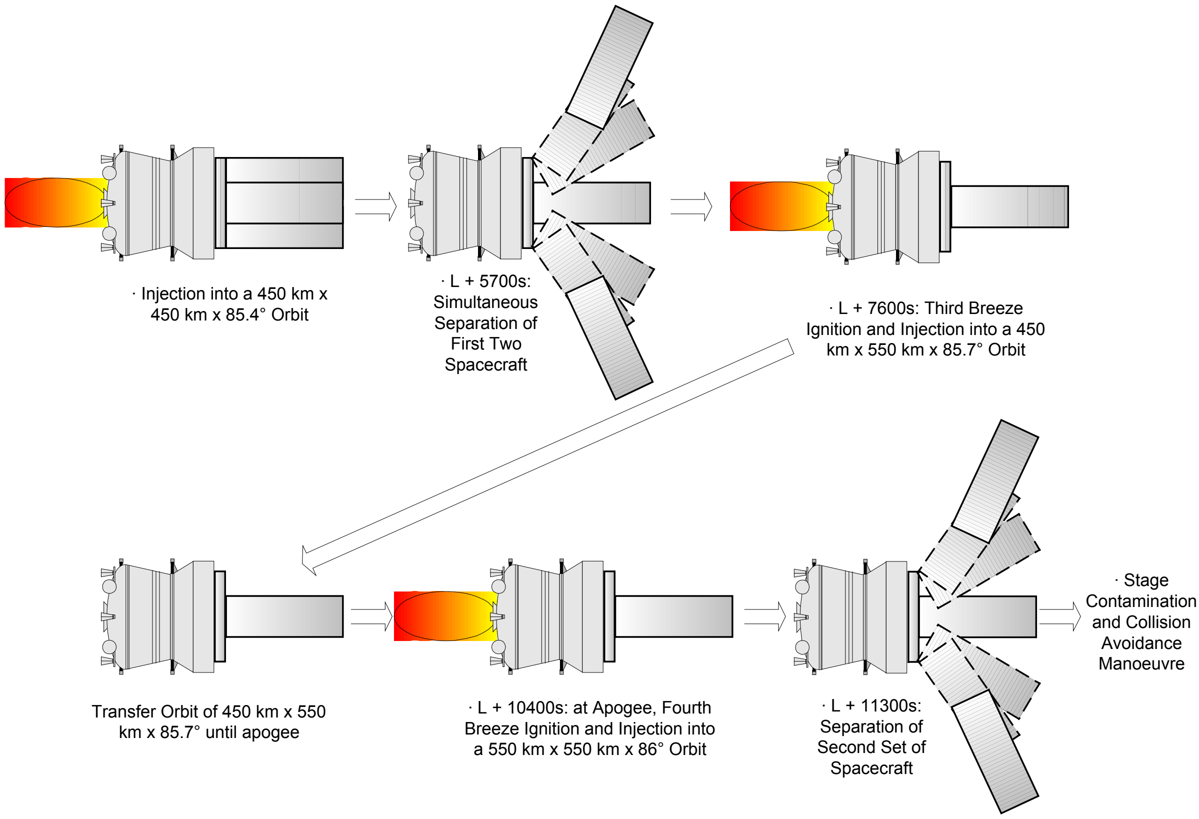


Figure 3.9. Rockot Flight Sequence for injecting swarm satellites into the required orbits

The ability of the *Rockot* to perform multi payload missions has been demonstrated both on on-ground and in-flight. On-ground qualification for the *Rockot* breeze upper stage has demonstrated over 20 re-ignitions. In-flight tests (e.g. CDF) have also demonstrated multiple re-ignition capability and manoeuvring of the breeze into different orbits (CDF). The manifested piggyback mission LAP-1 planned for 4Q 2002 will demonstrate in-flight capability of 5 to 7 re-ignitions with injection of spacecraft into different orbits. Hence, the heritage and flight capability of such as mission for *swarm* has been adequately demonstrated in the past and also in the near future.

3.4 Reliability

The *swarm* platform is using the AstroBus concept, which is designed with a full one-failure tolerance on all functions. Sole exceptions are structural parts and parts with a high record of reliability in areas where redundancy is out of scope. All spacecraft bus and instrument units will be designed to ensure full operability upon power up. Failure detection will be included for all critical functions and subsystems. Additionally, all units controlled by processors will have the capability to perform a built-in self-test. All single-point failures within the actual design will be identified and reported in the FMECA. They are reviewed and the associated risk approved by the customer on the regular reviews. In accordance with the AstroBus architecture, internally redundant units will be cross-strapped within the onboard data handling subsystem and the interconnecting data buses. Failure propagation will, as a general rule, be limited to the affected module and inputs and outputs will be short circuit protected, to avoid failure propagation to the redundant unit. No bus redundant functions will be located in the same part cavity. Detailed failure propagation effects and containment mechanisms are outlined in the FMECA.

3.5 Ground Segment Implementation

3.5.1 Mission Operations System Overview

The ground segment for control of the four *swarm* satellites consists of one ground station for up- and downlink (TT&C) and a satellite control center. The ground station and a supporting ground station network during Launch and Early Orbit Phase and for contingencies shall build the interface to the space segment. The satellite control center will be located at the German Space Operations Center in Oberpfaffenhofen and shall have close contact to the Mission Control Center (MCC). MCC is the interface to the scientific community.

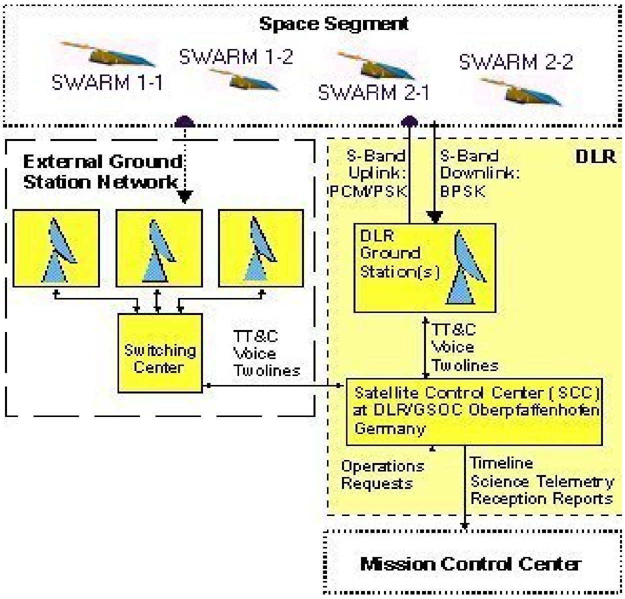


Figure 3.10: *swarm Mission Operation System Overview*

3.5.2 Ground Station(s)

Beside the supporting network it is assumed that only one ground station is utilised as routine uplink/downlink station. In order to take advantage of existing systems and to consider CHAMP heritage, the characteristics of the on-board communications system shall be:

- downlink channel in S-Band with BPSK modulation and a maximum bit rate of 1 Mbps
- uplink channel in S-band with PCM/PSK modulation and a bit rate of 4 kbps
- The ground station shall fulfil the following requirements:
- Conduction of a Radio-Frequency Compatibility Test
- Telemetry Reception
- Command Transmission
- Short Term Archiving of Raw Telemetry Data
- Generation of a Reception Report

3.5.3 Satellite Control Centre

To make use of the standardised software systems of the German Space Operations Center, the ESA Packet Standards for telemetry and command shall apply for the onboard data handling system (CHAMP heritage).

The main tasks of the satellite control center are:

- Extracting and distribution of science telemetry (level-0)
- Processing and display of housekeeping telemetry for satellite health monitoring
- Receiving of operations requests for the scientific instruments and generation of an onboard timeline and a derived sequence of events.
- Generation of commands and subsequent uplink
- Operational orbit determination and prediction
- Preparation of a reports (telemetry reception, satellite status)
- Failure analysis at contingencies and remedy operations

3.6 Mission Operations Concept

3.6.1 Operations Preparation Phase

The tasks for the operations preparations phase are:

- Conduction of an RF Compatibility Test
- Population of telemetry and command data bases
- Generation of a procedure data base
- Preparation of a Flight Handbook
- Acceptance Testing of the ground segment subsystems
- Conduction of operations training sessions
- Simulating specific mission phases
- Rehearsals

3.6.2 Launch and Early Operations

For the initial link acquisition a supporting ground station network has to be utilised (eg. 3 groundstations in the NASA polar network, which also is being used in the Grace mission). The specifik requirements on the ground station network characteristics depend on the launch vehicle, the communication system, the attitude control, and the specific onboard activities to be performed after launch. However, the operators will have approx. 90 Minutes for initial acquisition of the two fist satellites before deployment of the two last satellites. The duration of the launch and early orbit phase is approx. 10 days.

A typical ground station coverage pattern for the Walheim groundstation (WHM) during the first hours after launch is shown below under the assumption, that the two satellites in the 550 km orbit will be injected 93 minutes later than the two satellites in the 450 km orbit within the same orbital plane.

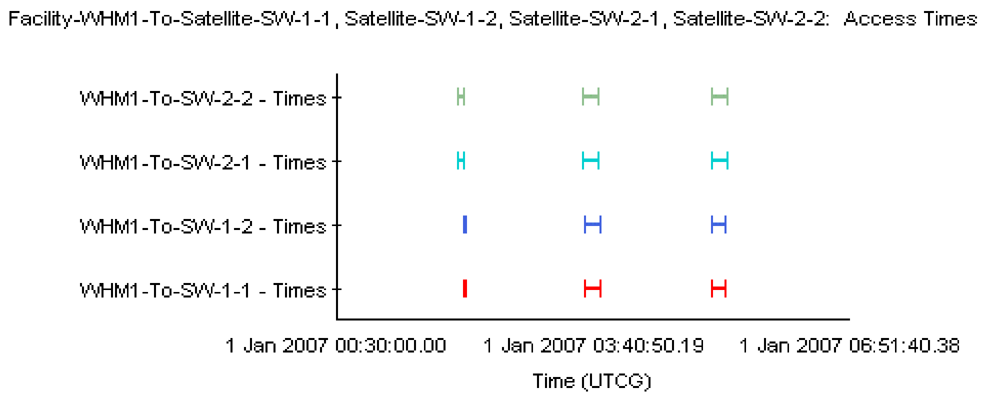


Figure 3.11: *Typical ground station coverage patterns for swarm during LEOP*

3.6.3 Commissioning Phase

After the Launch and Early Orbit Phase (LEOP) the scientific instrumentation shall be switched on and calibrated during the commissioning phase. The phase will last about 1-2 months. An additional supporting ground station network will be utilised as required during this phase (e.g. NASA Polar Network, which also is being used for the Grace mission).

3.6.4 Routine Phase

The maximum time in view above 5° elevation over a ground station is 8.7 minutes (450 km) or 9,9 minutes (550 km), respectively. Routine operations (TM&TC) shall be performed primarily with the DLR ground station in Weilheim (WHM). Each satellite will have at least four contacts per day above 5°degree elevation. In order to avoid conflicts in situations where more than one satellite is crossing a ground station visibility zone at a time, a TM/TC up-/downlink contact shall be established for each satellite only on 2 days every week. The satellite shall be operated at least 3 years.

Scientific data dump (1 Mbps) is needed every day for each satellite and requires 2 –3 ground station contacts per day. This is foreseen to be done at the data-reception station of DLR in Neustrelitz and an additional groundstation (e.g. the existing Danish Ørsted ground stations or the NASA Polar Network). A typical ground station coverage profile for WHM of all four satellites is given in Figure 3.12 indicating the migration of the coverage pattern with time.

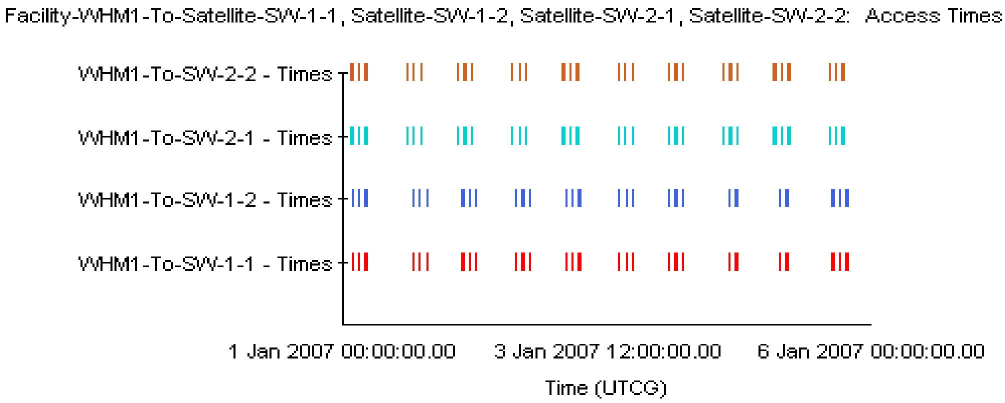


Figure 3.12: *Coverage pattern during early mission phase*

3.7 *Science Operation and Archiving*

The implementation of data pre-processing, archiving, and distribution for the *swarm* mission will adopt the philosophy developed for the CHAMP mission but also use the experiences gained with the Ørsted and the Ørsted-2/SAC-C missions. The systems will build on the facilities that already exist for these missions.

3.7.1 Science Operation

The purpose of the *swarm* mission is continual global monitoring of the geomagnetic field. The satellites and their orbit constellation have been designed to operate with a unique degree of autonomy to fulfil this.

3.7.2 *swarm* Information System and Data Centre

The data centre and archiving facility for the CHAMP mission placed at GFZ, Potsdam is proposed to be used as the base for the retrieval and archiving of the raw (zeroth level) data from the scientific instruments and housekeeping information. This will secure an efficient interface to the *swarm* ground station proposed to be at GSOC at very low cost (because already existing for CHAMP).

3.7.3 *swarm* Science Data Centre

The requirement of very high precision for the data necessitates qualified post-processing, for example, related to the verification of current instrument calibration parameters, which must be performed in close collaboration with the science team. It is proposed that these tasks be taken care of by a science data centre placed at DSRI which will be developed based on the experiences from the Ørsted and SAC-C missions[27].

[27] Description of the Ørsted Science Data Centre at URL: http://www.dmi.dk/projects/oersted/SDC/

In comparison to the single satellite missions, utilisation of the *swarm* data poses additional demands related to the multi-point aspect of the mission. For example, visualisation tools and clever search algorithms based on the combined database for all spacecraft must be developed to facilitate the use of the distributed measurements. This also will be the task of the science data centre already during phase A of the project. Some thought has been given to this problem in the context of magnetospheric cluster missions[28] and will also apply here.

3.7.4 Data Policy

The data rights for *swarm* will follow the ESA rules (ESA/C(89)93). All scientific data will remain the proprietary of the investigator team for a period of up to 6 months. After this period, the data (in calibrated and reduced form) will be made freely accessible to the scientific community. However, data that ESA considers useful for its communications and public relations effort will be made available immediately

3.8 Model Philosophy and AIT/AIV Approach

To reduce cost and schedule a critical re-examination of the classic build and test philosophy has been performed. The proposal is to lean on the classic philosophy of building and testing breadboard model - engineering model - qualification model and flight model providing units with minimum risk. However, restructuring the test sequences slightly such that the individual subsystems are more thoroughly tested at satellite level, to gain a very high confidence at systems level. Prior experience obtained with other programs, incl. CHAMP, Grace and the Danish Ørsted satellites, show that this approach is viable and that the end-product is tested to the same levels as using a ordinary approach.

Four (4) flight models of the *swarm* satellites should be built. Furthermore, enough spare subsystems or components should be available in case of minor failures on the flight equipment.

Like for the abovementioned missions the first *swarm* satellite should be built and tested as a proto-flight satellite. This means, that one complete satellite unit shall be fully assembled and tested for flight. This proto-flight satellite unit shall be tested in accordance with the environmental system test specification, consistent with the launch vehicle proto-flight test requirements.

3.8.1 Models Definition

The most important satellite models, which are essential for the success of the project, are described in the following.

AOCS and software test bed. . . This test bed is an electrical model of the spacecraft, which initially consists of OBDH breadboard model and the PCDU interface board and GPS, star camera engineering models. All other subsystems are implemented as software simulators until breadboard models or engineering models becomes available. The model will enable early debugging of the onboard SW/HW As the level of maturity of this test bed increases it will be converted into the Flat Sat Testbed described below.

Flat-sat testbed (FST) and satellite simulator. . . The model will function as a satellite simulator for troubleshooting during ground testing and in-orbit operations. First the set-up will be used as a debugging facility for engineering models and harness in a flat-table set-up. Later it will be used to functionally qualify the flight model subsystems before integration into the flight model satellites. Where hardware is not available, simple software simulators

[28] G. Paschmann, P.W. Daly (Eds.), Analysis Methods for Multi-Spacecraft Data, *ISSI Scientific Report*, **SR-001**, ESA Publications Division, 1998

shall be developed to act as the subsystem or special check out equipment (SCOE) shall be developed to provide the required stimulation of the subsystems. When the constellation of satellites is launched the FST model will be utilised as a satellite simulator for verification of operational procedures. The electrical ground support equipment (EGSE) controls the FST model. The EGSE supplies power to the FST model and provides means of communication with the FST model. The EGSE is also used for all ground-based tests of the satellite. The tests carried out on the FST model can roughly be divided into electrical tests, communication tests and functional tests to verify the electrical interfaces, functionality and performance of the subsystems and of the system as a hole.

Proto-Flight Model (PFM). . . It is suggested to adopt a proto flight approach to the *swarm* satellite development, i.e. use a PFM satellite with verification by environmental testing. This means that one complete satellite unit is will be fully assembled and tested before continuing with the remaining flight model satellites. Care shall be taken not to overtest the PFM, and thus risk inadvertent stress/damage to the flight hardware, which would then require costly refurbishment and retest. The PFM structure will first be equipped with flight like subsystem dummy masses. This will be utilised as a structural model to facilitate static finite element load analysis coupled with qualification level tests to measure the natural frequencies and modes of the satellite. The test results are then used for correlating the finite element analysis. The final dynamic model is then integrated into the launch vehicle dynamic model and a coupled load analysis can then be performed if required to verify the structural stability of both the satellite and the launch vehicle structures. This exercise may impose some design changes to the satellite structure if it turns out that the natural frequencies are too low and must be raised to prevent coupling between the satellite and the launch vehicle structures. Once the satellite structure has been qualified, the proto flight approach continues with integration of the environmentally tested flight model subsystems into the PFM satellite structure. The assembled PFM satellite hereafter continues with the functional and environmental test programme.

Flight Model. . . Based on the experiences with the proto flight model, the succeeding 3 FM satellites should be built and tested to acceptance level only.

Flight Spare equipment. . . Each subsystem consists of one or more individual equipment boxes/items, which in general are built/procured and delivered separately for satellite integration and testing. Whenever feasible, one extra unit should be built/procured of each flight equipment item thus providing one extra flight spare unit. Non-critical flight equipment can use the approach of having all parts and materials available but not assembled, i.e. resources will be saved by not assembling and testing specific hardware. In case of a major failure in one of these subsystems the possibility is still there to quickly produce a flight spare if deemed necessary.

3.8.2 Integration and Test Flow

Figure 3.12 (next page) indicates the proposed integration and test flow for the *swarm* mission.

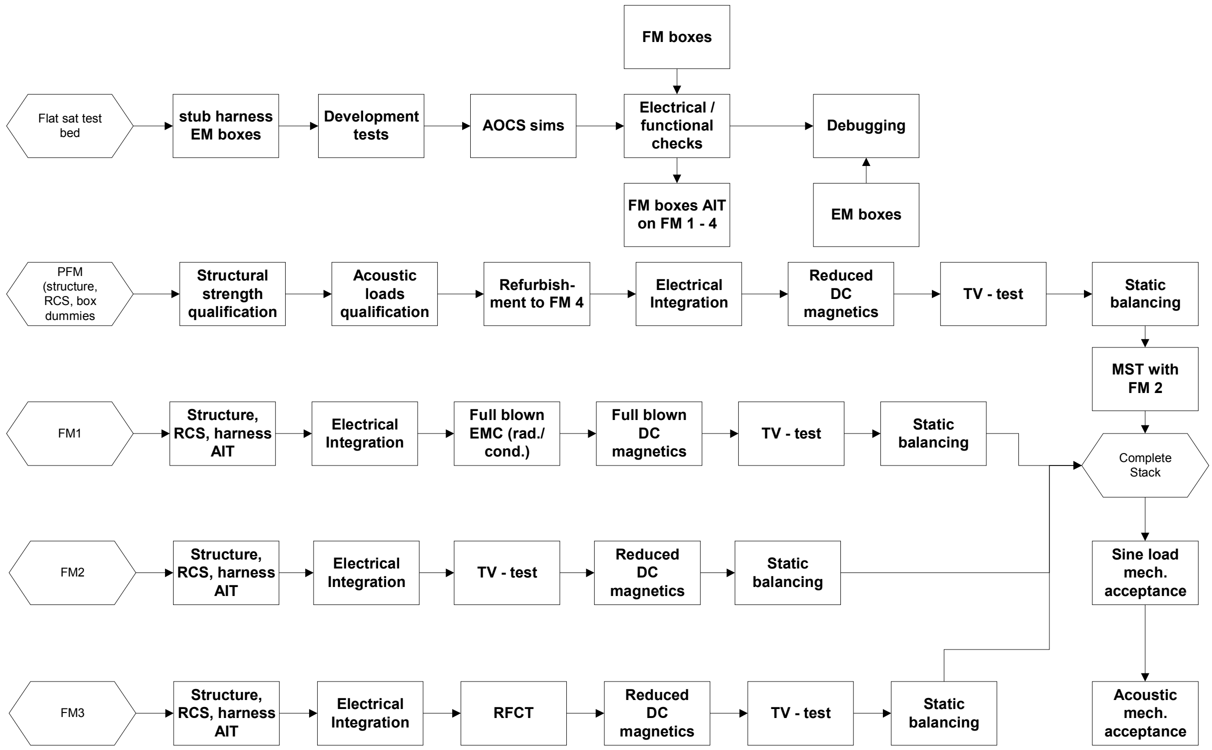


Figure 3.12: *Proposed swarm AIT flow*

4. Mission Elements and Associated Costs

4.1 Project Phasing

Reuse of experience in the form of a core team, which has experience from former magnetometry missions (CHAMP, Grace and Ørsted), and a base of mature technology is important to keep a low level of financial risk. This may be the nucleus for an integrated team with reduced project overhead, and a strong focus of maintaining the scientific value of the mission. The development lifecycle may still be kept in the usual A/B/C/D phases. However, each phase shall be kept very focussed on the primary objective. Due to the short time schedule and reuse of existing technology two phases are proposed: Phase A and Phase B/C/D.

Phase A (6 months duration). . . Will review scientific requirements based on experience from previous magnetometry missions, evaluate the existing instruments and subsystems, examine possible secondary mission objectives and recommend a concept and a preferred selection of instruments and subsystems. Further, this phase will consolidate the design and integration concept for reusable parts. Also the end-to-end aspects of the mission will be examined to ensure that the science data processing and distribution concept is in place. A core team representing satellite, instrument and science center should do this phase of the mission. Phase A also requires a clear involvement by the launch provider to analyse the orbit injection scenarios incl. separation analysis, collision avoidance analysis and to define a clear and viable baseline for the establishment of the *swarm* constellation.

Phase B/C/D (42 months duration). . . Will construct the system, both space and ground segment within an integrated team. Because of the high degree of heritage and reuse, focus will be on interface control between the various subsystems. Further focus will be put on efficiency in operations, where the large experience combined in the team allows a large degree of automation on mission/satellite management. Also reuse of pre-launch facilities may be considered during LEOP and early on-orbit operations. Figure 4.1 outlines the overall schedule.

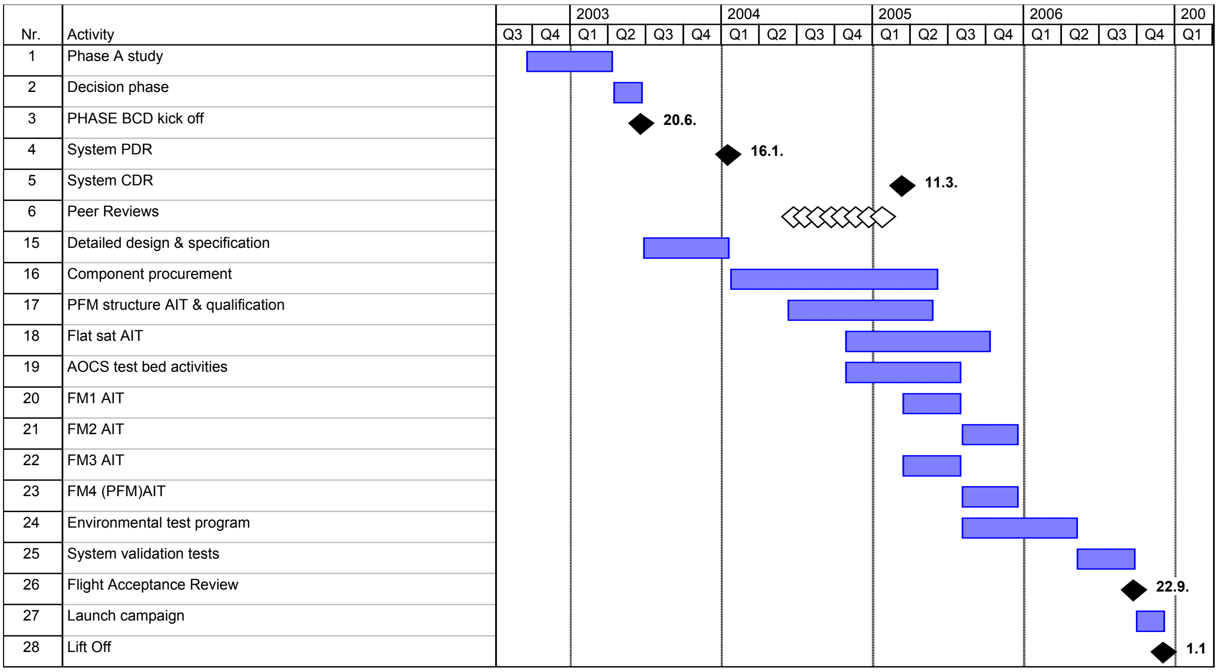


Figure 4.1: *Proposed swarm mission overall schedule*

4.2 Finance

4.2.1 Assumptions

Table 4.1 below identifies possible suppliers of the mission elements.

Mission element		**Implementation**	**Assumed Funding Source**
Lead Investigator and Project Office		Danish Space Research Institute	**ESA**
Science preparation	Scientific definition studies	Danish Space Research Institute, all members of the science consortium	**ESA & National**
	Campaigns	N/A	**N/A**
System engineering and assembly integration and test		Astrium GmbH GeoForschungsZentrum Potsdam	**ESA**
Space segment	Instrument(s)	Danish Technical University, Danish Space Research Institute, *NASA, CNES*	**ESA & National**
	Platform	Astrium GmbH	**ESA**
	Launcher	Eurockot or DNEPR	**ESA**
Ground segment facilities	Command and acquisition stations	German Space Operation Center	**ESA & National**
	Operations centre	German Space Operation Center	**ESA &National**
	Processing and archiving	Danish Space Research Institute, or CHAMP Science Data Center (GFZ)	**ESA & National**

/continued ...

Mission element		Implementation	Assumed Funding Source
Mission control and data exploitation	Mission Control	GeoForschungsZentrum Potsdam	**ESA & National**
	Data utilisation	Danish Space Research Institute (PI), GeoForschungsZentrum Potsdam (Co-PI), IPGP (Co-PI), all members of the science consortium	**National**

Table 4.1: *Mission elements and activities: implementation and funding source assumptions*

4.2.2 Cost Budget and Required Funding Profile

Table 4.2 gives an overall description on the assumptions for the cost estimates and the overall cost breakdown and funding profile is shown in Table 4.3. It includes all expenses pertinent to the *swarm* project except scientific work, which is funded individually by the participating institutions. The major cost elements are: System Engineering and AIT/AIV Activities, Instruments, Platform and Mission Operations. Considering the very large on-board and ground based heritage from the CHAMP mission, the Grace mission and the two Ørsted Missions the price and schedule estimates provided are considered solid and reliable and **both Astrium GmbH and Eurockot are already now ready to negotiate a firm fixed price contract based on the proposed budget**. Cost estimates are provided in 2002 economic conditions and the funding profile assumes a launch primo 2007 using a Rockot launcher.

Mission element		Assumptions
Lead Investigator and Project Office		Price estimates for PI and project office are based on adjusted cost figures from the Grace, CHAMP and Ørsted missions.
Science preparation		Price estimates are based on cost figures from Grace, CHAMP and Ørsted missions. Prices are reduced in accordance with the solid heritage and experience from these missions.
System engineering and assembly integration and test		Price estimates for Systems engineering and AIT are based on adjusted cost figures from the Grace, CHAMP and Ørsted missions, the price includes 1. Launcher interface management 2. Dedicated payload engineering 3. Dedicated payload development shadowing 4. Dedicated DC magnetic engineering 5. Phase A/B/C/D support from GFZ equivalent to 3 engineers/scientists over duration 6. 50% co-location of Astrium core team at GFZ for Phase A 7. 50% co-location of GFZ core team at Astrium/IABG for Phase B/C/D
Space segment	Instru-ment(s)	Estimates are based on escalated cost figures from Grace, CHAMP and Ørsted missions
	Platform	Estimate is based on escalated cost figures from Grace & CHAMP. The price includes 1. 6 months phase A study & 42 months phase B/C/D 2. Delivery of 4 FM satellites 3. Buy off with successful pre ship review in Germany 4. Environmental test facilities at IABG, Munich
	Launcher	1. Rockot has stated a firm fixed price not exceeding EUR 14.5 million (2007-8 prices) for a stand alone launch. This offer comprises all standard services listed in the standard Rockot SOW. For 2002 prices an estimate of EUR 13 million is based on typical ESA escalation clauses. 2. Currently Eurockot is planning to submit a proposal for the upcoming ESA procurement of Launch Services for Earth Explorer Missions. If the *swarm* launch is included as part of that purchase, the launch and all services can be provided at a significantly reduced price.

/continued…

Mission element		Assumptions
Ground segment facilities		Estimates for the groundsegment including groundstations, operations center, processing and archiving are based on cost figures from Grace and CHAMP. Prices are stated in accordance with the solid heritage and experience from these missions. Price includes availability of 4 Operators and CCS computers from GSOC over complete phase C/D
Mission ctrl. and data expl.	Mission Control	Estimates for the Mission control are based on cost figures from Grace and CHAMP
	Data Use	Estimates for data utilisation are based on cost figures from Grace, CHAMP and Ørsted

Table 4.2: *Assumptions for Cost Estimates*

Mission element		Cost Estimate 2002-2003 Phase A MEUR	Cost Estimate 2003-2007 Phase B/C/D MEUR	Cost Estimate 2007- Phase E MEUR	Total Cost Estimate MEUR
Lead Investigator and Project Office		0.1	1.3	0.1	**1.5**
Science preparation	Scientific definition studies	0.5	1.0	0.5	**2.0**
	Campaigns	N/A	N/A	N/A	N/A
System engineering and AIT		0.7	5.3	1.0	**7.0**
Space segment	Instrument(s)	1.0	9.0	0.0	**10.0**
	Platform	1.0	58.0	2.0	**61.0**
	Launcher	0.0	13.0	0.0	**13.0**
Ground segment facilities	Operations center & ground stations	0.5	4.5	1.5	**6.5**
	Processing and archiving	0.1	0.8	3.1	**4.0**
Mission control and data exploitation	Mission Control	0.0	1.0	4.0	**5.0**
	Data utilisation	N/A	N/A	N/A	N/A
Total		**3.9**	**93.9**	**12.2**	**110.0**

Table 4.3: *Overall Cost Breakdown and Funding Profile*

5. Implementation

5.1 Project Organisation

Organisationally the structure shown in Figure 5.1 is proposed. This structure emphasises coordination between the satellite implementation and the science teams as well as the international participation through subsystem/instrument responsibility.

The consortium consists of three main components. The lead investigator and the associated project office at the Danish Space Research Institute, DSRI, will be the official point of contact to ESA. Major project responsibilities are delegated to two partners. ASTRIUM GmbH in Friedrichshafen is proposed to be the prime contractor on the satellite platform and the launch vehicle. GeoForschungsZentrum Potsdam, GFZ, is proposed to act as Co-PI and take care of the payload team and the ground segment including mission operations and archiving. Management, requirements and mission analysis will be coordinated by DSRI.

This structure is proposed in order to take maximum advantage of past experience by these three groups who have performed similar tasks in previous missions, Ørsted, Ørsted-2, CHAMP and the Grace mission.

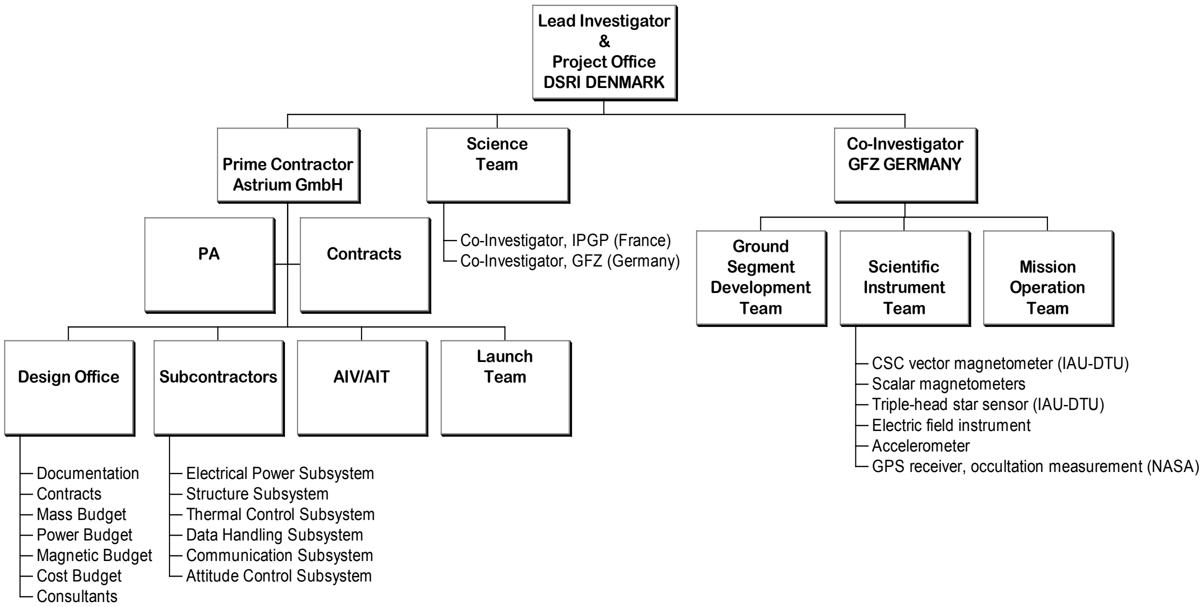


Figure 5.1: *Project Organisation*

5.2 Management Approach

This section describes the management and development approach for the *swarm* mission. The discussions have been based on the experiences from the CHAMP project, the Grace project and on the Danish Ørsted and Ørsted-2 missions, but the ambition level has been adapted to the ESA environment rather than the normal small satellite approach. Engineering approaches, brief design guidelines, documentation level, number of necessary development models etc. are included in the following discussion.

The diverse industry participation of projects of the *swarm* nature makes it important that the overall design, fabrication and testing process is based on existing and proven industrial and cost effective approaches whenever feasible. A strong science participation is also essential to the overall design and mission planning process frequently involving the trade-off of conflicting requirements and constraints.

The experience in developing CHAMP, Grace and the Ørsted satellites has shown that the design of a small low-cost satellite platform relies strongly upon teamwork. One way of assuring this is to create a small core team, collocated at the prime contractor premises to ease the intercommunication. The core system team could, as a ground rule, be formed by using one participant from each major subsystem combined with a small system engineering team and AIV team provided by the prime contractor.

During the complete design period each core team member should be able to participate on a dedicated full-time basis without conflicting demands from tasks unrelated to the development. Each team member should be directly responsible for one or more key technical task(s) or elements and should be fully cognisant for the quality of the product, including the interfaces with other elements and timely delivery.

In addition, experience shows that each team member should participate in the overall system design effort and thus develop a deep understanding of the satellite platform as a whole. This overview knowledge is essential to ensure surfacing of interface problems and possible misunderstandings early in the project before they become difficult and costly to solve. It is important therefore that problems are verbalised and/or documented as soon as they arise, so they can quickly be discussed and resolved. Tenacity shall be expected of everybody working on developing the platform. The challenge will always be to ensure that unanticipated factors are dealt with quickly and that back up plans are initiated as soon as possible.

Due to the many complex design issues that the engineering and science teams have to consider and to reduce the development time, there is a need to focus on concurrent engineering rather than of a sequential life-flow.

Minimum review requirements for *swarm* can be met by introducing an approach where the first formal satellite system design review incorporates all the satellite subsystems. This should then be followed later by a formal satellite system critical design review (CDR), which is not the detailed classic CDR of larger satellite projects, but a review, which confirms the selected overall final design of the satellite including the interfaces. This approach will encourage concurrent engineering contrary to the usual CDR approach, where each individual subsystem have their own CDRs. The usual individual CDR approach leads to many design reviews where it is necessary to document and review design methodology and to provide a means for discussion of the satellite and subsystem basic designs at each meeting. Further, the approach introduces waiting time between the design and manufacturing groups. These issues will be minimised by following the above suggested approach. Further, the common system design review forces the interaction and communication between the various subsystem groups, which is essential for a small satellite project. In the *swarm* case where four small satellites are to be built only one CDR should be held during the mission design phase.

5.3 Engineering Approach and Methodology

This section gives a brief list of design guidelines and policies summarizing the selected design approach intended to keep the *swarm* project within cost and on schedule.

- Keep design simple. Use off-the-shelf state of the art equipment and traditional and known design solutions, rather than having to embark on expensive and time consuming analysis or developmental testing to prove a new design.
- Avoid multiple design margins. For example, the mass and power estimates provided by each subsystem reflect best estimates, allowing all the margin to be maintained at the project level.
- Use the best components available within cost and schedule. Use space-qualified hi-rel parts when readily available. Otherwise, use mil-spec parts, or high-grade high-volume industrial parts with 1000 hours burn-in and a dependable production history.
- Test the hardware design and interfaces whenever possible, provided that the test is quick and easy. However, the test must be executed with care to avoid running the wrong test. To explain why bad test results have to be discarded can be very time consuming and costly.
- The interfaces for the central on-board computer - especially the on-board data handling bus - shall be baselined as early as possible.
- The use of rapid prototyping of selected electrical, mechanical, and data communication interfaces - inclusive up- and down-link protocols should be emphasized.
- PC compatible plug-in cards and software drivers simulating the on-board computer interface shall be developed and provided to all engineering teams building subsystems to be interfaced to the on-board data handling bus.
- Communicate frequently with the other team members/colleagues. Ask questions and discuss issues/solutions openly and often. Cross-fertilization creates surprising new ideas.
- Standardization of systems, using "off-the-shelf" systems or subsystems that can be incorporated into a spacecraft design, adding significant capability at little incremental cost.

- Utilization of the latest technology, especially electronics and new materials for the structures, enabling a spacecraft to achieve a high capability to mass ratio
- Design with satellite autonomy as a key feature, to minimize ground-to-space contact and command-and-control complexity
- Use cost effective systems which still meet mission goals
- Resist the escalation of requirements which will drive the satellite design to ever increasing levels of complexity and sophistication, forcing the mass, power and cost of an (intended) small system to that of a heavy, complex and expensive satellite
- Approach the development from a system perspective, viewing the satellite mission as a whole, maintaining a balance of requirements among segments of the system, the system cost, launch into orbit, on-orbit operations and required information gathering and transmission
- Flight hardware/software elements are not considered delivered by their respective organizations until fully integrated and tested on the satellite.

5.4 Product Assurance

5.4.1 PA Planning

The PA plan forming the basis for this proposal, is based on the PA plan implemented for the Grace program conducted for JPL/NASA. The purpose of this plan is to document quality assurance activities, specify requirements and define acceptable methods for meeting the requirements. This plan provides a tailored, cost effective, value adding assurance program. The project will maintain an effective and timely PA programme and will ensure that environmental qualification, quality assurance, reliability and safety requirements are satisfied throughout all phases of the project. The team will follow an already exercised “Total Quality Approach”, whereby the quality assurance aspects will be supervised and controlled by the combined industrial/customer engineering team itself. Personnel from PA and QA departments will only be directly involved for tasks which require specific knowledge and expertise as for example EEE parts procurement. With this approach, the team will not have an independent PA team, however a member of the engineering team will be appointed as the focal point for PA issues, in this role acting as the PA manager and reporting in this function directly to the program manager. Additionally all PA relevant documents (NCRs, ECRs, inspection and test reports, test procedures) will be independently verified and signed by at least two members of the engineering team, one of them the PA manager. The team is prepared to adjust its system to approaches and procedures exercised by the customer. The PA programme will be implemented according to the following guidelines:

- Significant reduction in formal project documentation
- Fixed cost (design to cost assumed) mission
- Analyses to be performed are based on highest anticipated payoff, with limited independent review by the customer
- Ongoing risk assessment by the project manager and system engineering manager
- Maximal use of heritage design, hardware and environmental requirements
- Verification by test, at unit and system levels
- Acceptance of contractor PA practices, processes and procedures, upon customer review and approval
- Limited mandatory independent oversight, inspection and verification
- Delegation of PA implementation to cognisant engineers under the continuous training and supervision of the contractor by customer quality assurance manager.

5.4.2 Reviews

Program level and peer level reviews will be conducted in accordance with the project management plan. The system assurance manager will support the project manager at all reviews and will present material on system assurance activities, as required. Additional, informal technical and peer reviews may also be convened at the customer's discretion to ensure critical issues are identified, understood, dispositioned and worked. At a minimum, peer reviews will be conducted prior to hardware delivery, to verify that the design meets the documented requirements and to address safety and reliability issues and analyses.

5.4.3 Parts and Materials Selection

To the extent that it is practical, the number of different part types and materials will be minimised. Where possible, preference will be given to using existing (heritage) parts as long as those parts satisfy the requirements.

Standard Parts and materials. . . Parts used in the design of the satellite design will be selected from a valid Qualified Parts List (QPL) or Preferred Parts List (PPL) of a recognised, mutually agreed upon (e.g. ESA, NASA, MIL, CNES) authority. Parts from these lists will be considered "standard parts".

Non-standard parts and materials. . . Parts that are not selected from a valid QPL or PPL are defined as non-standard parts. Non-standard parts will be assessed for their ability to meet the project requirements in terms of performance, construction, reliability and quality. Use of non-standard parts will be identified to the customer, prior to integration. This assessment requires additional testing. Parts and materials will be selected based on derating requirements and Radiation tolerance incl. Total Dose, Single Event Effects (SEE), Single Event Upsets (SEU) Single Event Latch-Up (SEL), Single Event Burn Out & Single Event Gate Rupture (SEB/SEGR) and Displacement Damage.

A complete list of all parts and materials within each subsystem is maintained by each subsystem.

5.5 Procurement Approach

The following preference check list shall be used as a guideline for the external procurement of flight equipment, ground equipment and services/testing.

- Obtain competitive bids from qualified suppliers whenever time allows.
- Fixed price and delivery schedule should be the norm. Sometimes a best-effort agreement for the universities is good enough as long as it does not affect any of the critical core requirements.
- Minimise/eliminate special hardware performance and test requirements and buy off-the-shelf equipment whenever feasible.
- Minimise/eliminate special documentation requirements.
- Strict adherence to magnetic cleanliness specification.
- Limited units (for protoflight and simulator) with option to buy one more (flight spare) if needed.
- Bulk procurement of selected items shall be done, if cost effective.

5.6 Documentation

As a ground rule, documentation shall be kept to a minimum. The documents shall contain all the formal high level specifications for the *swarm* project. The overlap between documents shall be minimised to the extent feasible, keeping in mind that some level of duplication is necessary for clarity.

High-level specifications initially developed during Phase A should be contained in a Project Document Book, and distributed to everybody working on the project. ICD's, one for each subsystem, shall also be developed at a very early stage in the project. All these key documents must be under strong configuration control. Other important documents are the overall plans for integration of the satellite and integration of the ground segment.

Detailed design documents and drawings shall be generated and managed by the organisation responsible for the associated hardware/software. Copies should be placed in a project design file together with other pertinent technical notes, accessible to all personnel on the project. The *swarm* Project Documents should be generated and maintained by the prime contractor, with support from appropriate members of the *swarm* design teams, as indicated on a sign-off sheet in front of each document. Changes/updates to these documents shall require review by all the signatories.

6. CV of Lead Proposer

Eigil Friis-Christensen **(**efc@dsri.dk, **Lead Proposer)**, since November 1997 Director of the Danish Space Research Institute. Head of the Solar-Terrestrial Physics Division at the Danish Meteorological Institute (DMI) 1991-1997. Principal Investigator of the Greenland Magnetometer Array 1976-1997. In 1992 he was appointed project scientist of the first Danish satellite, Ørsted, launched in February 1999. He was leading the Danish research and instrument teams and established an international science team consisting of more than 60 research groups from 16 countries. In addition he is adjunct professor in geophysics at the University of Copenhagen. His scientific career includes original work regarding fundamental solar wind-magnetosphere coupling processes. Eigil Friis-Christensen is author or co-author of more than 110 papers in international journals and monographs. He has presented more than 30 invited papers at international conferences in addition to a large number of contributed papers. He has been invited as a visiting scientist at several major research institutions and universities in USA and Russia. In 1995 he was elected member of the executive committee of the International Association of Geomagnetism and Aeronomy, IAGA. Appointed member of the International Steering Committee of the Solar-Terrestrial Energy Programme, STEP and S-RAMP, established by the International Council of Scientific Unions (ICSU) and Scientific Committee on Solar-Terrestrial Physics (SCOSTEP). Eigil Friis-Christensen received the "Director Ib Henriksens" research prize in 1995, and was elected Associate of the Royal Astronomical Society, London, in 1996. He was a member of the ESA solar system working group from 1995 to 1997, of ESAs Earth explorer surface and geophysics peer group, 1996, of ESAs explorer magnetometry mission working group, 1996, and he joined ESAs Science Programme Committee, SPC, in 1998.

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Per-Arne Lindqvist (lindqvist@plasma.kth.se). Ph.D. Plasma Physics, Royal Institute of Technology, Stockholm, 1997. Currently at the Alfvén Laboratory, Royal Institute of Technology, working with space plasma physics. Principal Investigator of the double probe electric field experiment on the proposed NASA/MIDEX mission Auroral Lites. Co-Investigator of the double probe electric field experiments onboard the ISEE-1, Viking, Freja, Cluster and Astrid-2 satellite missions. Co-Investigator of the Langmuir probe experiments on Rosetta and the proposed Langmuir probe experiment on Mars Express. Co-Investigator of a number of sounding rocket electric field instruments. Author or co-author of 65 scientific publications.

Lars G. Blomberg (blomberg@plasma.kth.se). Ph.D. Plasma Physics, Royal Institute of Technology, Stockholm, 1992. Currently Assistant Professor of Space Plasma Physics at the Alfvén Laboratory of the Royal Institute of Technology. Principal Investigator on the proposed Langmuir probe experiment on Mars Express. Co-Project Scientist of the Astrid-2 micro satellite mission. Co-Investigator of the double probe electric field experiments onboard the Viking, Freja and Cluster satellite missions and on the proposed NASA/MIDEX mission Auroral Lites. Co-Investigator of the Langmuir probe experiments on Rosetta. Author or co-author of 65 scientific publications.

UNITED KINGDOM:

British Antarctic Survey
Madingley Road
Cambridge CB3 0ET

Alan Rodger (A.Rodger@bas.ac.uk). DSc, Head of the Upper Atmospheric Sciences Division, British Antarctic Survey, Principal Investigator on the International Solar Terrestrial Physics mission, and co-investigator on Cluster, Oersted, Earth Observation System Missions. UK Correspondent to IAGA, Chairman of the IAGA Working Group on Antarctic Research, International member, Geospace Environment Modelling steering committee. Author or co-author of over 80 refereed publications corning the solar wind, magnetosphere ionosphere and thermosphere.

British Geological Survey
Murchison House
West Mains Road
Edinburgh EH9 3LA
Scotland

David J Kerridge (d.kerridge@bgs.ac.uk). He was head of the British Geological Survey's geomagnetism group from 1992, and was appointed manager of the Earthquake and Forensic Seismology and Geomagnetism Programme in April 1997. He holds a MA (University of Cambridge) and ph.d. (University of Newcastle upon Tyne). He has held administrative positions in the International Association of Geomagnetism and Aeronomy since 1991, and was elected President of the association in 1999. He is a member of the INTERMANGET executive council. He led the modernisation of UK magnetic observatory operations and was responsible for establishing a new UK magnetic repeat station network. He has worked on the production of UK, regional and global magnetic field models, including those used for the World Magnetic Charts published by the UK Admiralty and the International Geomagnetic Reference Field (IGRF), and is experienced in the use of both ground-based and satellite data for modelling. He has conducted applied research resulting in advances in the use of geomagnetic field models and observatory data products by the oil industry, and has carried out research in solar and geomagnetic activity forecasting, commissioned by the European Space Agency. He is the author or co-author of more than 70 scientific papers and technical reports.

Susan Macmillan (smac@bgs.ac.uk). Ph.d. from Robert Gordon's Institute of Technology, 1989. She has 12 years experience in geomagnetic field modelling, using satellite and ground-based data and in applications of the geomagnetic field in industry. She has worked with MagSat, POGS and Ørsted data and is a co-investigator for CHAMP. Co-chairs the IAGA Division V-8 on analysis of global and regional geomagnetic field and secular variation, and has made contributions to the last 3 revisions of the IGRF. Author or co-author of more than 40 scientific publications and reports.

Alan W. P. Thomson (a.thomson@bgs.ac.uk). Ph.d. from the University of Edinburgh, 1985. 10 years experience in geomagnetic field modelling and technological impacts and applications of space weather. He has worked with MagSat, POGS, Ørsted and CHAMP data. He is a member of the Ørsted International Science Team and co-investigator for the CHAMP mission. He co-chairs the IAGA Division V-3 on geomagnetic variations. His research interests include global magnetic field modelling, magnetospheric fields and understanding of internal and external field sources. Hi is the author or co-author of more than 30 scientific publications and reports.

Vincent Lesur (v.lesur@bgs.ac.uk). Ph.d. from the University of Montpellier, France, 1995. He is presently working with the BGS. His research interests covers the crustal magnetism, main-field modelling and geophysical inverse theory.

University of Bath
Department of Electronic and Electrical Engineering
Bath, BA2 7AY

Cathryn Mitchell (c.n.Mitchell@bath.ac.uk). Ph.d. and university lecturer. Her research interests include: Mathematical inversion of geophysical data using tomographic and other methods. Using GPS-satellites to image the troposphere, ionosphere and plasmasphere in four-dimensions. Currently, she is developing new inversion techniques to include the use of CHAMP radio-occultation data. She has received 5 prizes for her research work on tomographic imaging.

University of Leeds
Dept of Earth Sciences
Leeds, LS2 9JT

Andrew Jackson (jackson@earth.leeds.ac.uk). Ph.d. from the University of Cambridge, 1989. Reader in mathematical geophysics, Dept. of Earth Sciences, University of Leeds. Member of the Ørsted and CHAMP international science teams. His geomagnetic interests focus on historical secular variations (from c.1500), crustal magnetism, retrieval of core fluid flow and its implications on the rotation of Earth. Other research interests is fluid mechanics and geophysical inverse theory.

University of Liverpool
Department of Earth Sciences
Jane Herdman Laboratories
4 Brownlow Street
Liverpool L69 3GP

Richard Holme (holme@liv.ac.uk). Ph.d. from Harvard University, 1995. Lecturer. Member of the Ørsted and CHAMP science teams. Previously senior scientist at GeoForschungsZentrum Potsdam. Responsible for the main field modelling and vector data calibration for the CHAMP mission. His main interests are modelling of the main geomagnetic field, particularly methodology development (inverse theory, modelling of sparse data, modelling of covariant data errors, especially attitude errors in satellite data), and use the of main field models to constrain core-mantle boundary physics.

USA:

Harvard University
20, Oxford Street
Cambridge, MA 02138

Jeremy Bloxham (jeremy_bloxham@harvard.edu). Professor of geophysics and chair of the Department of Earth & Planetary Sciences, Harvard University. His research interests span observational and numerical investigations of the geodynamo, including dynamically self-consistent 3D dynamo modelling and inversion of magnetic field observations for the magnetic field and fluid flow at the core-mantle boundary. He produced the ufm series of field models, which are widely used in studies of the core field. He received the Macelwane medal of the American Geophysical Union and the Chapman medal of the Royal Astronomical Society.

NASA, Goddard Space Flight Center
Electrodynamics Branch, Code 696
Building 2, Room 209
Greenbelt, Maryland 20771

James A. Slavin (jslavin@pop600.gsfc.nasa.gov). Head of the Electrodynamics Branch at the NASA/GSFC Laboratory for Extraterrestrial Physics. He has served or continues to serve as a member of the Pioneer Venus, ISEE-3, CRAF, Dynamics Explorer, EOS, WIND, IMP 8, Phobos, Mars96, Mars Global Surveyor, Cluster, and MESSENGER magnetometer teams. He was also study scientist for the Mars Aeronomy Observer (1985-1986) and Mercury Orbiter (1989-1991) missions, ISTP deputy project scientist for POLAR (1988-1991), and co-chair of the Sun-Earth connection 2000 science and technology roadmap team. He is currently the project scientist for the Space Technology 5 Mission, deputy senior project scientist for Living with a Star, and Solar Terrestrial Probes. Finally, he is senior project scientist for Geospace. He is the author or co-author of more than 220 scientific articles.

NASA, Goddard Space Flight Center
Geodynamics Branch
Greenbelt, Maryland 20771

Michael Purucker (purucker@geomag.gsfc.nasa.gov). Ph.d. from Princeton University in 1984. Chief scientist, Geodynamics, Geophysics and Space Geodesy Program, Raytheon ITSS at Geodynamics Branch at NASA, Goddard Space Flight Center. His research interests have emphasised the role of magnetic fields as fingerprints of processes in the terrestrial and Martian lithosphere and ionosphere. He was co-investigator for the CHAMP, Ørsted and SAC-C missions. He is the author or co-author of more than 27 refereed publications.

National Center for Atmospheric Research
High Altitude Observatory
P.O. Box 3000
Boulder, CO 80307-3000

Arthur D. Richmond (richmond@hao.ucar.edu). Ph.d. in meteorology from the University of California, Los Angeles, 1970. Senior scientist at the National Center for Atmospheric Research. Research specialties: Ionospheric electric fields and currents, thermospheric dynamics and geomagnetism.

University of California
Institute of Geophysics and Planetary Physics
San Diego, La Jolla, CA 92092-0224

Steven Constable (sconstable@ucsd.edu). Ph.d. from the Australian National University in 1983. Professor of geophysics and a member of the Ørsted science team. Fields of study include electromagnetic induction in Earth, laboratory measurements of electrical conduction in mantle minerals, inverse methods in geophysics and instrument development. He has published more than 40 papers on electromagnetic topics in refereed journals.

Annex B: Technical Team

Astrium GmbH
Dept. ED21
D-88039 Friedrichshafen
(www.astrium-space.com)

Astrium, Europe's no. 1 space company and an industry world leader, is a joint venture owned by Europe's leading aerospace and defence companies, EADS with a 75% holding and BAE Systems with 25%.

Astrium's activities cover the whole spectrum of the space business, with expertise in all applications: Earth observation and science, telecommunications, ground systems, and military programmes, launch vehicles and orbital infrastructure.

Astrium continues to build on its national and regional identities, experience and expertise to create worldwide excellence. Underpinned by strong corporate vision and values, business divisions operate across national boundaries, facilitating the exchange of information and best practice, whilst respecting both local and national interests.

Astrium is European leader and no. 2 in the world in Earth observation systems. The Company designs and manufactures a wide range of highly versatile platforms, optical and radar instruments and ground segment equipment for the complete scope of remote-sensing applications, operations and services. It has participated in over fifty national, European and international programmes.

CEA-Direction de la Recherche Technologique LETI
17 rue des Martyrs
F- 38054 Grenoble Cedex 9
(www-leti.cea.fr)

CEA-LETI is a laboratory belonging to the French Nuclear Energy Commission (CEA). It is one of the largest applied research laboratories in Europe. Its main task is to satisfy the market needs thanks to the anticipation of the necessary research in order to help industry increase its competitiveness through technological innovation. It commits 80% of its activity to end-product research with partners outside the CEA and has an active patent policy (portfolio of about 800 patents). The activities of CEA-LETI are mainly focused on micro- and optoelectronics, sensors and microsystems development and instrumentation. Developments in high resolution magnetometry have been carried out for more than 40 years, mainly for defence or spatial applications.

Danish Space Research Institute (DSRI)
Juliane Maries Vej 30
DK-2100 Copenhagen Ø
(www.dsri.dk)

DSRI is a governmental Research Institute belonging to the Ministry of Science, Technology and Innovation. It was established as an independent institution in 1968 with the objective of conducting space research programmes based upon instruments developed and manufactured in-house and sent aloft with satellites, rockets and balloons. Originally DSRI conducted research concerned with plasma physics and cosmic ray physics. Today, the scientific areas of interest within astrophysics are mainly devoted to X- and Gamma-ray astronomy, based on the development of telescopes and detectors. In solar system physics main emphasis is on research topics that rely on precise magnetic field measurements, planetary as well as interplanetary. During its lifetime, the focus of interest at DSRI has changed between these fields, corresponding to mission opportunities in ESA programmes or programmes in co-operation with other agencies and partners.

DSRI has taken active part in approximately 10 satellite missions in the past and is currently heavily engaged in the final phase of producing flight hardware for the JEM-X experiment on ESA's Integral mission. In solar system physics the institute is responsible for the vector magnetometer on the Danish Ørsted and Argentine/US SAC-C satellite.

DSRI is managing the Danish Small Satellite Programme, which has been established as a follow-up of the Ørsted initiative. The geomagnetic field experiment on SAC-C is the first experiment in this programme. The next mission, which has been selected, is a stellar-seismology mission called Rømer, that is currently in the detailed design phase prior to a final approval expected at the end of 2002.

Danish Technical University
Ørsted•DTU
Measurement Science and Instrumentation Systems
Elektrovej, Building 327
DK-2800 Kgs. Lyngby
(www.iris.iau.dtu.dk)

Measurement Science and Instrumentation Systems (M&I) is a section under Ørsted•DTU at the Technical University of Denmark (DTU) in the sector concerning Communications, Computer Science, and Mathematics. The M&I works in a number of research areas relating to space instrumentation and radiation technology. The teaching and research areas are in general instrumentation technology and space instrumentation in particular. The instrumentation activities include general measurement and sensor technology, magnetic materials, magnetic field measurement equipment and optical navigation systems, especially for satellite applications, radiation based instrumentation and microcomputer technology for instrumentation and control. The space instrumentation group has delivered top-class scientific instruments to a large number of international sounding rocket and satellite experiments, including the Astrid-2, Ørsted, Ørsted-2/SAC-C, CHAMP, SMART-1 and Contour missions.

GeoForschungsZentrum Potsdam
Telegrafenberg
D-14473 Potsdam
(www.gfz-potsdam.de)

The GeoForschungsZentrum Potsdam (GFZ) is a non-university geoscientific research institute which was founded on January 1st, 1992 on the Telegrafenberg in Potsdam. As the first of its kind worldwide, the GFZ combines all solid earth science fields including geodesy, geology, geophysics, mineralogy and geochemistry, in a multidisciplinary research centre. In the field of interdisciplinary research, 22 sections are organised in five divisions according to the scientific main topics of the GFZ. Research is accomplished by the use of a broad spectrum of methods and techniques, such as satellite geodesy, magnetometry and remote sensing, geophysical deep sounding, scientific drilling, experiments under in-situ conditions and modelling of geo-processes. The GFZ maintains various instrument pools for field research and global measurement campaigns, a team of engineers for the development of geoscientific instruments and a group of specialists for the Task Force Earthquake. An underlying principle is to combine the geoscientific know-how of universities and other research centres in national and international joint projects.

German Space Operations Center (GSOC)
Att: Dr. Hubertus Wanke
DLR-GSOC
Münchener Strasse 20
D-82234 Wessling
(www.op.dlr.de/wt-rm/wtrbhome.htm)

In 1968 the German Space Operations Center (GSOC) of DLR, located at Oberpfaffenhofen near Munich, was founded to support the first German research satellite AZUR launched in 1969. Since that time GSOC has been responsible for the preparation and execution of approximately 20 national and international, co-operative space flight projects.

Besides the space flight operations facilities and its own remote site for satellite ground stations at Weilheim/Lichtenau, 30 km south of Oberpfaffenhofen, GSOC comprises a technology oriented section for simulations of in-orbit servicing and operations (In-orbit Operations Technology facility).

During preparation and execution of national and international space flight projects, the German Space Operations Center - GSOC - controls and monitors scientific satellites, communication satellites and manned space-flights.

GSOC has the necessary expertise and capacity available in-house to perform mission operations as well as to develop software systems (e.g. software for mission support, post mission data handling, and ground operations). In specific fields (primarily software, Satellite and Ground Station Operations) the DLR staff is supported by in-house contractors.

Eurockot Launch Services GmbH
Airport Center Bremen
Flughafenallee 26
28199 Bremen
P.O.Box 286146
D-28361 Bremen
(www.eurockot.com)

The ROCKOT launch vehicle is marketed and operated under the aegis of the German-Russian joint venture company EUROCKOT Launch Services GmbH jointly formed by the Russian Khrunichev State Research and Production Space Center (KSRC) and Germany's Daimler-Benz Aerospace (DASA). The company was founded in March 1995 with the aim of exclusively marketing this vehicle.

EUROCKOT is the interface to the customer. It is responsible for all commercial activities, launch contract condition and launch implementation as a single prime contractor towards the customer and its sole industrial partner for all legal aspects. EUROCKOT is a company established under German law and offers all legal safeguards provided by a western company.

Annex C: Letters of Endorsement

Agencies:

Centre National d'Etudes Spatiales (CNES)
Deutches Zentrum für Luft- und Raumfahrt (DLR)
International Association of Geomagnetism and Aeronomy (IAGA)
International Union of Geodesy and Geophysics (IUGG)
National Aeronautics and Space Administration (NASA)
National Oceanic and Atmospheric Adm. (NOAA), CEOS Global Datasets Task Team
National Oceanic and Atmospheric Adm. (NOAA), National Geophysical Data Center
National Oceanic and Atmospheric Adm. (NOAA), Research and Development Division
National Oceanic and Atmospheric Adm. (NOAA), World Data Center A

Institutions:

British Antarctic Survey
British Geological Survey
Danmarks Tekniske Universitet, Ørsted·DTU
GeoForschungsZentrum Potsdam
Institut de Physique du Globe de Paris
Istituto Nazionale di Geofisica e Vulcanologia
Kungliga Tekniska Högskolan
NASA, Goddard Space Flight Center, Geodynamics Branch
NASA, Goddard Space Flight Center, Laboratory for Extraterrestrial Physics
National Observatory of Athens
Universitat Ramon Llull, Observatori d l'Ebre
University of Bath
University of Brest, Institut Universitaire Européen de la Mer
Harvard University
University of Leeds
University of Liverpool
Universitat Politècnica de Catalunya

Prof. José Achache
Directeur de l'Observation de la Terre
ESA
8 – 10 rue Mario Nikis
75738 Paris Cedex 15

Paris, 28 DEC. 2001

DPI/EOT/PUG – 01- 224

Objet : Appel à propositions pour les missions d'opportunité du Programme "Earth Explorer " de l'ESA

Monsieur le Directeur,

Cette lettre a pour objet de confirmer l'intention du CNES de soutenir la proposition SWARM (COM2-29), soumise à l'ESA en réponse à l'appel à propositions pour des Missions d'Opportunité du programme "Earth Explorer".

La proposition SWARM, destinée à la mesure du champ magnétique terrestre, a été évaluée favorablement en octobre 2001 par les instances *''ad hoc''* du CNES, qui ont considéré qu'elle répond à des besoins bien identifiés de la communauté scientifique.

Dans le cas où cette mission serait sélectionnée par l'ESA, le CNES étudiera la possibilité de contribuer à sa réalisation, en particulier au travers de la fourniture de certains éléments de la charge utile.

Confirmant l'intérêt du CNES pour cette proposition, et dans l'attente des résultats du processus de sélection de l'ESA, je vous prie d'agréer, Monsieur le Directeur, l'expression de mes sentiments les meilleurs.

Stéphane JANICHEWSKI

Directeur des Programmes
et des Affaires Industrielles

CENTRE NATIONAL D'ETUDES SPATIALES
SIEGE SOCIAL : 2, PLACE MAURICE QUENTIN - 75039 PARIS CEDEX 01 - TÉL. 01 44 76 75 00 - TÉLÉCOPIE : 01 44 76 76 76 - TÉLEX 214 674 F
RCS PARIS B 775 665 912 - SIRET 775 665 912 00082 - CODE APE 731Z

2 1 DEC. 2001

Deutsches Zentrum
für Luft- und Raumfahrt e.V.

DLR

Institut für Kommunikation und Navigation

Navigations- und Leitsysteme

DLR Institut für Kommunikation und Navigation
Oberpfaffenhofen, D-82234 Weßling

Dr. Eigil Frijs- Christensen
Director, Danish Space Research Institute
Juliane Maries Vej 30

DK-2100 Copenhagen, Denmark

Ihr Schreiben	
Ihr Zeichen	
Unser Zeichen	
Ihr Gesprächspartner	Dr. F. Kühne
Telefon (0 39 81) 480-	+49- 8153 -28-2811
Telefax (0 39 81) 480-	+49- 8153 -28-1442
E-Mail	Friedrich.Kuehne@dlr.de
Oberpfaffenhofen,	December 17, 2001

Subject: SWARM, Letter of Endorsement

Dear Dr. Frijs-Christensen,

the "swarm" proposal for a small multi-satellite mission to observe the dynamics of the Earth's magnetic field offers the spin-off capability for an effective monitoring of the ionosphere by using the complete set of GPS measurements onboard the swarm- satellites.
The Institute of Communication and Navigation (IKN) of the German Aerospace Center (DLR) is interested in these measurements and offers to contribute to the planning and execution of the SWARM mission if corresponding work packages are supported by ESA.
DLR/IKN could contribute
in the pre-launch phase:
- to define mission requirements
- to develop retrieval techniques and algorithms for deriving key parameters of the ionosphere and to generate corresponding value-added products,
- to reconstruct the 4D-electron density structure of the global ionosphere,
- to establish an operational data processing system for data product generation

in the operational phase:
- to establish automatic data processing and archiving systems
- to control and certify data quality
- to provide operational data products for the European Space Weather Program

Generally it should be mentioned that DLR/IKN contributions to selected work packages can be realized cost-effective because DLR takes benefit from its current participation in the German CHAMP satellite project and the available infrastructure.

I wish you success in your efforts to realize the swarm mission concept.

Sincerely,

Dr. F. Kühne

DLR Institut für Kommunikation und Navigation
Oberpfaffenhofen, D-82234 Weßling
Telefon (0 8153) 28-0

31/12 '01 12:28 FAX 055 21226 GET IT TYPED 001

- 2 JAN. 2002

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

IAGA

International Association of Geomagnetism and Aeronomy

British Geological Survey • Murchison House • West Mains Road • Edinburgh EH9 3LA • Scotland • UK

Tel: +44 (0) 131 650 0220 *Fax: +44 (0) 131 667 1877* *E-mail: djk@bgs.ac.uk*

Prof Eigil Friis-Christensen
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
Denmark

28th December 2001

Dear Prof Friis-Christensen

SWARM: a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System

Thank you for sending me details of the SWARM proposal.

With four satellites in the proposed configuration, the SWARM mission offers, through simultaneous multi-point measurements, new opportunities to collect data enabling separation of the various sources of the geomagnetic field. This will enable better description of the source fields in the Earth's core, the crust, and the ionosphere and magnetosphere, and so help to advance understanding of Earth processes including the secular variation of the main (core) field, the electrical conductivity structure of the Earth's interior, and the dynamics of external current systems.

I note that, with the proposed timing of the mission, SWARM will follow on from the geomagnetic satellite surveys carried out by the Ørsted and CHAMP missions. Together, the three missions will provide high-quality data with global coverage spanning a decade, a time scale commensurate with important changes in the core field. The data will thus be invaluable for studies of the internally generated geomagnetic field.

There will be strong international interest in data from SWARM. Many of the scientists who stand to benefit from SWARM are active members of the International Association of Geomagnetism and Aeronomy (IAGA), and so I am happy to express support for your proposal on behalf of IAGA. This view has been expressed formally by an IAGA Resolution recognising the value to research of data from geopotential field survey satellites. I also note that the International Geomagnetic Reference Field (IGRF), which is used widely in science and industry applications, is produced under the auspices of IAGA. SWARM data will help to ensure the quality of future versions of the IGRF.

Yours sincerely

David Kerridge

Dr D J Kerridge
President, IAGA

02-01-07;11:59AM;岡山大学固体地球研究センター DSRI ;0858432184 # 1/ 1

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

Masaru Kono
Institute for Study of the Earth's Interior
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7 January 2002
MK/00/068/GG

Dr. Eigil Friis-Christensen, Director
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
Denmark
FAX: +45-3536-2475

Re: SWARM satellite mission

Dear Eigil,

In 1998, I wrote a letter of support for the SWARM mission as the President of IAGA. In my present capacity of the President of the IUGG, let me repeat the support for this important satellite mission.

The mission you are about to propose to ESA seems to be quite interesting for the geophysics community for a number of reasons. The satellites will provide

1. Closely coordinated observations at 450 and 550 km altitudes,
2. Mesure the magentic field of internal and external sources,
3. Probe the electrical conductivity of the solid Earth,
4. Determine the lithospheric field with improved precision.

The satellite observations will thus provide very important informations related to the geomagnetic field as well as the space environment near the Earth.

The IUGG already made a resolution regarding the international decade of geopotential research, and this satellite mission appears to be one of the key projects to fulfil this goal. I would like to take this opportunity to express strong support from the IUGG community, and hope that ESA would take up this proposal.

Sincerely yours,

Masaru Kono
President, IUGG

Cc: JoAnn Joselyn, Secretary-General, IUGG

2002 01/07 MON 08:45 FAX 001/001

UNION GEODESIQUE ET GEOPHYSIQUE INTERNATIONALE
INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

Boulder, CO January 5, 2002

Dr. Eigil Friis-Christensen
Director, Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
DENMARK

Dear Dr. Friis-Christensen,

The objectives of the International Decade of Geopotential Research have been repeatedly supported by the International Union of Geodesy and Geophysics, and most especially by the International Association of Geodesy and the International Association of Geomagnetism and Aeronomy. Resolutions seeking to encourage missions that measure the global gravity and magnetic fields were passed at both the 1995 and 1999 IUGG General Assemblies.

In particular, the proposal entitled "SWARM: a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System" will determine the position and development of the radiation belts and their near-Earth effects, and investigate the time-space structure of the magnetospheric and ionospheric sources on all time scales. This work will bear on an important scientific issue - the accelerated decay of the axial dipole component of the Earth's magnetic field apparently due to changes in the field beneath the South Atlantic Ocean.

The design of this experiment (a constellation of 3 near-Earth orbiting satellites in two polar, orbiting planes) will allow the contributions of the multitude of currents that encircle Earth to be separated and evaluated. The established expertise of the collaborating investigators will insure that the scientific results are maximized and disseminated to the world scientific community as quickly as possible.

It is my pleasure to endorse SWARM as the geomagnetic component of ESA's initiative for the International Decade of Geopotential Research.

Sincerely,

JoAnn Joselyn, Ph.D.

President
MASARU KONO
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awh@gfy.ku.dk

JAN 07 '02 12:11 FR 202 358 2770 TO 90114535362475 P.01/01

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

January 4, 2002

Reply to Attn of:

Dr. Eigil Friis-Christensen
Director, Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen Denmark

Dear Dr. Friis-Christensen,

NASA's Solid Earth and Natural Hazards Program strongly endorses your proposal for SWARM, a constellation to study the dynamics of the Earth's magnetic field and its interactions with the Earth system.

NASA's Solid Earth Science Working Group (SESWG; http://solidearth.jpl.nasa.gov), a panel of distinguished scientists charged with the formulation of a long term strategy in the solid Earth sciences, strongly endorsed advanced measurement of the spatial and temporal variability of the geomagnetic field. The SESWG recommended a constellation of geomagnetic satellites such as SWARM as the best method to make such long term high quality measurements of the geomagnetic field. Constellations of geomagnetic satellites such as SWARM will provide the key space-time sampling needed to separate the various sources of the geomagnetic field, will provide an important next step in understanding the physics of Sun - Earth interactions, and will probe the structure and dynamics of the solid Earth from earthquakes and Earth rotation to the geodynamo. NASA therefore endorses many of the goals outlined in the SWARM proposal.

The NASA Solid Earth and Natural Hazards program will support scientific collaboration of US scientists with the SWARM mission, using competitive proposals as we have done for the Ørsted, SAC-C, and CHAMP missions. I propose that we also explore the feasibility of other forms of collaboration in the planning and development of the SWARM mission, including the combined GPS/star camera being developed for GRACE, launch opportunities, and other related instrumentation. This collaboration will of course require full NASA review and approval.

As the original proponent for the International Decade of Geopotential Field Research, I am heartened by the broad international participation in SWARM. SWARM will provide the much needed observations to support the geomagnetic field measurement requirements for the latter half of the International Decade of Geopotential Field Research. The selection of the SWARM proposal will also provide an important framework for the continued fruitful cooperation between NASA and the European science community in solid Earth science.

With the very best wishes for a successful SWARM mission,

John LaBrecque, Manager
Solid Earth and Natural Hazards Program

** TOTAL PAGE.01 **

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE

NATIONAL GEOPHYSICAL DATA CENTER
325 Broadway
Boulder, Colorado 80303-3328

7 January 2002

Dr. Eigil Friis-Christensen
Director, Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen Denmark

Dear Dr. Friis-Christensen,

Thank you for the opportunity to comment on your proposed *swarm* mission, a constellation of satellites to study the dynamics of the Earth's magnetic field and its interactions with the Earth system. As a former MAGSAT principal investigator two decades ago, I am heartened by *swarm*'s objectives and observation methods. Your design offers great potential for improving our understanding of the Earth system in a manner beyond what previous technology and approaches could support.

As current Chair of the Committee on Earth Observation Satellites (CEOS) Global Datasets Task Team, and Co-Chair of International Society for Photogrammetry and Remote Sensing Working Group IV-8 (Global Environmental Databases), I welcome the opportunity for research and increased understanding of the Earth System that should be offered by *swarm*.

Sincerely,

David A. Hastings
Chair, CEOS Global Datasets Task Team
Co-Chair, ISPRS Working Group IV-8 (Global Environmental Databases)

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UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE

NATIONAL GEOPHYSICAL DATA CENTER
325 Broadway
Boulder, Colorado 80303-3328

January 7, 2002

Dr. Eigil Friis-Christensen
Director, Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen Denmark

Dear Dr. Friis-Christensen:

I am writing to endorse the proposal concerning SWARM a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System. The National Geophysical Data Center provides data to support studies of the Earth's physical environment from Earth's core to the surface of the Sun. *swarm* offers a unique opportunity to add significantly to the body of data necessary for these studies. This mission will directly impact understanding of the variations in length of day, global analysis of geomagnetic jerks, electric conductivity in the mantle, transient magnetic fields, lithospheric fields, and ocean currents. This is an important opportunity to collect data from one experiment, which will improve understanding in a broad range of geophysics. This directly impacts our mission to improve understanding of the Earth environment, as well as the safety of the observing platforms necessary to our mission.

swarm's unique configuration of multiple paired satellites will enable identification and separation of the core, lithospheric, and ionospheric contributions to Earth's magnetic field. The potential to understand some basic questions about Earth's environment, including the core-mantle interface, the origin and extent of crustal anomalies, effective separation of the main, crustal, and lithospheric signals, and geomagnetic pulsations and jerks is enormous. We strongly support the objectives of swarm including the determination of the position and development of the radiation belts and their near-Earth effects, and investigating the time-space structure of the magnetospheric and ionospheric sources on all time scales. *swarm* provides great potential to gain insight into two important related problems, namely the unusual decay of the axial dipole component of the Earth's magnetic field over the last 150 years and the growth of the South Atlantic anomaly. The timing of the mission is important, closely following the Orsted and Champ missions and taking place during solar minimum. In short, the potential for advancement in numerous geomagnetic and related studies is enormous.

With the potential to improve understanding of so many aspects of the Earth and near-Earth environment, I strongly endorse the *swarm* mission.

Sincerely,

Susan J McLean

Susan J. McLean
Geomagnetism Group, National Geophysical Data Center

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UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Oceanic and Atmospheric Research Laboratories
Space Environment Center
325 Broadway - David Skaggs Research Center
Boulder, Colorado 80303

December 26, 2001

Dr. Eigil Friis-Christensen
Director, Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
DENMARK

Dear Dr. Friis-Christensen,

The NOAA Space Environment Center is pleased to endorse your proposal for a small multi-satellite mission to investigate the dynamics of Earth's magnetic field (SWARM). Your concept, aimed at an accurate measurement of Earth's magnetic field, addresses many of the problems of decoupling the sources of electric currents that are inferred from measurements on the ground and single-points in space. The SWARM's data will fill a void in our understanding of one of Earth's basic physical properties.

SWARM is of interest to the Space Environment Center (SEC) because we provide real-time monitoring and forecasting of solar and geophysical events, conduct research in solar-terrestrial physics, and develop techniques for forecasting solar and geophysical disturbances. The improved understanding expected from SWARM offers SEC the opportunity to improve its services. SEC's parent organization is the U.S. National Oceanic and Atmospheric Administration (NOAA). SEC's Space Weather Operations is jointly operated by NOAA and the U.S. Air Force and is the national and world warning center for disturbances that can affect people and equipment working in the space environment.

Best wishes for the success of your proposal.

Sincerely,

Howard J. Singer

Dr. Howard J. Singer, Chief
Research and Development Division
NOAA Space Environment Center

cc: Dr. E. Hildner, Director
Space Environment Center

01/07/2002 16:15 303-497-6513 NOAA*NESDIS*NGDC PAGE 02/02

WORLD DATA CENTER A
for
SOLAR-TERRESTRIAL PHYSICS

National Environmental Satellite, Data, and Information Service
NOAA, E/GC2, 325 Broadway
Boulder, Colorado 80303-3328 U.S.A.

SOLAR AND INTERPLANETARY PHENOMENA;
IONOSPHERIC PHENOMENA;
FLARE-ASSOCIATED EVENTS;
GEOMAGNETIC VARIATIONS;
MAGNETOSPHERIC AND
INTERPLANETARY MAGNETIC PHENOMENA;
AURORA; COSMIC RAYS; AIRGLOW

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IN REPLY REFER TO:

January 7, 2002

Dr. Eigil Friis-Christensen, Director
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
Denmark

Dear Dr. Friis-Christensen,

Thank you for the opportunity to review your proposal "SWARM, a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field" to operate two pair of magnetic satellites. Your effort to separate the magnetic contributions from each of four components, i.e. the main field, lithospheric fields, fields from external currents and fields from induced mantle currents, is to be commended. I would like to focus my scientific comments on the external current, or solar-terrestrial, component.

As you know, the space community is embarked on national and international space weather programs (SWPs). SWPs seek to significantly improve space weather specification, climatologies and forecasts; especially those events that effect man's technology in space and on the ground. This extremely large volume of electrically charged space has very few measurements. Thus SWPs focussed their efforts on the development of robust and accurate physical models. But these models are "data starved". SWARM offers a unique opportunity to the to fill the critical gaps in data coverage. SWARM data are desperately needed by all space scientists participating in space weather programs. In addition, SWARM data will complement the WDC archives of geomagnetic variations from ground-based observatories. I strongly recommend the SWARM program for ESA support.

I also send my strongest endorsement for Professor Friis-Christensen as the Principal Investigator. I have worked with Professor Friis-Christensen for many years and have found him to be very professional and productive. I have also worked with data he has provided and it has always been of the highest quality.

Sincerely,

Herbert W. Kroehl

Herbert W. Kroehl, Director

WORLD DATA CENTERS CONDUCT INTERNATIONAL EXCHANGES OF GEOPHYSICAL OBSERVATIONS IN ACCORDANCE WITH THE PRINCIPLES SET FORTH BY THE INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS THROUGH THE ICSU PANEL ON WDC'S. INITIATED FOR THE INTERNATIONAL GEOPHYSICAL YEAR 1957-58, THE DATA EXCHANGE CONTINUES ACCORDING TO RECOMMENDATIONS OF VARIOUS ICSU SCIENTIFIC ORGANIZATIONS. WDC-A IS ESTABLISHED IN THE UNITED STATES UNDER THE AUSPICES OF THE NATIONAL ACADEMY OF SCIENCES.

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

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18 December 2001

Dr Nils Olsen
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100
Copenhagen
Denmark

Dear Dr Olsen

RE SWARM - a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System

I warmly welcome this novel satellite proposal. It offers a unique series of measurements of the Earth's magnetic field that can be used to address many important science questions across several different scientific disciplines. In particular, your measurements will be highly complementary to our ground-based measurements of the upper atmosphere over Antarctica. We have just deployed a network of low powered magnetometers, almost geomagnetically conjugate to the Danish Greenland stations. Combining the data from the ground and from space should provide critical new insight into symmetries and asymmetries of the three dimensional current systems that drive the ionosphere-magnetosphere system.

This proposal has my strong endorsement and support.

I wish you every success.

Yours sincerely

Alan Rodger

Dr Alan Rodger
Head, Physical Sciences Division

20/12 '01 13:29 FAX 01316671877 GSGG BGS 002

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Your ref:
Our ref:

Prof Eigil Friis-Christensen
Danish Space Research Institute
Juliane Maries Vej 30
DK2100 Copenhagen
Denmark

20th December 2001

Dear Prof Friis-Christensen

SWARM - a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System

The Seismology and Geomagnetism Programme of the British Geological Survey (BGS) fully endorses the SWARM proposal. The mission will provide data on the Earth's magnetic field, which changes on a wide range of time and length scales, for a variety of studies on geomagnetism and the solar-terrestrial environment.

Because of the proposed arrangement of the four satellites, SWARM data will ease the separation of the various sources of the geomagnetic field, and this will lead to a better understanding of the underlying physics. In particular, SWARM will enable the effects of transient external and induced magnetic fields to be minimised to an unprecedented degree. This will be of great benefit for modelling both the core-generated and crustal fields. Such models will help advance scientific knowledge and understanding of processes in the Earth's magnetosphere, ionosphere, crust and deep interior, and, in practical terms, provide essential information for navigation using magnetic referencing.

SWARM will complement the Ørsted, SAC-C and CHAMP missions, which together will provide high-quality global geomagnetic field data spanning more than a decade, the timescale needed to study the dynamics of the core-generated field. For example, on decadal timescales, changes in the length-of-day appear to be linked to changes in the geomagnetic field. SWARM data will help elucidate the underlying processes. BGS scientists have been active members of the Ørsted and CHAMP scientific teams and I look forward to the opportunity to continue our research through participation in the SWARM project.

Yours sincerely

David Kerridge

Dr D J Kerridge
Manager, Seismology and Geomagnetism Programme

Ørsted•DTU
Technical University of Denmark

Dir. Eigil Friis-Christensen
Danish Space Research Institute
Juliane Maries Vej 30
2100 Copenhagen Ø

7 January 2002
jlj/ib

Letter of Endorsement for:

SWARM,
a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System"

Proposal to ESA, January 8, 2002

We express our strong endorsement of the participation of Measurement & Instrumentation Systems (M&I,) Ørsted•DTU in the joint proposal to ESA: "SWARM, a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System" as being well conceived, well projected and exceedingly well timed for filling the lacuna after the very successful Danish Earth's magnetic field mapping missions Ørsted 1 & 2 and the Danish core instruments on the German CHAMP mission, planned to terminate in the 2005 time-frame.

The resumed Earth's field mapping missions with the two Ørsteds and CHAMP, after a 20 years pause since the bench-marking NASA Magsat mission, has fortunately gained increasing momentum from the widespread recognition by the science community of the importance of continued absolute mapping of the chaotically changing Earth's magnetic field. The undisputable science contribution from Magsat would have been manifold augmented, had the importance of continuous Earth's field survey been recognized earlier.

Projected for a probable 2009 launch the multi-satellite mission SWARM is strongly needed to ensure continuity in Earth's magnetic field science. This so much the more, because no other major Earth's field mapping mission is under way for the 2009+ time-slot. The mapping mission **Ampère**, -a proposal to CNES under discussion-, will, if selected, fly in the 2005 time frame.

The Technical University of Denmark, Ørsted•DTU, Measurement & Instrumentation Systems was fortunate to be selected for developing and supplying the core instrumentation (Star Cameras and Vector Magnetometers) for the two Ørsteds and for the CHAMP mission. Ongoing instrument development towards miniaturization and combination of the two instruments is part of the Ørsted•DTU contribution to SWARM, and holds great promise for even better joint system performance.

Yours sincerely

Erik Bruun, Professor
Head of Department

Ørsted·DTU
Measurement & Instrumentation Systems

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08/01/02 10:57 GFZ POTSDAM TELEGRAFENBERG → +45 35362475 NUM042 P02

GeoForschungsZentrum Potsdam
Stiftung des öffentlichen Rechts

Vorstand

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The Earth Science Division (VR)
ESTEC
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P.O. Box 299
NL-2200 AG Noordwijk ZH
Niederlande

Fax: 0031 71 565 5675

Potsdam: 07 Jan. 2002

Letter of Endorsement
Proposal for a EEOM magnetic field mission SWARM

Dear Sirs,

We are pleased to announce our participation in the proposal "SWARM, a constellation to study the dynamics of the Earth's magnetic field and its interaction with the Earth system" which is in response to ESA's Call for Earth Explorer Opportunity Missions.

We look forward to a fruitful co-operation with ESA in this vanguard mission. It will shed light on the various rolls the geomagnetic field plays for the system Earth and its impact on our environment.

Based on the experience of our CHAMP satellite project GFZ is prepared to take over significant responsibilities during the hardware phase of the project. During the mission we will play an active roll in the scientific data interpretation.

Yours sincerely,

R. Emmermann

Prof. Dr. Rolf Emmermann
Executive Scientific Director

Hermann Lühr

Prof. Dr. Hermann Lühr
Project Lead SWARM (GFZ)

20-12-2001 14:39 DE GEOMAGNETISME A 0004535362475 P.01/01

IPGP
INSTITUT DE PHYSIQUE DU GLOBE DE PARIS

LE DIRECTEUR

Claude Jaupart

Directeur

INSTITUT DE PHYSIQUE DU GLOBE DE PARIS

4, place Jussieu BP 89 75252 PARIS Cedex 05 FRANCE

T: 01 44 27 36 12
F: 01 44 27 33 73
email cj@ccr.jussieu.fr

Paris, December 18, 2001

Dr. Eigil Friis-Christensen
Danish Space Research Institute,
Julianes Maries Vej 30,
DK-2100 Copenhagen, O
Denmark

Re: Proposal for Earth Explorer Opportunity Missions,
"SWARM, a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System"

Dear Dr Friis-Christensen,

The Institut de Physique du Globe de Paris enthusiastically endorses the SWARM mission co-proposed under your leadership by Dr Gauthier Hulot and his team. This proposal is fully consistent with the kind of research we are promoting at IPGP: making continuous series of high quality measurements in order to achieve a better understanding of how the Earth works.

I have been impressed by the success of the Oersted and Champ missions with which IPGP and several of its members have been involved. Furthermore, the active participation of these scientists in the French project Ampere (the last single satellite magnetic mission to fly before the multi-satellite SWARM mission) shows that they are on the ready. As a consequence, I have no doubt whatsoever that the SWARM project will be a success.

If I can be of any help in promoting the SWARM project, do not hesitate to call on me.

Yours sincerely,

Claude Jaupart

Professor of Geophysics
Chairman, IPGP

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TOTAL PAGE(S) 01

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prot.n.° 3202
del 17/12/2001

Istituto Nazionale di Geofisica e Vulcanologia

Rome, December 13th, 2001

Dr. Nils Olsen
Center for Planetary Science,
Danish Space Research Institute
Juliane maies Vej 30
DK -2100 Copenhagen
Denmark

e.p.c.:
The Earth Sciences Division (VR)
ESTEC,
Keplerlaan 1,
P.O. Box 229,2200 AG Noordwijk ZH
The Netherlands

Subject: Letter of endorsement for the Project "SWARM, a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System"

Dear Dr. Nils Olsen,

I am writing in support of the proposed mission "SWARM, a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System"
This project will be able to address many questions of interest to the geophysical scientific community, being some of them of great importance for the understanding of the dynamics of our planet. Separation of the various fields composing the observed magnetic field, including the better individuation of the distinct internal/external sources, space weather now- and fore-casting, climate change correlations, are some of the valuable objectives that this project can potentially reach. The Istituto Nazionale di Geofisica e Vulcanologia, the leader Institute of Geophysics in Italy, considers this project a turning point in particular for the Earth's magnetic field investigation and, more in general, for the geophysical related implications.

Yours Sincerely,

Dr. Bruno Zolesi
(Director of Geomagnetism Aeronomy and Environmental Geophysics Dept.)

December 19, 2001

KUNGL. TEKNISKA HÖGSKOLAN
THE ROYAL INSTITUTE OF TECHNOLOGY

Professor Göran Marklund

Letter of Endorsement

SWARM

a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System.

The Alfvén Laboratory at the Royal Institute of Technology, Stockholm, fully supports the participation of Professor Göran Marklund and his colleagues in the proposed SWARM-mission. The space group at the Alfvén Laboratory welcomes the proposed collaboration with the Danish Space Research Institute and the Danish Technical University on the development of the Compact Spherical Coil vector feedback magnetometer (CSC), one of the proposed instruments for the SWARM-payloads.

Funding for the Alfvén Laboratory participation will be applied for from the Swedish National Space Board and if additional funding support is needed also from other funding authorities.

Based on the success in receiving funding for similar magnetometer experiments on previous missions such as Auroral Turbulence-I and II, Astrid-2, Ørsted and on the long and fruitful collaboration we have maintained with the Danish magnetometer teams we are confident on our possibilities to be able to participate and complete our tasks in the SWARM-mission.

Göran Marklund
Head of the space group

Jim Drake
Director of the Alfvén Laboratory

A copy of this Letter has been sent to the Swedish National Space Board

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Alfvén Laboratory
Royal Inst. of Technology
S-10044 Stockholm Sweden

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JAN 07 2002 12:29 FR NASA SSAI OFC MGMT 301 614 6522 TO 0 P.02

National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: Herbert Frey/Code 921

7 January 2002

Dr. Eigil Friis-Christensen
Director, Danish space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen Denmark

Dear Eigil:

I am writing this letter in support of the proposed SWARM mission, which I consider to be of high importance and promise. The multi-satellite approach you have adopted offers an unprecedented ability to map the main and lithospheric magnetic fields of the Earth in both a temporal and spatial sense. This will permit far better separation of the different components of the magnetic field than has been possible to date, and much improved horizontal definition of the sources. Multi-satellite observations will also allow better characterization of the time-varying external fields. The lowering of one of the satellites during the third year of the mission will provide greatly improved resolution of the crustal anomaly field, which is of particular interest to us here at Goddard.

As you know, we have been studying for some time the advantages provided by gradient measurements of the field and are particularly happy to support missions like this which can accomplish this objective.

We look forward to continuing our close association and collaboration in the study of the Earth's magnetic field, and wish you great success in your proposal for this important and timely mission.

Sincerely,

Herbert Frey
Head, Geodynamics Branch

** TOTAL PAGE.02 **

– 8 JAN. 2002

National Aeronautics and
Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Reply to Attn of: 690 January 3, 2002

Professor Eigil Friis-Christensen, Director
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
DENMARK

Eigil
Dear ~~Professor~~ Friis-~~Christensen~~:

It is my pleasure to endorse the participation of one our scientists, James A. Slavin, as a Co-investigator on the SWARM proposal being submitted to ESA's Earth Explorer Opportunity Missions Program. It is my understanding that Dr. Slavin will provide scientific and technical advice on the design and implementation of this multi-spacecraft geomagnetism and ionospheric physics mission and participate in the post-launch data analysis.

We wish you every success in this important undertaking.

Best regards,

Richard R. Vondrak

Richard R. Vondrak, Chief
Laboratory for Extraterrestrial Physics

20-DEC-2001 11:32 NATIONAL OBSERVATORY ATH 0030 1 34 63 803 P.01

20 DEC. 2001

NATIONAL OBSERVATORY OF ATHENS

Lofos Nymfon, Thission, 118 10 Athens, Greece
tel.: +30 1 3490104, fax: +30 1 3490120
e-mail: lelas@env.meteo.noa.gr

Athens, 20 December 2001
Ref. No. 1961

Dr Eigil Friis-Christensen
Director, Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
Denmark
FAX +45 3536 2475

Subject: Letter of endorsement for the Project "SWARM, a Constellation to study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System".

Dear Dr. Friis-Christensen,

I am writing in support of the Project "SWARM, a Constellation to study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System". The Ionospheric Group of the National Observatory of Athens under the leadership of Dr Anna Belehaki is being actively involved as Co-Investigator in the CHAMP mission with the systematic use of electron density profiles from Athens Digisonde for the needs of scientific interpretation and validation of electron density profiles obtained by CHAMP mission. Our studies gave very promising results showing that the radio occultation technique is capable of deriving accurate vertical profiles of atmospheric refractivity and this is very important since no other profiling technique unifies electron density distribution through the entire ionosphere with global coverage.

The proposed configuration of SWARM mission with four CHAMP-like satellites, carrying a GPS receiver for radio occultation measurements, is very promising since it has the potential to establish global data sets of electron density profiles for developing and improving global ionospheric models, because of the spatial and temporal resolution that the system architecture provides, and furthermore to provide accurate operational space weather information.

1

The National Observatory of Athens considers that the SWARM project is a turning point in particular for the more sophisticated modeling of the Earth's ionosphere and strongly endorses the proposed mission. Our Ionospheric Group researchers would be glad to contribute to the scientific interpretation of the results.

Sincerely,

P. Lal

Prof. Dimitri Lalas
Director & Chairman of the Governing Board

14/12 '01 14:27 ☎34 77 50 46 60 OBSERVATORI EBRE 001

OBSERVATORI DE L'EBRE
Centre associat del CSIC

Universitat Ramon Llull

14 December 2001

Dr. Eigil Friis- Christensen
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhaguen
Denmark

Dear Dr. Friis- Christensen,

Ebre Observatory is pleased to endorse your "SWARM, A Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System" proposal. Our Research Group would indeed like to join your team and be part of the proposing consortium. We would also like to insist in the necessity of this kind of satellite magnetic field measurements to further our knowledge of the changes of the geomagnetic field and to learn from both the Earth's interior and the processes in the external environment. In particular, we will be positively interested in using those measurements for improving models of both the main field, is secular variation, and the litospheric anomaly field; for improving our knowledge of many conditions and processes related with the Solar-Terrestrial Physics; and for studying its possible connections with the "Global Change" and the possibility of mitigaze hazards of magnetic and geospace activity.

Yours sincerely,

J. Miquel Torta Margalef
Director

c/ Horta Alta, 38
43520 - ROQUETES (Tarragona). Spain
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Fax +34.77 504660

UNIVERSITY OF
BATH

Professor P A Watson
Head of Department
Professor R K Aggarwal
Professor P S Cannon
Professor J Chambers
Professor D M Monro
Professor D Rodger

Department of Electronic and Electrical Engineering
Bath BA2 7AY · United Kingdom
Telephone 01225 826327
Facsimile 01225 826305

17 December 2001

Letter of Endorsement

Re: **SWARM** - a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field (ESA "Earth Explorer Opportunity Mission").

The University of Bath strongly supports the SWARM mission.

Recent research in the Radio Systems and Radio Science Research Group has resulted in a technique for inversion of dual-frequency differential-delay measurements to produce four-dimensional maps of electron concentration in the ionosphere. Initial results show great promise for the imaging technique. We are very enthusiastic in our support for the radio-occultation instruments proposed for the SWARM mission as these will provide unprecedented global coverage for ionospheric mapping. We look forward to the opportunities for collaborative research in Europe that this mission will offer.

CMitchell

Dr C N Mitchell,
Lecturer in Electronic and
Electrical Engineering.

Pete W

Prof P A Watson,
Head of Department,
Electronic and Electrical Engineering.

THE QUEEN'S
ANNIVERSARY PRIZES
2000

17 DEC. 2001

INSTITUT UNIVERSITAIRE
EUROPEEN DE LA MER
UNIVERSITE DE BRETAGNE OCCIDENTALE

Brest le 13/12/01

Dr Eigil Friis-Christensen
Director
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
Denmark

Dear Dr Friis-Christensen

Pr Pascal Tarits from our Institute has informed me that you are preparing a proposal called "*SWARM: a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System*" in response to ESA's "Call for Earth Explorer Opportunity missions.

Our Institute is involved in many aspects of Marine Sciences. Satellite missions are essential in our fields. Pr Tarits has been involved for several years in Earth Sciences studies involving satellite data. I think that this opportunity to propose an experiment such as SWARM is very important. Pr Tarits is already proposing a magnetic satellite mission AMPERE to CNES. SWARM is the natural follow-up of this effort that must be co-ordinated at the European level.

I strongly support this important initiative for the Institut Universitaire Européen de la Mer. and I wish you a great success for your proposal.

Yours sincerely

Pr Paul Treguer

INSTITUT UNIVERSITAIRE EUROPEEN DE LA MER IUEM U.B.O. BREST

Director

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JAN-02-2002 14:00 EPS-BLOXHAM/SHAW 617 495 7660 P.01/01

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January 2, 2002

Dr Nils Olsen
Center for Planetary Science
Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen
Denmark

Dear Dr Olsen,

I write to provide my enthusiastic support for the SWARM Proposal.

This proposal comes at what is already an extremely exciting time in the study of the Earth's magnetic field with advances in numerical modeling of the geodynamo and new insights from the Ørsted and CHAMP satellite missions. However, with the innovative observations promised by the SWARM constellation, which will provide measurements made simultaneously at different local times, there is the very real prospect that we will be able to jump to an entirely new level of understanding of the geodynamo process that generates the Earth's magnetic field.

SWARM represents the future of satellite measurement of the Earth's magnetic field and I provide my unreserved support.

Yours sincerely,

Jeremy Bloxham

Professor of Geophysics
Chair, Dept of Earth & Planetary Sciences

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From the School of Earth Sciences

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December 19, 2001

Dear Sir,

Re: "SWARM: A Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System. ".

The Dept of Earth Sciences enthusiastically endorses the proposed SWARM mission, designed for investigation of the Earth's magnetic field and its interplay with the Earth. This, to us, represents a unique opportunity for the earth and environmental sciences: the idea of having a constellation of satellites is an exciting one, and represents a leap forward in our ability to understand the time-varying magnetic field, and many other questions of broad interest within the fields of deep-earth geophysics and crustal magnetism. We consider that this mission represents a well-planned experiment which will operate in a innovative configuration, using state-of-the-art microsatellite technology.

The geomagnetism group within the Department of Earth Sciences has considerable interest in all aspects of geomagnetism, with a total of six researchers. Investigations into the data produced by SWARM will be lead by Dr. A. Jackson, in conjunction with myself. Dr. Jackson is personally a member of the Orsted and Champ International Science Teams, and has over 15 years of experience in this research area.

I give my wholehearted backing to this project.

Sincerely

David Gubbins

David Gubbins
Professor of Geophysics, Leeds University

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THE UNIVERSITY
of LIVERPOOL

Department of Earth Sciences

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L69 3GP

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4th January 2002

Re: SWARM: a constellation to study the Dynamics of the Earth's magnetic field and its interactions with the Earth System

The Department of Earth Sciences at the University of Liverpool strongly endorses the proposed SWARM mission, to provide the next logical development in the characterisation and modelling of the geomagnetic field. This is the field of research of our new lecturer in Geophysics, Dr Richard Holme, who has extensive experience in modelling and processing satellite data, most recently as a key member of the CHAMP team at GeoForschungsZentrum, Potsdam, and should help lead a strong UK involvement in the project.

The data also lead logically to questions of field generation and evolution, which is a research theme of the Geomagnetism Research Group here at Liverpool.

We wholeheartedly support the implementation of this project.

N.J. K

Professor N.J. Kusznir
Professor of Geophysics

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European Space Agency
The Earth Sciences Division (VR)
ESTEC, Keplerlaan 1, P.O. Box 229
2200 AG Noordwijk
ZH, The Netherlands

Dear Colleagues,

We strongly support, on behalf the Universitat Politecnica de Catalunya, the dedicated satellite mission proposal "SWARM, a Constellation to Study the Dynamics of the Earth's Magnetic Field and its Interactions with the Earth System", in response to ESA's announcement of "Earth Explorer Opportunity Missions".

Indeed, the SWARM will implement a novel and powerful concept for ionospheric radio occultations. It consists of four satellites carrying dual frequency GPS receivers on board, among other instrumentation., which orbit the Earth at two altitudes (e.g., 550 and 450 km) and with two spacecraft following each other in the same orbit. Such a configuration is well suited to distinguish between spatial and temporal variations, of the ionospheric electron density in particular. The improvement of such knowledge will be very useful in applications, such as precise navigation with Global Navigation Satellite Systems, in which the precise knowledge of the electron content is one of the main issues.

Barcelona, January 7th 2002

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