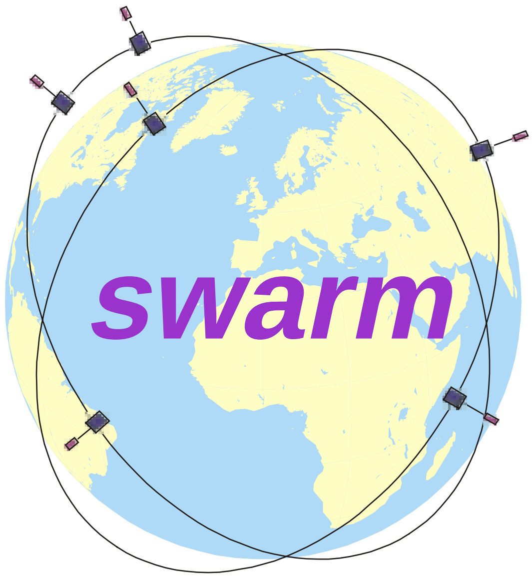
Proposal for Earth Explorer Opportunity Missions



a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field

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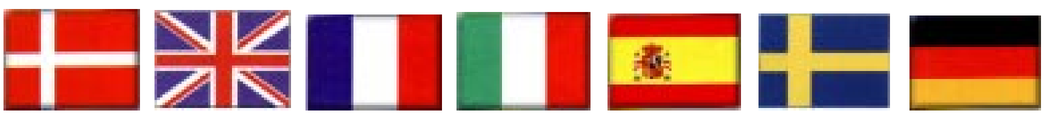

Executive Summary

Accurate measurements of the geomagnetic field is one of the very few ways by which we can probe the properties of the Earth’s interior, especially concerning dynamic processes in the core and mantle. In addition, the geomagnetic field and its interaction with the solar wind play an important role in forming the external environment of the Earth in a way that also affects atmospheric processes related to climate and weather.

The magnetic field measured at or near the surface of the Earth is the superposition of the contributions from a wealth of sources: the fluid core, the magnetisation of rocks in the Earth's crust, electric currents flowing in the ionosphere and magnetosphere, and currents induced in the Earth by the time-variations of the field. The benefit and the challenge of the *swarm* mission are related to the sophisticated separation of these various sources, and the accurate determination of the spatial and temporal structure of them all. The currently planned geomagnetic satellite missions, Ørsted, SAC-C and CHAMP, will not be able to accomplish this with sufficient accuracy. Mainly because they all are single satellite missions, which introduces a significant time-space ambiguity in the determination of the dynamic behaviour of the sources. Multi-point measurements, like *swarm*, are required for this. Furthermore, the duration of these missions is not sufficient to investigate secular variation and solar cycle effects. A mission extending into the next solar minimum is needed for this.

The *swarm* concept consists of a constellation of six satellites in two different polar orbits. 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 all sources of the geomagnetic field.

The mission will provide a new model of the near-Earth magnetic field every 2-4 weeks. This will enable, for the first time, the investigation of the global dynamics of the fluid core. It also will provide details of the induced currents that will give new insight into the conductivity structure of the mantle and thereby help to study subduction zones connected to geodynamic mantle processes. Combined with previous single satellite missions it will provide accurate models of the contribution from external sources that cover a full solar cycle. This, in turn, enables re-analyses of data from previous satellites at lower altitudes to obtain, for example, much improved models of the lithospheric anomaly field.

In addition to its crucial contribution to Solid Earth Science the mission will provide significant improvements to geomagnetic field models that will have practical implications 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. Introduction

This proposal uses the scientific and technical knowledge gained from geomagnetic high-precision missions like Magsat, Ørsted, SAC-C/MMP, Champ, and others as the starting point for a new and exciting mission to investigate hitherto hidden features of the geomagnetic field, especially concerning its dynamics. In recognition of the need for global, continuous, and long term high-precision magnetic field measurements we propose for a multi-satellite mission to be operated into the next solar minimum.

This mission facilitates the analysis of the spatial structure of the time evolution of Earth's magnetic field at large scalelengths (of several thousands of km) as well as at intermediate scalelengths (hundreds of km) and timescales between seconds and years. The combined analysis of the data obtained with the proposed set of satellites will drastically enhance the signal-to-noise ratio in the extraction of the various sources of the field, enabling a unique separation hereof. The multi redundancy inherent in the mission will help secure a long mission lifetime of at least one satellite, answering the need for long-term, order of solar cycle, monitoring of the geomagnetic field.

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 tomography of mantle conductivity • Determine remnant 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 sources on all time scales • Monitor the global magnetospheric activity and the energy input into the upper atmosphere (*Joule heating*) • 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"

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

The main scientific objectives of the mission are listed in Table 1.1 together with the themes of the Earth Observation programme to which they will contribute.

We propose that micro, or even nano, satellite technology is used to build a number (e.g. six) of μ-satellites combined with “Puppets” each carrying vector magnetometer, scalar magnetometer, star imager and GPS receiver. The satellites will measure the vector components of the magnetic field with a sampling rate of 100 Hz and accuracy better than 0.4 nT. They will fly in two circular polar orbits of varying local time orientations. Initial altitudes of the orbits will be as low as possible considering a target lifetime of 5 years. For the technical implementation described here 700 km has been adopted.

2. Scientific Justification

2.1 Science Case

2.1.1 Scientific Motivation

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. This core field and, in particular, its time changes, known as secular variation, are among the very few means that are available to us 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**.

What we measure at or near the surface of the Earth, however, is the superposition of the core field and fields caused by magnetisation of rocks in the Earth's crust, by electric currents flowing in the ionosphere and magnetosphere and by currents induced in the Earth by these time-varying external fields. The benefit and the challenge of the *swarm* mission is related to the sophisticated separation of these various sources which each have their specific characteristics in terms of spatial and time variations. In this respect therefore, *swarm* may be regarded as a remote sensing mission.

Although field changes of internal as well as external origins occur at all time scales, a common practice in separating them relies on their different time behaviour. 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 being heavily attenuated due to the non-vanishing conductivity of the mantle. Hence variations with time scales longer than 4 years are usually attributed to internal field variations (the field due to magnetisation in the lithosphere is assumed to be time-independent), whereas those with periods shorter than 1 year are attributed to external field contributions. However, interesting features occur at time scales where both external and internal sources contribute. **Jerks** are sudden changes in the secular variation, which occur within 1 to 2 years. The spatial characteristics of jerks are still not well known, since no jerk could be observed using the global covering data from a satellite. Recent studies indicate that they may have a recurrence of about 10 years, which complicates their separation from the 11-year solar cycle variation of external origin. The study of jerks sets constraints on the electrical conductivity of the lowermost mantle, which is of crucial importance, for example, for studies of the electro-

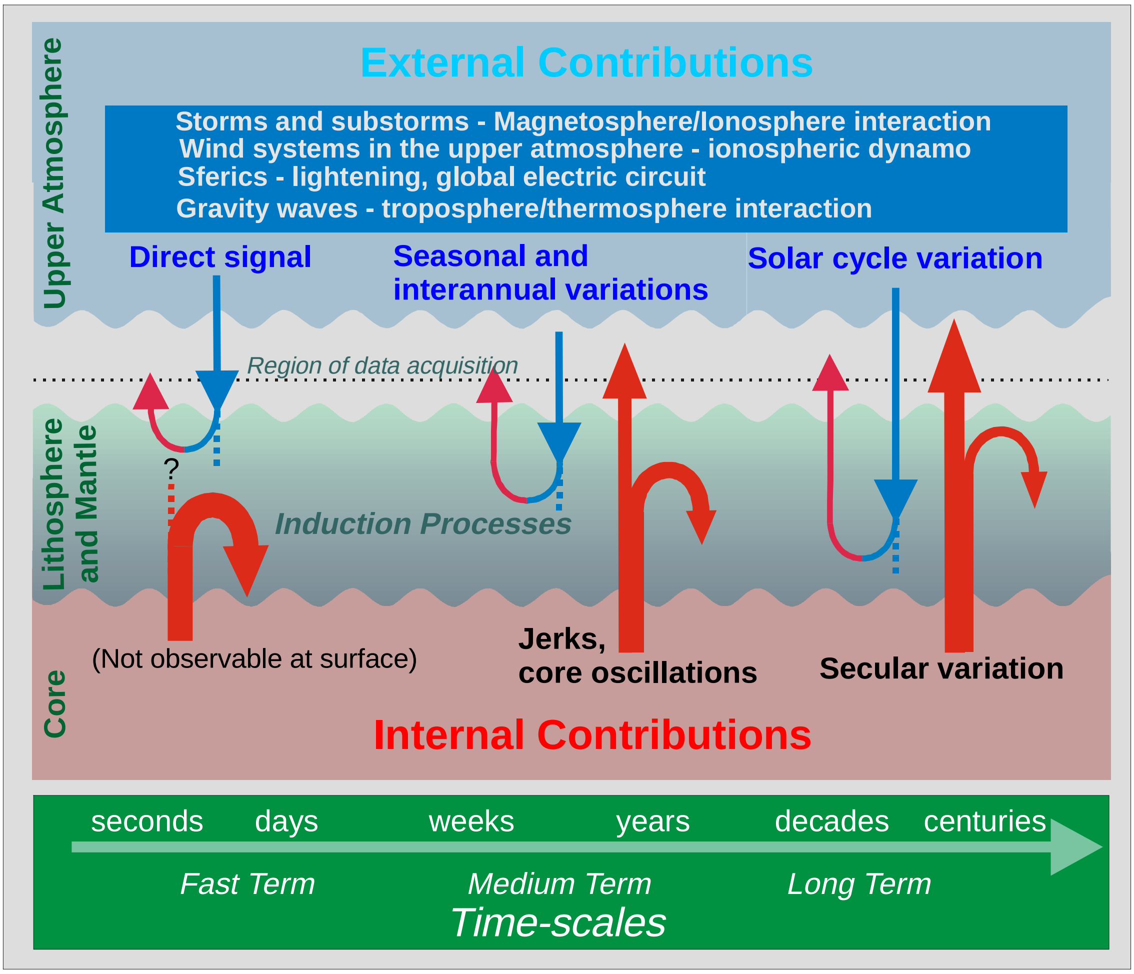


Figure 2.1 *The objective of swarm is to separate the various sources and processes that contribute to the geomagnetic field at different time-scales*

magnetic **core-mantle coupling** and the **variations in the length of day**. **Oscillations of the Earth's core** on time scales of months are another hot topic under discussion.

A serious limitation for the investigation of internal processes at time-scales of months to years are geomagnetic variations of external origin since they contribute on time scales up to that of the 11 year solar cycle. This all clearly demonstrates the need for a comprehensive understanding of external and internal processes.

Although geomagnetic variations of external origin contribute as "noise" when determining models of the core and crustal field, they also serve as a "signal" to probe the conductivity of the mantle. To perform **3D tomography of mantle conductivity** requires good knowledge of the time-space structure of the geomagnetic field from simultaneous measurements over different regions of the Earth, which the *swarm* satellites will provide.

Furthermore, 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. It acts as a shield against high-energy particles from the Sun and from outer Space. It controls **the radiation belts**, and also the trajectories of incoming **cosmic-ray particles**. For example, the **South Atlantic Anomaly** of low magnetic field intensity has a significant effect on the distribution of the energetic particles in the near-Earth part of the radiation belts. The movement of regions of low magnetic intensity and hence high radiation, such as the South Atlantic anomaly, is a direct consequence of the secular variation of the geomagnetic field. These high radiation environments cause radiation damage to spacecraft and enhanced radiation exposure to humans in space. Recent instrument failures on some low-earth-orbiting spacecraft suggest that the South Atlantic anomaly has shifted to the Northwest. Continuous spacecraft monitoring of the magnetic field at low Earth orbit, and the derivation of field models, plays an important role in predicting radiation hazards within the space environment.

A controversial topic in atmospheric science is the possible effect of electric field and charges in the atmosphere. It has been proposed that ionisation by high-energy particles that penetrate deep into the atmosphere may affect the optical transparency by changing aerosol chemistry or by affecting cloud formation processes. It has recently been found that the Earth's cloud cover observed by satellites is strongly correlated with the flux of high-energy cosmic radiation. The geographical distribution of this flux is controlled by the Earth's magnetic field and studies of the possible effects on **climate and weather** need accurate global information about the main field and how it behaves with time. 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 to the ultimate source of life on Earth, namely the Sun.

Current Status of Geomagnetic Modelling

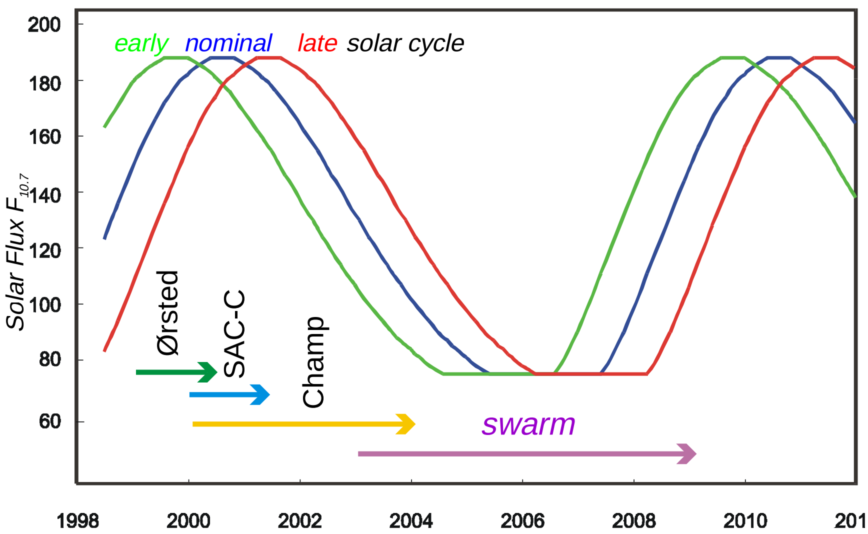
Until now, only one high-precision satellite mission has flown namely the U.S. Magsat mission almost 20 years ago. The main-field models derived using data from short-term geomagnetic missions like Magsat provide us with a snapshot of the geomagnetic field at a particular time instant. Because there has been no comparable satellite geomagnetic survey since Magsat, the quality of available main-field information and models has declined over the past fifteen years. We have had to rely very largely on data from the network of magnetic observatories to help us describe and attempt to predict the secular variation and this data set has a notoriously patchy distribution over the surface of the Earth. In regions remote from magnetic observatories the uncertainties in current field models are unacceptably high for many uses to which the models are put (they can reach 1 degree or more in the field direction and several hundred nT in field strength). The upcoming Ørsted, SAC-C, and CHAMP missions will greatly improve on the situation. They will not, however, be sufficient in duration and accuracy.

Progress

Recent progress in modelling the Earth's magnetic field indicates that the limiting factor in the accuracy of present geomagnetic models is the dynamic behaviour of the external current configuration. Single satellite missions are not able to describe this. Models derived with data from single satellite missions can therefore be obtained with accuracy no better than a few nT, which is much more than the accuracy of the current magnetometers (better than 0.4 nT). Hence, single satellite missions are not able to take advantage of the enormous improvement in instrumentation, which has been achieved during the last 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 from the extrapolations based on statistics and on ground observations at selected sites that is used now. At the same time this monitoring has important **space weather applications**.

Furthermore, the large number of satellites of the *swarm* mission means an enormous enhancement of the global coverage. *Swarm* will be able to provide an accurate model of the near-Earth magnetic field that is including both the internal and external sources, as frequently as every 2-4 weeks. In comparison, a good statistics model is expected every 3 months for the Ørsted, SAC-C and CHAMP missions. Frequent high accuracy models with an improved description of the external contribution over a 5 year period provides an unprecedented tool to examine the faster features of the internal field changes with a good separation of the seasonal and solar activity effects.

Another limitation concerns the requirement for long term measurements. The current planned missions hopefully will provide continual measurements for 5 years starting 1999. *Swarm*, in addition to the improved model capabilities, will stand a very good chance to continue this beyond 2007 hence getting close to the **full solar cycle coverage** that is needed to properly distinguish the solar activity and secular variation effects. It will provide for the first time **satellite data during a solar minimum**. Launch in 2002-2003 would be perfect in terms of providing sufficient overlap with the CHAMP mission to use the better capabilities of the *swarm* mission to calibrate the previous satellite-based models, in this way greatly enhancing the usefulness of the former satellite data and securing the consistency between the outcome of the two missions.



2.1.2 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 will facilitate investigation of hitherto undetected features of the Earth's interior, especially concerning processes in the core and the mantle.

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

Large electric currents are driven in the core by a self-sustaining dynamo process: fluid flowing across magnetic lines of force of the field generates electromagnetic forces, which drive electric currents, which maintain the magnetic field. On time scales shorter than about 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 in the core. Thus, **the fluid flow in the core** produces the advection of the lines of force of the magnetic field. Consequently, temporal variations of the main geomagnetic field observed at the surface of the Earth, namely secular variation, directly reflect the fluid flow in the outermost layer of the core[1]. This can only be recovered from observations of the magnetic field and its secular variation and may then be used to infer the kinematics of the flow in the bulk of the core. Hence, secular variation provides a unique experimental constraint on dynamo theory and the geodynamo mechanism.

The **Earth's rotation** presents irregularities with different time scales: fluctuations of the length of day (l.o.d.) with time constants from a few days to a few decades are superimposed on a quasi-linear increasing trend. The low frequency variation has to be attributed mainly to the exchange of angular momentum between the mantle and the core; no other angular momentum sink is big enough to account for it. Although the **coupling mechanism between the core and the mantle** has been addressed for forty years this is still a timely and controversial question[2]. It is of fundamental importance for understanding the **decadal variations of the length of the day** and, to a lesser extent, the motion of the pole (e.g., the Chandler wobble). At the same time, the very mechanism of the core-mantle coupling is not yet definitely elucidated: is the torque coupling the mantle and the core electromagnetic, topographic, or both? The discussion of electromagnetic coupling raises the question of electrical conductivity in 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.

Two strategies can be used to extract secular-variation information from the *swarm* data sets. In the first alternative subsets of the data, each spanning the shortest time sufficient to give a good global data distribution, are selected. The six satellites of *swarm* will be able to obtain the necessary amount of global data in a much shorter time than single satellite missions can. Each subset is analysed to give a series of "snapshot" main-field models. The time dependence of the individual coefficients of this series of field models then gives information on secular variation and on long-term variation of external origin, especially concerning seasonal and solar cycle variations. In the second technique, this time dependence is included in the model (for instance by means of spline functions in time), and data spanning months or years are used.

From that part of the models, which describes the core field, fluid flow patterns will be derived and used to study how the core and mantle are coupled. In particular, an attempt will be made to ascertain which of the two most likely mechanisms, electromagnetic or topographic coupling, is dominant or whether both are important. Correlation of computed momentum transfer with changes in length of day will also be investigated.

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

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

Jerks: Abrupt Changes in the Earth's Magnetic Field

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 impulses or jerks. There have been four, or possibly six, such events this century, irregularly spaced in time. They appear to be discontinuities in the second time derivative of the field (the secular acceleration), although new methods of analysis[3] promise to refine this statement.

There has been some discussion on the global character of jerks. The availability of well-distributed global data from *swarm* will enable a more definitive answer to be given to 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[4].

A typical jerk occurs rapidly and the conducting mantle alters the amplitude and frequency content of what is observed at the Earth's surface and from satellite altitudes by acting as a sort of filter. 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 its coverage of the Earth. A combination of ground-based observatory data plus data from *swarm* is an approach to this ideal situation and the improvement in our knowledge of the time scales involved will help to refine our estimates of the electrical conductivity of the lower mantle.

The availability of high accuracy main-field and secular-variation models on a more-or-less continuous basis from early 1999 (the launch of Ørsted) until about 2010 will have far- reaching implications for studies of the interior of the Earth. We might reasonably expect a jerk to occur sometime during this interval.

A careful search will be made to detect any jerks that may occur during the lifetime of the satellite. If any are found, satellite and ground-based data will be analysed to discover when the jerk happened and what the dominant time scales of the process were. 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 jerks are 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 in the outer core, the implications for lower mantle electrical conductivity will be investigated.

Reducing the Noise from External Sources

For studies of the Earth's core, 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, whose sources are located at 110 kilometres altitude, behaves as an "internal" field. However,

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[3] Alexandrescu, M., D. Gibert, G. Hulot, J.-L. Le Mouël, and G. Saracco, Worldwide wavelet analysis of geomagnetic jerks, *J. Geophys. Res.*, **101**, 21,975-21,994, 1996

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

external field contributions are – in contrast to the crustal field – highly time variable, which can be used to extract the core- and crustal field.

Recent investigations have shown that field models may be contaminated by external contributions more than hitherto expected[5]. They have also demonstrated the great advantage of modelling Earth's main field and its secular variation simultaneously with ionospheric and magnetospheric contributions by means of a joint inversion of ground-based and satellite magnetic measurements[6]. This goes beyond the usual division in "internal field science" and "external field science" and opens a potential for very fruitful exchange between scientists of the two subdisciplines (cf. Section 2.1.3).

3D Tomography of the Upper 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 less extent, to changes in mineralogy.

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. Mantle conductivity can also be probed "from the top" by the analysis of natural geomagnetic variations at various frequencies. This method requires a good knowledge of the space-time dependence of the magnetic field of external origin. If measurements are performed for one 11-year solar cycle, it will be possible to obtain the conductivity of the middle and lower mantle without making prior assumptions.

It has been shown that it is possible to extract the external field and its induced counterpart in satellite data and hence probe the mantle conductivity from space[7]. The joint analysis of the transient magnetic field recorded in space and at ground 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

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[5] Engels, U. and N. Olsen, The Influence of External Current Systems on the Expansion Coefficients of the Geomagnetic Main Field, in preparation for *Geophys. J. Int.*

[6] Langel, R. A., T. J. Sabaka, R. T. Baldwin and J. A. Conrad: The near-Earth magnetic field from magnetospheric and quiet-day ionospheric sources and how it is modeled, *Phys. Earth Planet. Int.*, **98**, 235-267, 1996
Olsen, N., R. A. Langel and T. J. Sabaka: Geomagnetic field models including contributions from quiet-time ionospheric and magnetospheric sources (abstract, session 5.11), *8th Scientific Assembly of IAGA*, Uppsala, 1997

[7] Olsen, N. Induction Studies with Satellite Data, *Surveys of Geophysics*, submitted, 1998

that will be provided by *swarm* is even greater. Much 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.

Knowledge of the crustal field is important not only scientifically in its own right, but for the insights it can give to the exploration geophysicist in the search for mineral and hydrocarbon deposits. With previous satellite mission an impressive number of results have been obtained about the magnetisation of the crust and uppermost mantle and its relationship with geodynamics. Still several fundamental questions remain such as:

- the origin of some of the anomalies that cannot be explained by the induced or remnant magnetisation of known structures either in the crust or the 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 absence of information about north-south magnetic anomalies at all wavelength, always obliterated by 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.

The relatively high altitude (700 km) of the *swarm* satellites is a limiting factor for a direct determination of the small-scale features of the lithospheric field. However, *swarm* will contribute at least indirectly to crustal field studies through better models of the core field and external field, which enables a re-analysis of data from previous satellites at lower altitude.

2.1.3 Science Objectives, Earth Environment

The external environment of the Earth is controlled primarily by the Earth's magnetic field, which also provides a partial shield against corpuscular radiation from the Sun and from outer Space. The region where the Earth's magnetic field dominates constitutes the region in Space that is called the magnetosphere. The magnetosphere is the seat of highly complex and time-varying processes that have a direct effect on the upper atmosphere and on the surface of the Earth. Among those effects are the polar auroras and the Van Allen radiation belts of energetic particles encircling the Earth.

Our understanding of the global processes which determine the coupled interactions between the electromagnetic and corpuscular emissions from the Sun and the neutral and ionised species in the Earth's environment, and the flow of energy from the Sun to the Earth that results from these, is still poor. For example, it does not allow prediction of the response of the Earth system to changes in the solar output. As a consequence, several international research programs have recently been initiated to improve our knowledge of the solar-terrestrial system. Advances in the understanding of magnetospheric processes and their generation through the complex interaction between the solar wind, the magnetosphere and the atmosphere are conditional on adequate observations of key parameters. The small but highly time varying component of the measured magnetic field of the Earth that is of external origin constitutes one of the prime parameters describing the physical conditions in the magnetosphere. This, for example is a key element of the ESA Cluster mission. The *swarm* mission would be an extremely important near-Earth complement to this and other international solar-terrestrial efforts.

Configuration and Dynamics of the External Current Sources

The geomagnetic field lines provide a strong electromagnetic link between the outer regions of the magnetosphere and the lowest part, the ionosphere. The link is sustained by electric currents that flow easily along the magnetic field lines because of the highly anisotropy conductivity in the magnetosphere. The only available means of direct measurements of these currents are in the form of magnetic field measurements on board low altitude polar orbiting satellites. Measurements from a few such satellites in the past have provided indispensable information that has made it possible to describe, albeit only in gross terms, this important component of the coupling between the magnetosphere and the ionosphere. The measurements from Ørsted, SAC-C, and CHAMP are expected to lead to major advances on this issue. However, the configuration of the field-aligned currents is complex and highly dynamic[8]. The problem of separating spatial and temporal structures which is inherent to single satellite missions means that they will not be able to address this important aspect of the problem. The *swarm* mission, in contrast, is specifically aimed at this. It will provide, for the first time ever, multi-point observations of the field-aligned current system from space to match the multi-point measurements of various upper atmosphere parameters made by the extensive networks of ground stations which have come into operation over the last couple of years. Particularly, the networks at polar latitudes, such as the net of HF-radars of the SuperDARN project[9], have been very successful in providing new insight into the complex solar-terrestrial coupling and its dynamics. The *swarm* mission would provide exactly what is needed to supplement this and advance the progress further.

The long operational lifetime of the mission will provide an unprecedented database for statistical analyses of the distribution of the external magnetic field as a function of local time, season, and conditions in the solar wind. Together with the data from the preceding missions, Ørsted, SAC-C, and CHAMP, chances are very good for full solar cycle coverage to be obtained. An empirical model of the magnetospheric response to given average solar wind conditions is an important tool not only for improvement of the models of the internal field as discussed in the previous section. It is also an important tool to test theoretical models describing the interaction between the solar wind and the magnetosphere.

Global Geomagnetic Index, Geomagnetic Monitoring of Space Weather

Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to serious economic losses. This is known as space weather. 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 six spacecraft of the *swarm* mission. The potential of this for space

[8] T. Moretto and E. Friis-Christensen, Ground observations of dayside small-scale dynamic features, in *Results of the IASTP Program, Advances in Space Research*, **20**, 863-872, 1997

[9] R.A. Greenwald et al., A global view of high-latitude convection, *Space Science Review*, **7**, 763-796, 1995

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. The possibilities of using geomagnetic satellite missions for these purposes, of course, are completely unexplored.

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, Ørsted and others in the 100-1000 km altitude range damage has frequently occurred and will continue, for example, over the South Atlantic Anomaly, which is an area of particularly low geomagnetic field strength between South America and South Africa. The low magnetic field allows particles from the radiation belts around the Earth to penetrate into the upper atmosphere and create intense radiation. The South Atlantic Anomaly is an important example of a region where the magnetic field cannot be monitored well with ground stations. Recent instrument failures on some low earth orbiting spacecraft have suggested that the South Atlantic Anomaly has shifted to the Northwest, but with no new models based on satellite data for almost 20 years it is not know whether this shift is real. Accurate and timely geomagnetic field models clearly play a pivotal role in space operations[10] as do good estimates of the rate and form of change of the field to know what to expect in the planning for the coming years. The *swarm* mission will continue the efforts of the geomagnetic missions already planned to provide improved models and predictions of the identification of the problem regions, their position, strength and evolution during the period when, amongst other, the operation of the International Space Station makes this issue highly relevant.

Modulation of the Cosmic Ray Flux

A potential source of climate variations is the varying cosmic ray flux that in the atmosphere creates ionisation changes, which affect microphysical processes, such as the nucleation and growth of ice particles in high-level clouds. Both the continuous flux of Galactic Cosmic Rays that is characterised by very high energies and the Solar Cosmic Rays of typically lower energies that are associated with solar eruptions contribute to the particle fluxes impinging on the Earth atmosphere. The flux distribution, in particular for the lower energy part, is highly dependent on the strength and form of the geomagnetic field. Consequently, detailed models of the geomagnetic field and its evolution will be an important factor in the discussion of anthropogenic impact versus internal variability of the Earth climate system.

Furthermore, the *swarm* mission is believed to advance our understanding of how the solar wind and magnetosphere interact, and how this is reflected in the fluctuations of the geomagnetic field on a global scale. This will greatly improve the possibilities to deduce solar wind conditions back in time, as far as 130 years, on the basis of geomagnetic fluctuations at ground magnetic observatories. During the past ~ 120 years, Earth's surface temperature is correlated with both decadal averages and solar cycle minimum values of the geomagnetic *aa*-index[11]. The

[10] 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

[11] E.W. Cliver, V. Boriakoff, and J. Feynman, Solar variability and climate change: Geomagnetic *aa* index and global surface temperature, Geophys. Res. Lett, 25, 1035-1038, 1998

modulating effect on the cosmic ray flux of the solar wind magnetic field has been proposed as the key to explain the reported correlation between solar variability and climate changes[12].

2.1.4 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 tomography of mantle conductivity describing properties of the mantle. 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" candidate of the "Earth Explorer Core Mission" program. The *swarm* mission would be an important supplement to this mission.

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 create ionisation and may thereby affect cloud condensation processes that are crucial for the radiation balance.

The geomagnetic field and its interaction with the solar wind play an important role in forming the external environment of the Earth. The magnetic field controls the radiation belts and the trajectories of incoming cosmic-ray particles. The *swarm* mission is aimed at advancing our understanding of these processes and their effect on the upper atmosphere and the surface of the Earth. This all constitute a variable background, the importance of which must be understood if one is to fully benefit from the missions concerned with changes of the Earth climate. As such it lies at the heart of the objectives of the Physical Climate theme that concerns the understanding of the variability of the various components of the climate system.

2.2 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 project counts 50 groups from 14 countries both in Europe and overseas, the collaboration of which will continue in the SAC-C and CHAMP proj-

[12] E. Friis-Christensen and H. Svensmark, What do we really know about the Sun-climate connection?, *Advances in Space Research*, **20**, 913-921, 1997

ects. 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, which the Ørsted, SAC-C and CHAMP missions demonstrate, for the next decade.

2.2.1 The *swarm* Science Team

The team of co-investigators on the proposal includes 14 groups from 7 European countries. That this has been possible in the very short time available for the preparation demonstrates the great 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 already during the phase A/B of the project. Interest in the *swarm* mission has also been voiced from research institutions in the US. Letters of support from NASA, Goddard Space Flight Center and NOAA, are included in Annex C together with those of other institutions and agencies internationally.

2.2.2 Interdisciplinary Gain

A unique feature of the Ørsted science team is that it joins scientists from the internal and external communities. Already, through the preparing science meetings of the Ørsted project both sides have benefited from this interaction. The multi-point aspect of swarm and its dedicated objective to investigate the external current sources will further strengthen this cross-field collaboration.

2.2.3 Relation to Other Programmes

The mission will act as a geomagnetic contribution to the upcoming "International Decade of Geopotential Research" as proposed by the International Association of Geomagnetism and Aeronomy (IAGA), the International Association of Geodesy (IAG) and the International Association of Seismology and Physics of the Earth's Interior (IASPEI).

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, including the ESA Cluster-II mission.

2.3 The Ampère Mission

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. Originally, the Ampère project consisted of two microsatellites with scalar magnetometers and turbo-rogue GPS, launched at the same time into orbits with different altitudes.

The objective is to use the gradient information determined from the magnetic measurements of both satellites to infer the vector components of the magnetic field. The sciences objectives are to study both internal (core field, secular variation, lithospheric field, induction) and external phenomena (variability of the dynamics of the magnetosphere, magnetosphere/ionosphere coupling, and space weather).

Originally several scenarios for the Ampère mission have been proposed, one of which has the satellites in a low altitude (300-400 km) and low inclination (45-50 deg) orbit, which for instance enables to study of the absence of N-S going magnetic anomalies found in present maps of the crustal field.

In the framework of the *swarm* mission, the scientific team of the Ampère project proposes an evolution of the Ampère concept toward a complementary mission to the basic *swarm* concept: We propose to use the flight spare *swarm* satellite as the low inclination (< 50 degree) low altitude (< 400 km) orbit Ampère implementation. In such a situation, the scientific objective of Ampère will be completely fulfilled and the science possibilities of the *swarm* project will be enhanced accordingly. The flight spare (seventh) *swarm* satellite should be launched separately as part of the ASAP/Ariane 5 launch opportunities (available several times a year), after successful completion of the initial commissioning phase of the *swarm* mission.

3. General Mission Characteristics

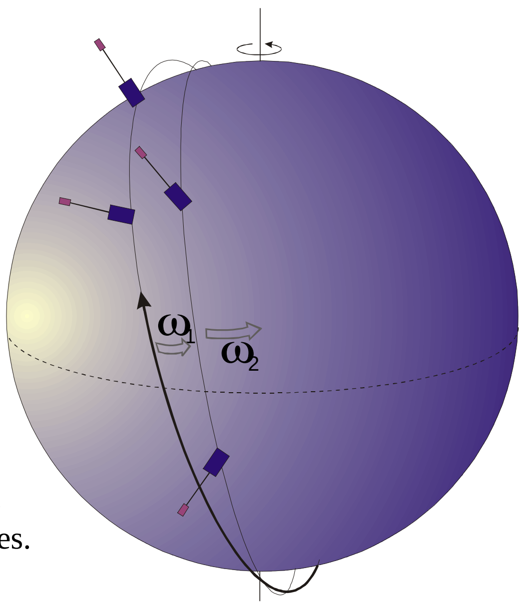
3.1 Scientific and Technical Requirements

In general terms, the requirement to the mission set by the scientific objectives is for the vector components of the geomagnetic field to be measured globally, continually and very accurately.

3.1.1 High-Precision Vector Magnetic Field Measurements

The absolute accuracy of the magnetic field measurements should be better than 0.4 nT. The major limitation for the accuracy of the vector measurements is the accuracy of the attitude determination. The omni-directional star tracker and the "puppet" construction, which secures a common frame of reference for the magnetometer sensor and the attitude determination, provide the solution for this. The high accuracy requirement furthermore sets tight limits on the magnetic disturbance level, from the satellite system, that can be tolerated at the sensor. This demands that the sensor be displaced a considerable distance from the satellite, 10 m or more depending on the magnetic cleanliness of the satellite. Finally, an accuracy of 0.4 nT for the magnetic field measurements translates into an additional requirement for the position determination to be better than 15 m. The latter is easily obtained with current GPS receivers.

3.1.2 The Constellation Concept



The science goals rely on the possibility to obtain multi-point measurements of the near-Earth magnetic field. A variety of different distributions of the measurements are needed. Two satellites in each of two different polar orbits (2+2) are the minimal realization of a constellation providing this.
Adding a third satellite in each of the orbits, however, will serve to secure a long operational lifetime of the minimum constellation (redundancy of instrumentation) while being able to relax costly requirements of reliability and durability on the spacecraft design in terms of redundancy at equipment and system level and electronic parts quality. In addition, the observations of the two extra satellites in themselves constitute a valuable extension of the constellation possibilities.

The requirement of global coverage concerns both geographic and local time coverage. This is met by launching the six satellites (3+3) into two near-polar circular orbits, as illustrated in the figure, with slightly different inclinations resulting in different orbit drift rates (ω_1, ω_2), the exact values of which are not important. The satellites in each orbit will, of course, drift apart slowly providing the multitude of distributions that the scientific investigations require. Six satellites in two polar orbits will provide a very good coverage of the Earth surface, as needed, in less than one day.

3.1.3 Orbit Altitude and Mission Lifetime

Altitude of the orbits is subject to two counteracting constraints. Resolution of the smallest scale structures of the geomagnetic field requests the altitude as low as possible. On the other hand, investigation of secular and solar cycle variation effects requests a lifetime of at least 5 years. Re-entry time and system lifetime of the satellites depend on the exact design of the spacecraft and cable-boom length as well as on solar activity. With the current knowledge 700 km seems a safe option for the injection altitude.

3.1.4 The Ampère Mission

As proposed in section 2.3 the French Ampère project can be implemented as an enlargement of the *swarm* mission. This requires the flight spare (seventh) *swarm* satellite to be launched separately, and after successful completion of the initial commissioning phase of the *swarm* mission, into a low altitude (below 400 km), low inclination (< 50°) orbit.

3.1.5 Launch Time

Launch in December 2002 is optimal for several reasons. It will make the *swarm* mission a direct continuation of the German CHAMP mission to be launched late 1999 with sufficient overlap for an intercalibration of the two missions to be performed. Together also with the Ørsted and SAC-C mission, chances are very good that satellite measurements of the geomagnetic field can be obtained for a full solar cycle. At the same time, the *swarm* mission, contrary to all previous geomagnetic missions, will be a solar minimum mission.

3.1.6 Summary of Orbital Parameters

A feasible implementation of the *swarm* constellation , c.f. the description of launch possibilities in section 4.4, could have the following parameters:

- 2 different orbits, both at 700 km altitude
- One orbit is at 82° inclination (ω_1 = -1.0°/day), i.e. covers all local times in 3 months
- Other orbit at 88º inclination (ω_2 = -0.2°/day), i.e. covers all local times in 6 months
- Three satellites are launced into each orbit with a difference in velocity of approximately 10 m/s

3.2 Relation to Other Missions

The *swarm* mission should be seen as a natural extension of the three missions, Ørsted, SAC-C, and CHAMP, planned to be launched within the next year, all of which will 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 greatly improve their results. The improved understanding and modeling capabilities of the near-Earth magnetic field to result from the *swarm* mission will enhance the value of data also from these missions preceding it. The *swarm* mission will extend this geomagnetic effort to cover a full solar cycle, and provide the first ever solar minimum geomagnetic mission, c.f. Figure 2.1

In several ways, the *swarm* mission can be seen to supplement the missions chosen as candidates for the "core missions" of the Earth Explorer element of the Earth Observation programme. Accurate measurements of the geomagnetic field provide one of the few means to gain insight into the properties of the outer core and mantle. The gravity field is another source of information and is the objective of the "Gravity Field and Steady State Ocean Circulation" 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 the missions concerned with changes of the Earth climate.

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[13], including the ESA Cluster-II mission.

[13] URL: http://www-istp.gsfc.nasa.gov

4. Technical Concept

4.1 Science Payload Concept

The basic concept is to obtain high quality measurements of Earth's magnetic field by use of instrumentation with the capability of ultra low noise, high stability and ultra linear in-orbit measurements of this magnetic field vector and of the vector direction relative to the inertial stellar coordinates. This is achieved by placing a combination of the critical sensors, "The Puppet", at the end of a boom, deployed (at least) 10 m from the host satellite. Thereby most local magnetic field perturbations from the main spacecraft instrumentation and structure are eliminated. Power will be supplied via thin cables in the boom, and a digital/analogue link between the Puppet and the host satellite will carry all data transfer to the main spacecraft telemetry. Part of the instrumentation is contained in the Puppet and another part is placed in the host satellite Puppet Support Unit (PSU) including the digital/analogue link to the Puppet.

The boom relieves the main satellite body and instrumentation from cost driving magnetic cleanliness requirements, and no need for an expensive and time consuming spacecraft level magnetic cleanliness and calibration program exists. Magnetic calibration and inter calibration with the stellar sensors will be necessary at the Puppet-level only and will be the responsibility of the science instrumentation teams.

4.1.1 Science Payload Elements

The science payload consists of three instruments supported by timing and orbital position from the Global Positioning System receiver (GPS):

- Compact Spherical Coil vector feedback magnetometer (CSC).
- Advanced Stellar Compass system (ASC).
- Overhauser Scalar Magnetometer (OSM).

The CSC measures the magnetic field vector 100 times per second with a magnitude resolution better than 0.1 nT and an angular resolution better than 0.5 arc sec relative to the magnetic sensor axes.

The ASC measures the orientation of the magnetometer sensor axes relative to the fix star coordinates once per second with a resolution better than 0.5 arc sec.

The OSM measures the scalar magnitude of the magnetic field with an absolute accuracy better than 0.2 nT and at a rate of up to 3 measurement per sec.

The OSM sensor is fastened to the boom 2-3 m from the Puppet and is supported by an electronics unit in the main satellite via a 2 mm overall diameter twisted pair/twisted shielded pair in the boom. Alternatively, the basic OSM front-end electronics can be included in the Puppet, and the scalar data is transferred to the main satellite Puppet Support Unit (PSU) via the digital/analogue link. The OSM sensor cabling will then run only over the distance to the Puppet.

The CSC sensor and the three camera heads of the ASC are integrated in the Puppet structure, Fig. 4.1. The Puppet also carries the digital/analogue transceiver for communication to a matching transceiver system in the main satellite Puppet Support Unit (PSU), and a power regulator unit connected via a 1 mm diameter twisted shielded wire pair to the satellite PSU. The ASC camera head units contain the CCD support electronics in digital link contact with the

ASC computer in the main satellite, and the CSC sensor is supported by the analogue link to the CSC support electronics in the main satellite PSU.

4.1.1.1 Compact Spherical Coil Vector Feedback Magnetometer

The fluxgate principle chosen for the vector magnetometer gives high stability and low noise measurements of the Earth's magnetic field vector components. The fluxgate is the workhorse of space magnetometry in simple and reliable instruments, and the NASA Magsat 1979-80 mission established the benchmark for almost the following two decades of space mapping magnetometry. The long development leading to the Danish Ørsted CSC vector fluxgate magnetometer draws heavily from this heritage.

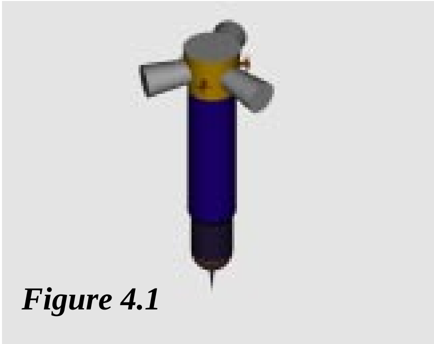


Figure 4.1

The Compact Spherical Coil (CSC) for vector magnetic field feedback is a tri-axial approximation to the spherical geometry offering the smallest external dimensions for the largest internal homogeneous field volume. Fig. 4.2 shows the CSC sensor Ørsted model, and Fig. 4.3 presents a cut view of the sensor.

All three fluxgates are placed in the common vector 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 spherical coil. The coil current is an exact measure of the corresponding external magnetic field component. The vector nulling of the field over the large homogeneous volume makes the magnetic axes dependent only on the CSC axes, and not at all

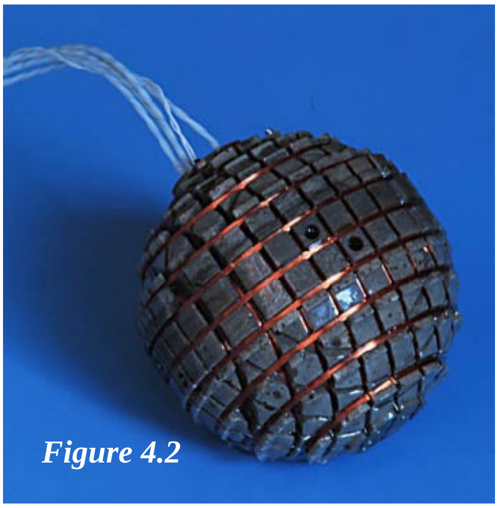


Figure 4.2

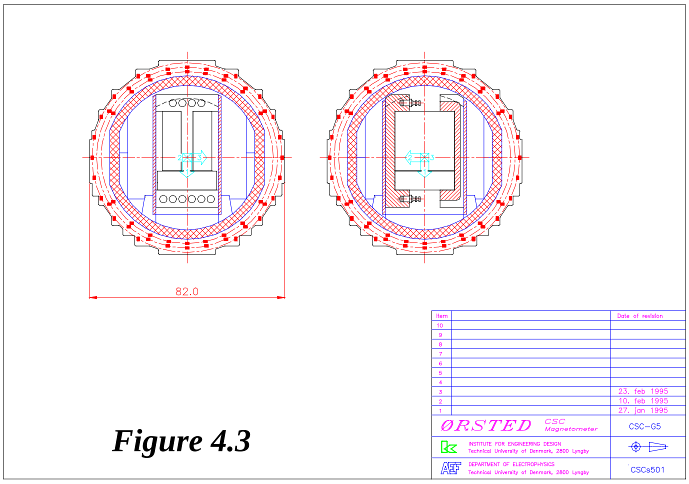


Figure 4.3

on small positional and angular changes of the fluxgate ring cores.

The development highlights (see the CSC block diagram in Fig. 4.4) can be summarised as:

- Compact Spherical Coil (CSC) Vector Feedback
- Stress-Annealed Amorphous Magnetic Metal Ring Core Fluxgates
- Short-circuited Fluxgate Element Output Current Detection
- All-Even Harmonics Output Signal Detection
- Digital Magnetic Field Signal Detection and Feedback Control

The CSC sensor is placed in the puppet, and the interface electronics is placed in the host satellite as part of the Puppet support and interface unit (PSU). The Puppet part weighs 340 g (sensor) and 225 g (cabling and connections). This part consumes 200 mW and is supported inside the Puppet structure. The satellite part weighs 1000 g including a portion of the PSU box and consumes 1800 mW. Total CSC magnetometer power consumption is 2000 mW, not including the digital link power.

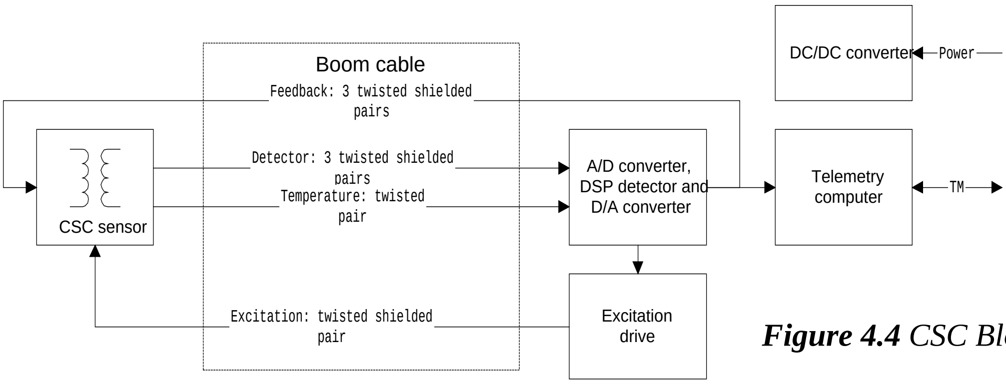


Figure 4.4 *CSC Block Diagram*

4.1.1.2 Overhauser Effect Proton Precession Absolute Scalar Magnetometer

The absolute scalar magnitude of the Earth's magnetic field is measured most precisely by a proton precession magnetometer based on Nuclear Magnetic Resonance (NMR). The proton NMR frequency in the Earth's field (roughly 50 000 nT) is 2.13 kHz. It is determined by the gyromagnetic ratio for the proton, which is one of the fundamental constants of nature used to define the Ampère and the Tesla in the SI[14].

NMR in the Earth's field is observed by placing a small sample (spherical, 25 mm OD) of proton rich liquid inside an Aluminium wire pickup coil in the field. The measurement requires an enhancement of the sample proton magnetic polarisation, which, in the classical instruments, is obtained by sending a strong DC-current through the pickup coil, thereby creating a sample polarising magnetic field of about 15 mT for 500 msec. Immediately after switch-off of the polarisation, a 2 kHz decaying μV-signal is observed for about one second[15].

The OSM sensor may be operated up to three times per second giving a decaying 2 kHz signal burst, which is digitised at16 bit resolution at a rate of 10 kHz. The sampling rate is under tight control and related to the absolute frequency standard provided by the GPS timing signal. A block diagram of the instrument is shown in Fig 4.5.

The spectral analysis algorithm provides a resolution below 10 pT, and the overall instrument absolute field accuracy is better than 0.2 nT at 3 samples per second. For in-flight calibration purposes the sampling rate needs only be one sample per several minutes. A calibration will

[14] Cohen, E.R. and B.N. Taylor, The 1986 Adjustment of the Fundamental Physical Constants, *Rev. Modern Phys.*, **59**, 1121-1148, 1987

[15] Primdahl, F., Scalar Magnetometers for Space Applications, *in: Pfaff, Borovsky and Young (eds.),* Measurement Techniques in Space Plasmas, Fields, *Geophysical Monographs*, **103**, 85-99, American Geophysical Union, Washington, DC, 1998

take one to two days, and needs only be repeated at intervals of several weeks, depending on the in-flight stability of the CSC-magnetometer.

The OSM sensor is fixed to the boom 2-3 m inward from the Puppet. The OSM electronics unit may be placed in the host satellite, which requires the sensor cabling to be included in the boom. The cabling consists of one shielded twisted pair and one twisted pair of about 2 mm overall diameter. Alternatively, the front-end basic sensor support electronics may be included in the Puppet, and the OSM sensor cabling then runs between the OSM sensor and the Puppet only. The Puppet power supply current flowing in the (tightly) twisted pair along the wire boom is estimated not to present any problem for the measurement accuracy of the OSM sensor.

The weight of the OSM sensor is 500 g, and the OSM electronics for Puppet front end accommodation weighs 200 g, and the support unit in the satellite weighs 400 g including cables and connectors. The total electronics unit if placed in the satellite will weigh 500 g, excluding the cable along the boom (estimated to extra about 15 g/m).

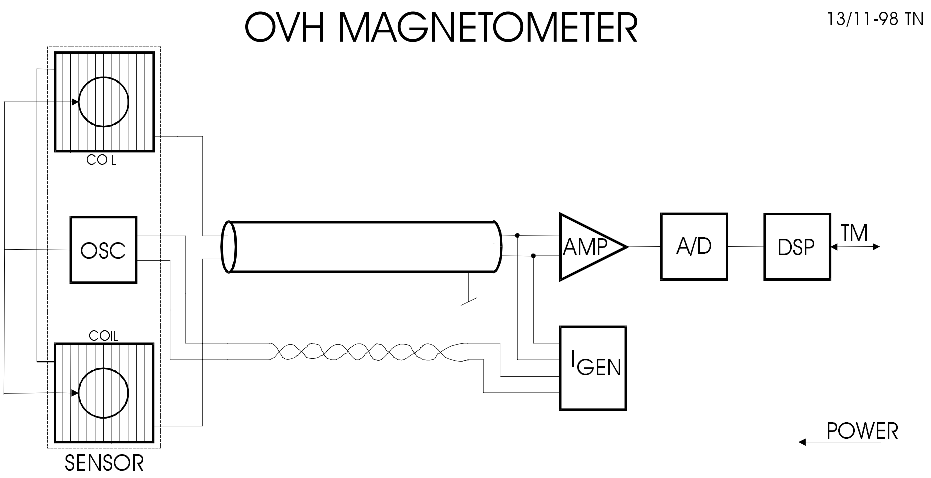


Figure 4.5

If the OSM is placed in the Puppet, then the power consumption is estimated to be 800 mW for the Puppet part of the OSM. The additional power consumption in the PSU in the satellite is estimated to 600 mW. Total power consumption for the OSM is thus estimated to be 1.4 W, and that will be the power consumed from the satellite bus, if the OSM electronics unit is placed in the satellite.

4.1.1.3 Advanced Stellar Compass

The ASC has been developed as a fully autonomous star tracker, following all brighter stars in the camera Field Of View (FOV). Furthermore, the instrument has been optimised towards supplying the best possible overall attitude accuracy for the spacecraft. This has been achieved by splitting the instrument into a Camera Head Unit (CHU) and a Data Processing Unit (DPU), which may be separated by more than 15m.

Because each CHU dissipates 0.35W only, and its mass is less than 250g, the CHU may be placed close to the instrument setting the highest attitude requirements. Furthermore, the thermal dissipation and the thermal radiation through the lens are arranged to ensure full performance without active thermal control. The DPU might drive a single CHU at a user selectable update rate from 0.0625Hz to 4Hz; two CHU’s from 0.0625 to 2Hz or four CHU’s from 0.0625 to 1Hz.

After the CPU receives the digitised image, it analyses the star positions and calculates the attitude of the boresight and the rotation about this axis. These coordinates are then transformed to a user defined spacecraft coordinate system, and are output in the form of quaternions.

In a number of situations, for example after power cycling, after a SEU, or following an invalid image (bright objects etc.), the previous attitude is invalid or missing. In this case an extra image-processing step, initial attitude acquisition, is included: The hyper-accurate star positions are analysed for triplets of nearest and next nearest neighbours. The resulting set of triplets is then matched to a pre-flight-compiled version of the star catalogue, the star database, which contains all conceivable triplets. Based on this match a crude attitude is obtained. This attitude is then used as a bias, instead of the previous invalid attitude, in the consecutive processing.

In order to transform the relativistic attitude to heliocentric attitude, the velocity vector of the spacecraft relative to the heliocentric system is needed. This vector is obtained via the day of year and an orbit model. The orbit model needs to be updated at intervals from hours to days depending on the orbit-perturbing forces (air-drag). Typically, these updates are based on GPS data. The correction amounts to maximum 26 arcseconds for LEO.

The ASC is a highly autonomous instrument that can handle several anomalies and is not damaged by, even prolonged, direct sunlight exposure.

The Camera Head Units (CHU) each weighs 250 g plus 60 g for the baffle. The 3 CHU's and baffles on the Puppet will weigh, in total, 930 g. The total power consumption for the three CHU's in the Puppet is 1800 mW. The ASC computer in the satellite PSU weighs 900 g and consumes 7 W.

The ASC provides the full accuracy (0.5 arcsec resolution) at 1 Hz output rate for up to 0.6°/sec rotation rate and up to 6°/sec at 5.5 Hz output rate. The attitude data package contains the quaternion and consists of 32 bytes. The housekeeping information can be sent upon command or regularly at a given frequency.

4.1.2 Puppet Subsystem Elements

4.1.2.1 Digital/Analogue Link Puppet/Satellite

The ASC needs 30 Mbit/s for the cameras and the OSM needs 200kbits/s. This is from the Puppet to the satellite. The other way, the ASC needs 10 Mbit/s and the OSM 10 bits/s. The CSC-sensor needs 7 twisted shielded pairs and 2 twisted pairs. The following resources are estimated for the Puppet, similar resources will be required in the satellite.

Estimated weight 400 g. Estimated power 500 mW.

4.1.2.2 Puppet Structure

The Puppet mechanical structure (see the sketch in Fig. 4.1) serves several purposes:

- Mechanically Stable Support of the ASC Camera Heads and the CSC Sensor. Optical bench performance stability is required for maintaining the necessary relative orientation stability between the CSC magnetic axes and the ASC camera heads' axes. Composite materials with the same properties as those of the CHAMP boom optical bench will be used.
- Support and Housing of the Electronic Circuit Boards. In order to save weight, the Puppet structure will serve as instrumentation printed circuit boards support

- Mechanical Fixture for the Boom. Environmental Control of the Puppet Instrumentation. The thermal condition of the Puppet will be passively controlled by balancing the solar irradiation (input) against the radiated heat (output) for the desired mean temperature (about -10°C).

The total weight of the Puppet mechanical structure, including fixtures and interface brackets, is estimated to be 900 g. The construction of the Puppet is a mechanical engineering task, and thus the science experiment teams will need mechanical engineering support for the design, production and integration of the Puppet, similar to the division of responsibilities for the construction of the Ørsted boom Gondola. The thermal modelling of the Puppet similarly requires an expert team effort.

4.1.2.3 Instrument Calibrations

Instrument level calibrations of the CSC and the OSM magnetometers will be performed at a magnetic observatory, thereby establishing a directly traceable link to the international Earth's magnetic field observatories standard. For the CSC the sensitivities, inter-axes-angles and the offsets will be determined together with their temperature coefficients. For the OSM magnetometer the relation to the international standard and the level of heading errors will be established.

The ASC system cameras will be intrinsically calibrated against real stars at an astronomical observatory having low atmospheric turbulence and excellent astronomical seeing.

At the integrated and fully operational Puppet level, the determination of the interrelation between the ASC camera coordinate systems and the CSC orthogonalized magnetic coordinate system will be performed at a high quality astronomical observatory, where a temporary standard magnetic observatory will be established. This was done at the Table Mountain Observatory of NASA's JPL for the Ørsted, CHAMP and SAC-C satellite. Owing to the large distance between the host satellite body and the Puppet combination, no magnetic coil facility calibration at satellite level is required. The magnetic calibrations and the ASC-CSC intercalibrations will be the responsibility of the science instrumentation teams.

4.1.3 Critical Requirements

The magnetometers are proposed to be removed at least 10 m from the main satellite. Allocating (for the sake of the argument) maximum 1 nT magnetic signature from the satellite, this would allow for about 10 Am^2 magnetic dipole moment in the spacecraft. This should be compared to the allocation for the Ørsted satellite of 1 $Am^{2,}$ and the actually obtained 0.25 Am^2.

The CSC magnetometer and the ASC camera system are omnidirectional, which means that no specific attitude is required for the *swarm*. The ASC performs at full specifications at 1 Hz output rate up to 0.6°/sec rotation rate. At 5.5 Hz output rate the rotation rate may be up to 6°/sec at occasionally degraded accuracy, because the shorter integration time will detect fewer stars.

During in-flight calibrations the OSM sensor null axis should be directed at an angle of more than 10° away from the Earth's field vector for more than 80% of the measurements. This is estimated to be a very relaxed requirement, and it is the same requirement as for Magsat or for SAC-C.

4.1.4 Science Requirements and Implementation

Based on the current level of scientific knowledge of the Earth's geomagnetic field and the capabilities of modern science magnetometry instrumentation, and considering the development in digital processing, the science requirements for the *swarm* mission is stated as:

Resolution:	0.1 nT in each vector component
Absolute accuracy	0.2 nT in scalar magnitude
Absolute attitude	0.5 Arc seconds

The instrument complex errors will consist of the intrinsic instrument noise and errors:

CSC	< 0.5 nT absolute, < 0.1 nT noise per vector component
OSM	< 0.2 nT absolute in the scalar value
ASC	0.5 Arc sec resolution corresponding to 0.12 nT in 50 000 nT 1.2 Arc sec absolute corresponding to < 0.3 nT in 50 000 nT

The Puppet instrumentation perturbation on the OSM sensor is negligible (distance > 2 m). The perturbation on the CSC sensor is estimated to be < 0.5 nT static and < 0.1 nT dynamic based on the experience with the Ørsted and the SAC-C Puppets. The static perturbation will be compensated for in the in-flight calibration.

4.1.4.1 Mass and Power Budgets

Puppet	**Mass**	**Power**
Structure	900 g	-
CSC Sensor	340 g	200 mW
CSC cable and connector	230 g	-
ASC Camera Units	930 g	1800 mW
OSM Front End Electronics	200 g	800 mW
Digital Link	400 g	500 mW
Electronic Power Unit	400 g	500 mW
Total	3400 g	3800 mW
Boom Mounted Sensor		
OSM Sensor	500 g	-
Main Satellite Puppet Support Unit		
CSC Support Electronics	1000 g	1800 mW
ASC Computer	900 g	700 mW
OSM Support Electronics	400 g	600 mW
Digital Link	400 g	500 mW
Total	2700 g	3600 mW

4.1.5 Instruments Heritage and Development Basis

The fluxgate magnetometer has a long flight heritage based on many successful sounding rocket launches, and it is scheduled for launch on the Swedish Astrid-2 satellite on December 10, 1998. The CSC-magnetometer is onboard the Danish Ørsted satellite scheduled to be launched in January 1999; and second generation instruments are in the delivery phase for the German CHAMP mission and the Argentine/US SAC-C mission. For *swarm* the vector magnetometer will be based on the combined Astrid-2/CHAMP experience.

The ASC elements were developed for the Ørsted mission, and are ready for launch. Prior to Ørsted the system was successively flown onboard the “Thunderstorm” NASA sounding rocket mission and on “TeamSat” on the Ariane 502 launch. The system is also ready for flight onboard the Astrid-2 satellite and further, similar systems are under delivery for CHAMP and SAC-C.

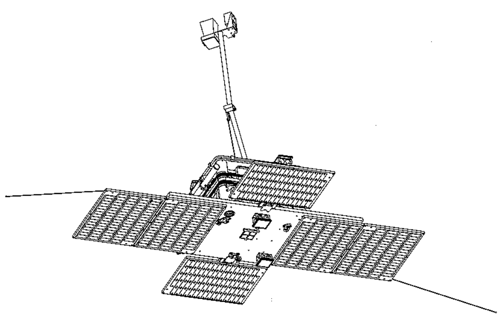
A total of 6 Danish proton magnetometers have performed successfully onboard Danish and NASA research sounding rocket payloads. The scalar magnetometer development continued at the Technical University of Denmark as a graduation project in 1990, and the development of the electron spin resonance polarisation technique, using the Overhauser effect, became the subject for a Ph.D. project, successfully concluded in 1994. Since 1995 the group has been funded for the development of a satellite instrument, all the critical elements have been tested and the operation verified, resulting in a working laboratory model

4.1.6 Technology Challenges and Critical Issues

The mechanical design and construction of the Puppet structure is recognised as a task for an expert group in composite materials. The challenge is similar to the task of building the CHAMP boom optical bench part, and Dornier in Friedrichshafen, Germany has successfully completed that. Based on the experience from the very successful magnetic cleanliness program for the Ørsted satellite, the science instrumentation teams will be responsible for keeping the magnetic budget within the specifications for the Puppet.

4.2 Platform Concept

The Astrid-2 platform, like the experimental forerunner Astrid-1 which was successfully launched and operated 1995, is developed and built by SSC’s Science System division.



The Astrid-2 satellite

Astrid-2 will be launched in the middle of December this year. Astrid is a spin-stabilised, sun-pointing satellite and has the weight of 30 kg. The scientific goals are to explore electric and magnetic fields in the upper ionosphere, and to measure neutral and charged particles and electron density.

Key figures	Astrid-2	*swarm*
Mass (kg)	30.7	41.2
Dimensions (mm)	950*45*40 (stowed configuration)	600*600*600 (stowed configuration)
Payload mass (boom incl) (kg)	8.8	7
Solar panel power (W)	70.5	62.5
Payload power (W)	16.2	11
Downlink data rate (kbps)	132	512
Uplink data rate (kbps)	4.8	4.8
Attitude system	Spinning	Gravity gradient
Altitude (km)	1000	700
Inclination (degrees)	83	82, 88 degrees

4.2.1 *Swarm* Platform Requirements

Item	Requirement
Mass	45 kg
Power	33 W
Inclination	82, 88 degrees
Altitude	700 km
Down link bit rate	512 kbps
Life time	3 years
Stabilisation	Gravity gradient

4.2.2 Heritage/Development Base

This table lists the modifications needed to the Astrid-2 platform

Astrid 2	*swarm*
Structure	Similar basic construction, with some changes in dimensions
Separation system	Same as Astrid-2
ASU (Astrid System Unit)	Same as Astrid-2
RF system	The same as Astrid except for adjustments for using the GSOC ground station
Power	The same design as Astrid 2. Another location of solar panels and preferably more capacity in the battery.
Thermal	New thermal analysis of the system has to be done.
ACS (spinning and sun-pointing, with spin- and precession coil as actuators)	Same as Astrid –2. The sun-sensor has to be adjusted to a non-spinning satellite. The two coils could be used during the acquisition phase.

4.2.4 Mass Budget, Power Budget, Link Budget

***swarm* Mass budget**

Item	Mass (kg)
Astrid system unit	4.25
Mass memory	0.5
TX	1.0
RX	0.7
RF harness etc.	0.4
S-band antennas	0.25
Nutation damper	0.7
Spin and prec. Coil (for the acquisition phase)	1.4
Sun-sensor	0.3
Magnetometer	0.1
Harness	0.5
MLI	0.1
Pyros	0.3
Solar panels	4
Battery	1.8
Structure	5.6
Separation system	1.0
Boom	3.0
Puppet	4.0
GPS	1.4
Balancing mass	3.0
20% margin	6.8
Total	**41.2**

***swarm* Power budget**

Equipment	Power (W)	Duty cycle	Normal mode (W)
Astrid system unit	3.5	1	3.5
DC/DC	1	1	1
TX S-band	33	0.2	6.6
RX	7	0.2	1.4
Sun-sensor	0.3	1	0.3
Magnetometer	0.4	1	0.4
Heater	7.5	0.5	3.75
GPS	5.0	1	5.0
Puppet	11	1	11
Boom			
Total	**68.7**		**32.95**

Link Budget

The *swarm* S-Band Telecommand/Telemetry (TM/TC) link budgets are shown in the following table. They are based on the performance figures of the Astrid-2 Communications Unit and the GSOC 4 m Ground Station in Weilheim (47.88° N, 11.08° E). The budgets include worst case depolarization losses and realistic assumptions of demodulator performance. The modulation formats are 4 kbit/s PCM/PM/PSK with 16 kHz subcarrier on the uplink and 512 kbit/s BPSK modulation on the downlink. The use of forward error correction coding is not foreseen. The budgets show good margins to overcome worst case atmospheric losses down to 5° elevation.

Clear sky propagation conditions

Parameter	Uplink	Downlink	
Carrier frequency:	fu = 2.109	fd = 2.290	GHz
Bit rate	Bu = 4	Bd = 512	kbit/s
Probability of frame loss (design point):	Pfu = $1.0 \cdot 10^{-5}$	Pfd = $1.0 \cdot 10^{-5}$	
Demodulator implementation margin:	Mis = 2.0	Mie = 1.0	dB
Transmitter power (At SSPA output):	Pte = 13.0		dBW
Transmitter power (At RF-connector):		Pts = 7.5	dBW
TX antenna depointing loss:	Adu = 1.0		dB
TX antenna gain: #	Gte = 37.2	Gts = −2.2	dBi
TX antenna diameter:	De = 4.0		m
Transmitter EIRP: #	EIRPe = 48.4	EIRP0s = 3.6	dBW
Free space propagation loss at horizon:	Lp0u = 168.7	Lp0d = 169.4	dB
Worst case propagation losses due to rain, ionospheric scintillation, multipath etc.:	Alu = 2.0	Ald = 2.0	dB
RX antenna depointing loss:		Add = 1.0	dB
RX antenna gain: #	Grs = −2.2	Gre = 37.9	dBi
RX antenna diameter:		De = 4.0	m
System figure of merit, G/T:		GTe = 12.0	dB/K
Target values of Eb/No:	EbtN0u = 13	EbtN0d = 12	dB
Subcarrier frequency:	fscu = 16		kHz
Subcarrier modulation index:	Θcu = 1.2		rad
Margin at horizon:	Mh0u = 19.6	Mh0d = 1.7	dB
Margin at 5 deg elevation:	Mh5u = 21.3	Mh5d = 3.4	dB
Margin at 10 deg elevation:	Mh10u = 23.0	Mh10d = 5.1	dB
Margin at zenith:	Mhzu = 37.7	Mhzd = 19.8	dB
Minimum margin required due to propagation losses:	Alu = 2.0	Ald = 2.0	dB

¤ Conceptually, 3 dB worst case depolarization losses have been associated with the ground station.
The satellite antanna gain and EIRP are given in the direction of the horizon corresponding to squint angle s0. Earth station parameters are given at boresight.

4.2.5 Technical Implementation

Structure

The basic satellite structure consists of two platforms, made of Aluminium honeycomb, connected by four beams. The size of the bottom platforms will be close to 550 * 550 mm and the top platform will have the size of 400 * 400 mm.

The separation system (used in Astrid-1 and Astrid-2) is based on the release of a three-point hook assembly. The height of the separation system is 61 mm. On the satellite side there are only three small hooks, which is easy to accommodate.

The System Unit

All essential platform electronics are located inside one single box called the System Unit, which has the following constituents: power regulators and distribution electronics; on-board computer; telemetry encoder; telecommand decoder; housekeeping data signal conditioner; pyro firing electronics; and attitude determination computer. The grounding system uses a single point ground (SPG) concept whereby currents are prevented from flowing in the structure. Separate grounds are required for power and signal returns. All external electrical units have dedicated DC/DC converters.

Power

The satellite is powered by eight solar panels; four body mounted panels and, possibly, four deployable panels, depending on the height of the final design. The four deployable solar panels will be deployed as soon as possible after separation from the launcher, to ensure enough power for the system. There will also be solar cells on the backside of the deployable solar panels to be able to have power during the initial phase.

There will be one solar string on each panel and to charge the batteries there are additional strings. These can also be used to power the main bus when charging is terminated. Each solar array string is connected to the main bus via a series regulator.

The onboard battery will be of the space-proven Nickel-Cadmium type

TM/TC

The antennas on the *swarm* satellite will be located in the same way as on Astrid-2, i. e. one transmitting and one receiving antenna on the top side and on the bottom side of the satellite. Since *swarm* will be gravity gradient stabilised (Astrid-2 is spinning and is pointing towards the sun) and therefore always pointing towards nadir, the link budget will be better compared to Astrid 2. This is mostly due to the fact that the antennas have higher gain in the angles towards the earth. The receiver and the transmitter are connected to their antennas via coaxial switches.

ACS

There will be one sun-sensor and one magnetometer onboard, which will be used for attitude determination of the satellite. Attitude control, except for the gravity gradient boom, is not required, but it is important to know which side of the satellite is facing the earth. The most critical part of the mission is the deployment of the boom. It is important that the drift rates of the satellite are as low as possible. The spin coil and the precession coil could be used if the spin rates of the satellite, after separation from the launcher, are high.

4.3 Satellite Mechanisms

The mechanisms onboard the *swarm* satellite can be divided into two groups:

- mechanisms, necessary for attachment, release and the deployment of the puppet and the Overhauser Scalar Magnetometer (OSM) to distances of 10 m and 8 m, respectively, from the satellite
- mechanisms for the separation of the satellite from the launcher

In the following the possible approaches for these mechanisms will be described, their heritage and development base and their associated technological challenges.

4.3.1 Deployable Boom

The deployable boom has to fulfil the following requirements:

- fixation of the puppet and the OSM during launch and initial acquisition of the S/C
- release and deployment of the puppet and the OSM to 10m and 8m distance, respectively, from the mother S/C
- gravity gradient stabilisation of the whole S/C
- harness for providing the puppet's payload and the OSM with electrical power and data transfer

For realisation of these major functional two different options are considered:

- adoption of a modified Ørsted boom
- flexible cable boom (upwindable)

4.3.1.1 Modification of the Ørsted Boom

The boom was developed especially for the Ørsted magnetometer mission. Therefore it fulfils the magnetic cleanliness requirements. It is divided into two sections. The section nearest the satellite body is 6 m long and holds a package of instruments which interfaces to the outer section of the boom which is 2 m long and holds a second instruments package at the end. The design principle of the boom is illustrated in Fig. 4.6. The boom has three longerons, which are uninterrupted in the length of the boom section. To support the legs, spacers are placed at intervals throughout the boom. Cross-wires are mounted to stiffen the boom when fully deployed.

Longerons and spacers are manufactured by Polycarbonate and Glass. The outside diameter of the mast is 170 millimetres and the weight is 55 grams per meter. During launch the boom is retracted in a canister which is 300 millimetres long. The boom is folded into a canister like a coil spring. Consequently, the Boom is loaded with its own spring force. To control the extension of the Boom a servomotor acts as a brake. The extension rate of the boom is one meter per minute. The boom is a space-qualified design. For the *swarm* mission the design has to be modified to an overall length of 10m. Additional modifications for the accommodation of the boom onboard the Astrid satellite bus may also be needed.

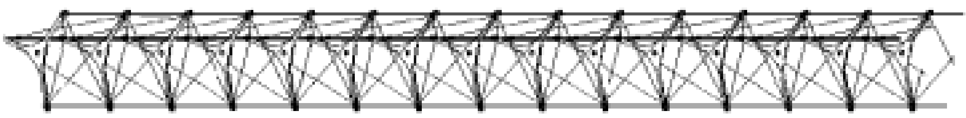


Figure 4.6: *Design principle of the Ørsted Boom*

4.3.1.2 Upwindable Boom

As an alternative to the Ørsted boom another present development can be used for the deployment of the magnetometers. At DLR in Germany CFRP booms have recently been developed, which combine high stiffness with high strength and low density. They can be stored into a small volume during launch. Such a boom consists of two laminated 3-ply sheets, which are bonded at the edges to form a tubular shape. For storage they are pressed flat around a central hub. To deploy the boom a step motor uncoiling the boom from the hub rotates the hub. Once free of the deployment mechanism the boom resumes its original tubular shape with high buckling strength.

A present boom design for the Solar Sail project has a cross section of about 180x100mm and a mass lower than 100g/m. For application in the *swarm* project it is necessary to realise a cross section smaller than 50x50 mm to reduce the aerodynamic drag of the boom. The mass would then be reduced accordingly.

The boom would consist of the following parts: CFRP-boom; hub; hub-drive (step motor); structure for hub with housing; release mechanism for the puppet on the structure; harness for power and data transmission. The envelope of the proposed boom concept would be 300∗200∗200 mm. The expected mass is 3 kg. Presently development models exist for the upwindable boom.

Both of the proposed concepts have their advantages and disadvantages. The feasibility of both concepts has to be studied in more detail during phase A and the favoured design will be selected.

4.3.2 Satellite Dispenser

The mission requires the simultaneous launch of six satellites with one launcher and a dedicated separation of each of the six satellites from the upper stage according to the mission scenario.

The satellite will be stored on a structure, which acts as an interface between the launcher and the satellites. The actual design of this structure depends of the room available under the fairing and on the launch loads. The structure is equipped with six separation systems- one for each satellite- which will hold the satellites during launch.

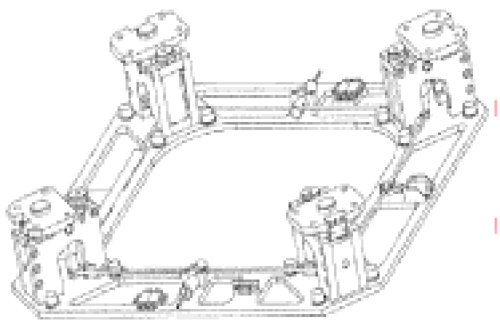


Figure 4.7

It is intended to use the microsatellite separation system developed by Swedish Space Corporation (c.f. Figure 4.7). In this case the satellite is equipped with four small hooks, which are held firmly to the bottom support plate (which is bolted to the dispenser structure) by grappling hooks. The grappling hooks are held by a single tensioned steel cable, which forms a square between the four hook positions. The cable is pretensioned by a spring. At separation the cable is cut by a pyro cutter, the grappling hooks then fold back, leaving the satellite hooks free. The four separation springs accelerate the satellite to about 0.7 m/s. The mechanical I/F to the dispenser structure consists of a square aluminium plate fixed with four M6 bolts. The electrical I/F is a 4-pin connector to the separation pyro.

4.4 Launch Opportunities

The *Rockot* launcher that is now being marketed by Eurockot GmbH, Bremen is selected as the optimum launcher in cost and performance view for the *swarm* Mission. It fully satisfies the mission requirements as discussed in the following chapters.

4.4.1 Rockot Launch Vehicle Description

Rockot is an adaptation of the highly reliable SS-19 ICBM. This SS-19 provides the first two *Rockot* stages and has a flight record of 140 successes out of 143 launches. The complete *Rockot* system has been flight proven three times with a 100 % success rate. In addition to the test flight series, all components have undergone an extensive ground qualification test program.

The third stage, *Breeze* that provides the orbital capability of the launcher is newly manufactured and has successfully demonstrated its capabilities in space. This upper stage contains a modern control / guidance system which controls all three stages. 12 x 16 N attitude control engines control the pitch, roll and yaw of the *Breeze* vehicle. 4 x 400 N verniers, which are located at the base of the Breeze, are for ullage control and orbital manoeuvres. The main engine has a total vacuum thrust of 20 kN and can be restarted up to eight times. All engines use UDMH / N_2O_4 system as propellant.

Rockot ´s launch site, Plesetsk Cosmodrome is an inland launch site located about 200 km south of the port city of Archangel in northern Russia at geographical coordinates 62.7°N and 40.3°E. The location of populated areas dictates the allowable launch azimuths and drop zones available from this launch site and hence influences the payload performance of the Rockot vehicle into the chosen orbits. A direct ascent trajectory to the requested 82° is available with a launch azimuth of 18°. The total payload performance to the orbits with 82° inclination are listed below:

82° Orbit Altitude	**600 km**	**700 km**	**800 km**
***Rockot* Performance**	**1520 kg**	**1480 kg**	**1440 kg**

For a detailed description of *Rockot* and its capabilities, reference is given to „User's Guide for Commercial Launch Services using Rockot Launch System“, Rev. 2, May 1998. It can be requested from Eurockot Launch Services GmbH, P.O. Box 28 61 46, D 28361 Bremen, Fax: +49 421 539 6500, e-Mail: eurockot@ri.dasa.de.

4.4.2 Launch Concept

Accommodation

As shown in Fig. 4.8 six *swarm* satellites each of the dimension (600x600x1090 mm³) can easily be accommodated within the available dynamic payload envelope of *Rockot* in one plane. Unobstructed cylindrical segment of the fairing has extensive height to allow increase of the satellite height for any change in the design of the boom mechanism.

The satellites will be deployed using the SSC separation system qualified for „ASTRID“ satellites. The attachment holes of this system will be adapted to the attachment hole pattern of the Breeze by using an intermediate plate.

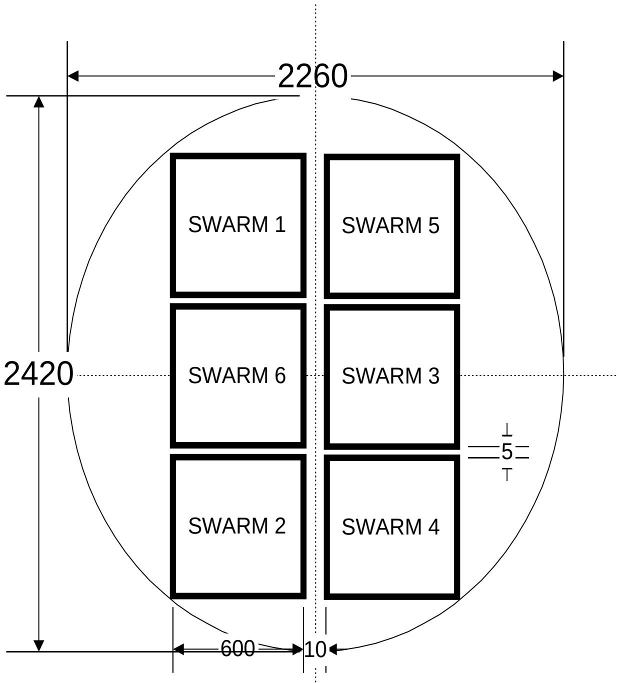


Figure. 4.8 *Arrangement of six swarm satellites in one plane on Rockot*

Mass Budget:

6 Satellites each 45 kg, including 6 x 3.8 kg mass reserve and separation system	270 kg
Intermediate plate (base adapter)	80 kg
Payload System Total	350 kg
Add-on batteries	200 kg
Propellant for plane change maximum 6°	600 kg
Total performance requested	**1150 kg**

versus 1440 kg available to the highest orbit under discussion for the *swarm* mission.

Flight Sequence

A nominal flight sequence of the *Rockot* to a 700 km orbit at 63° inclination is shown in Figs. 4.9. Almost the same sequence will be applicable for the *swarm* Launch with the exception of the launch azimuth. For an 82° inclination an azimuth of 18° is necessary and viable from Plesetsk. Having injected the Breeze with payload in the circularised final orbit at 82° inclination the separation manoeuvre as illustrated in Fig. 4.10 will start:

Step 1: Yaw (pitch is also considerable) Breeze about 12.5° with ACS thrusters, 40 s

Step 2: Release *swarm* 1 with a velocity of 0.3 m/s at an angle of 26.5° (proposal)

Step 3: Stabilise Breeze and hold to avoid contamination, 60 s

Step 4: Reorient Breeze into velocity vector, 45 s

Step 5: Ignition of 4 x 400 N vernier thruster for delta v of 10 m/s, 20 s

Step 6 to 10: Repeat steps 1 to 5 in respective manner to separate *swarm* 2 and 3

Step 11: Prepare Breeze for plane change, approx. 100 s

Step 12: Reignite main engines at the next node for plane change of 6°, approx. 300 sec.

Step 13: Complete plane change at the next node crossing, approx. 300 sec.

Step 14 to 23: Repeat Steps 1 to 10 to deploy *swarm* 4 to *swarm* 6.

All values given in this sequence are rough estimates and require detailed ballistic calculations. The most critical issue during the separation manoeuvre is the change of the centre of gravity after release of each satellite. The projected mass of the satellites, however, is small so that the maximum displacement stays within the allowable range of 30 mm. Due to available mass margins, no other shortcomings are expected for the launch and deployment the *swarm* satellites as requested.

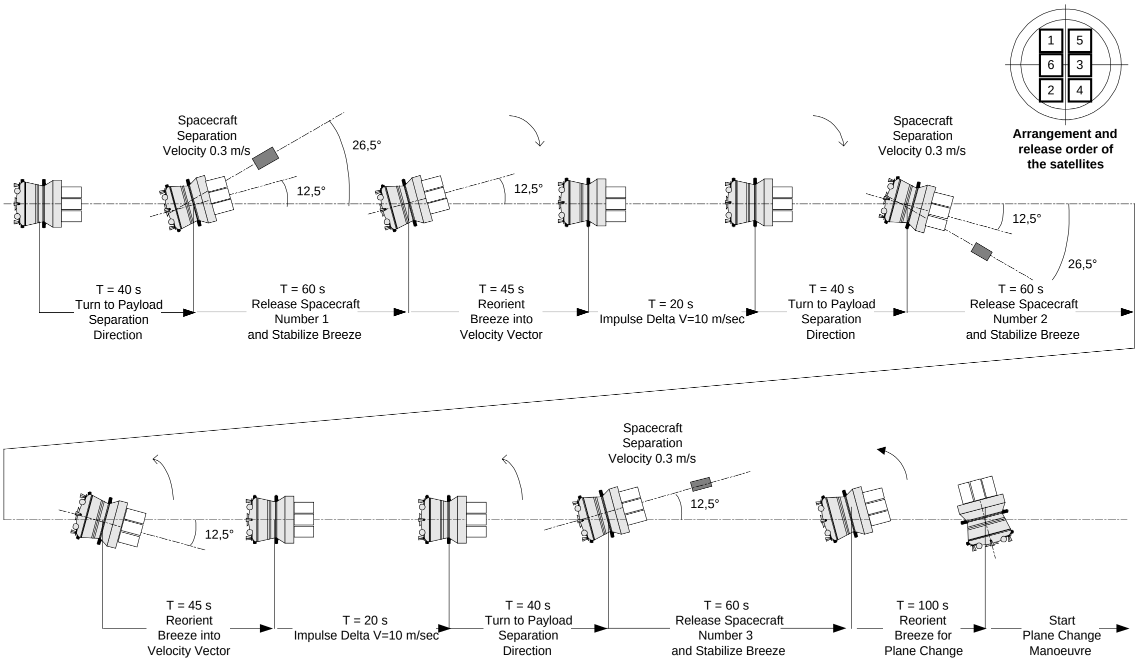


Figure 4.9 *Swarm separation manoeuvre in the first orbit of 82° inclination*

4.5 Reliability

In principle, there will be no redundancy on equipment level or on subsystem level. This will reduce the cost of the satellites. The redundancy will be on satellite level. The six satellites will be placed in two different orbits, 82° and 88° inclination, with three vehicles in each orbit.

Reliability analyses have to be performed to confirm the ability to meet the requirement of three years lifetime for two satellites in each orbit. One other requirement is that one satellite, in total, shall be alive after 5 years. At Swedish Space Corporation, usually Relex is used as the tool for these calculations.

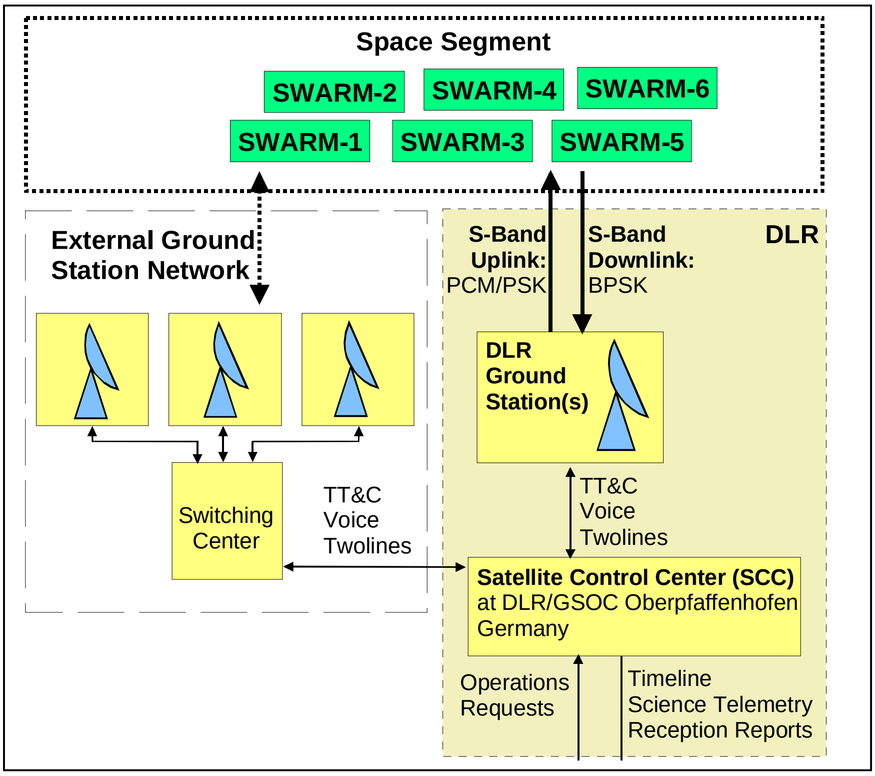
4.6 Ground Segment Implementation

4.6.1 Mission Operations System Overview

The ground segment for control of the six *swarm* satellites consists of one ground station for up- and downlink (TT&C) and a satellite control centre. 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 centre at the German Space Operations

Centre in Oberpfaffenhofen shall have close contact to the Mission Control Centre (GFZ), which is the interface to the scientific community.

4.6.2 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/PM/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

4.6.3 Satellite Control Centre

The Satellite Control Centre is located at Oberpfaffenhofen near Munich. To make use of the standardised software systems of the German Space Operations Centre, 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 centre 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

The Satellite Control Centre will utilise the subsystems:

- Level-0 Data (Science Data) Processing Subsystem
- Housekeeping Telemetry Processing Subsystem
- Telemetry Display System
- Timeline and Sequence of Events Subsystem
- Command Generation Subsystem
- Data Archive Subsystem
- Data Transfer Subsystem
- Voice Communications Subsystem

4.7 Mission Operations Concept

4.7.1 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

4.7.2 Launch and Early Operations

The six *swarm* satellites shall be launched in late 2002. Three satellites shall be injected into 82° inclination orbit with different drifts and the other three into an 88° inclined orbit. Both orbits shall have an altitude of 700 km.

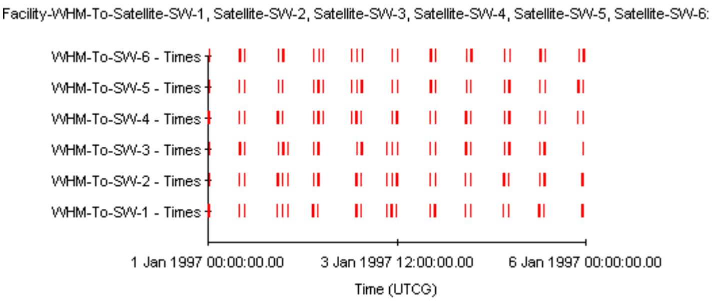
For the initial link acquisition a supporting ground station network has to be utilised. The requirements on the ground station network characteristics depend on the launch vehicle, the communication system, the attitude control, and the onboard activities to be performed after launch. The duration of the launch and early orbit phase is approx.10 days.

4.7.3 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.

4.7.4 Routine Phase

The satellite shall be operated at least 5 years. The maximum time in view above 5° elevation over a ground station is 11.6 minutes. The orbit period will be 98.77 minutes. Each satellite will have 14.6 revolutions around the Earth per day.



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, the simple strategy shall be to have a downlink to each satellite once every 36 hours. The advantage is that only one ground station is necessary for that support in every constellation of the satellites. Once every week an uplink contact shall be established. Shortly after orbit injection all six satellites will be in the visibility zone of one ground station.

From the constraints for the downlink the requirements for the onboard data handling can be derived:

The onboard mass memory shall be capable to store the data of 48 hours (including operational margin). The bit rate of the downlink shall be sufficient to dump the complete buffer in less than 10 minutes (i.e. in one contact).

4.8 Science Operation and Archiving

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

4.8.1 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. No dedicated science campaigns or other operations are involved in the mission.

4.8.2 *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).

4.8.3 *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[16].

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/B of the project. Some thought has been given to this problem in the context of magnetospheric cluster missions[17] and will also apply here.

4.8.4 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.

4.9 Model Philosophy

To reduce cost and schedule a critical re-examination of the classic build and test philosophy should be performed. The classic philosophy of building and testing Breadboard Model - Engineering Model - Qualification Model and Flight Model provides units with minimum risk and is well proven over many years and programs. However, experience gained with prior programs, including Ørsted and the Swedish Freja and Astrid satellites, show that considerable reduction in cost and improvements in schedule can be achieved by restructuring the overall test approach at the subsystem and satellite levels.

Six Flight Models and one complete Flight Spare Model of the *swarm* satellites should be built. Furthermore, enough spare subsystems should be available in case of minor failures on the flight equipment.

Like for the above-mentioned missions the first *swarm* satellites should be built and tested as a protoflight satellite. This means, that one complete satellite unit shall be fully assembled and tested for flight. This protoflight satellite unit shall be tested in accordance with the Environmental System Test Specification, consistent with the launch vehicle protoflight test requirements. The satellite shall be tested to qualification levels for acceptance time. The subsequent six *swarm* satellites should be tested to acceptance levels only.

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

RF Model: This mechanical mock-up aims at defining all the outer dimensions in order to simulate the antenna environment. The mock-up consists of a satellite structure with aluminium side walls, and shall be used to measure the antenna radiation pattern using a radio anechoic chamber.

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

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

Wiring Harness Mock-up: This mechanical mock-up aims at having a satellite structure with all basic dimensions close to the final sizes. The structure shall be complete with cardboard mock-ups of electronic boxes with the correct connector placements. This mock-up shall be used to define and route the wiring harness. It should be noted that this model is very important and that this exercise will likely impose several minor or major changes to the final detailed design.

Modal Survey Test Model: This is a structural model to facilitate static finite element load analysis coupled with a modal survey test. 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.

The modal test unit consists of the mechanical structure mounted with all subsystem units or dummy masses of the subsystem units. The important thing is that the hardware is close to being "flight like". I.e. that the structural and mechanical behaviour is close to the flight equipment. The model shall be used to measure the natural frequencies and modes of the satellite. This exercise can also 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.

Protoflight Model, Flight Model and Flight Spare Model: It is suggested to adopt a protoflight approach to the *swarm* satellite development, i.e. use a protoflight model satellite with verification by environmental testing. This means, that one complete satellite unit is fully assembled and tested. Care shall be taken not to overtest the protoflight unit, and thus risk inadvertent stress/damage to the flight hardware, which would then require costly refurbishment and retest.

The succeeding 5 FM satellites and 1 Flight spare unit should be built and tested to acceptance level.

Satellite Simulator: This can be partially assembled during satellite integration using a combination of engineering models and flight spare models. This unit can be assembled to a point where it will function as a satellite simulator for troubleshooting during ground testing and in-orbit operations. The quality of this simulator will depend on the amount of flight spares available after integration. Where hardware is not available, simple software simulators shall be developed to act as the subsystem.

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. The units shall be made using flight grade parts, materials and processes. 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.

4.9.1 Integration and Test Approach

The verification program for the satellites will cover all needed activities to assure that the design fulfils all specified requirements under all specified operational and environmental conditions. The successful completion of the verification program shall lead to qualification of the design (when required) and the acceptance of the spacecraft flight models.

The Bench Test Model (BTM) is used for tests on unit, subsystem or system level, without working on the satellite itself. It is an electrical model of the spacecraft, i.e. a configuration of unit and subsystem models that represents an electrical model of the S/C. The purpose of the model is to be able to start the electrical tests of the satellite equipment as early as possible. Its configuration evolves as the items mature. It is built up by EMs, QMs, PFMs, FMs, spares or simulators.

The Electrical Ground Support Equipment, EGSE, controls the model. The EGSE supplies power to the BTM model and provides means of communication with the BTM model. The EGSE is also used for all ground-based tests of the satellite.

The tests carried out on the BTM model can roughly be divided into electrical tests, communication tests and functional tests.

The purpose of the electrical tests is to verify the electrical interface and behaviour of the satellite equipment when connected to other equipment of the satellite. The communication tests include verification of the communication of the different equipment with the satellite system unit, and with other units when applicable. The functional tests provide means to verify proper functioning of the different equipment. When all equipment are acceptance tested successfully in the BTM, the integration of the satellite can start. During integration of the subsystems, different types of tests will be performed:

Limited Electrical Performance Test (LEPT). This test will be done on the satellite every time the satellite is powered.

Health Electrical Performance Test (HEPT). This test will be done after transportation or after environmental tests.

Comprehensive Electrical Performance Test (CEPT). This test will test all that can be tested. This test will be done two to three times during the test and verification phase.

The manufacturing of the *swarm* system units will be performed in a matrix organisation, i.e. one person is responsible for two units at each one time, and follows these units through the different phases. Other personnel are responsible for the different parts of the production line process.

The manufacturing of the satellite platforms will be performed in the same manner.

One person will be allocated full-time for configuration management.

5. Mission Elements and Associated Costs

5.1 General

Reuse of experience in the form of a core team, which has experience from former magnetometry missions, 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/E 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 combined phases are proposed Phase A/B and Phase C/D/E.

Phase A/B. Would 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/B is proposed to start primo April 1999 and is expected to be completed by the end of December 1999 (8 months duration)

Phase C/D/E .Will construct the system, both space and ground segment within an integrated team. Because of the high degree of 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 allow 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 (EGSE may be reused as simulator facility). The phase C/D is proposed to start in February 2000 and ends in December 2002 (22 months duration).

5.2 Finance

5.2.1 Assumptions

Following Table 5.1 indicates the possible suppliers of the mission elements.

5.2.2 Cost and Required Funding Profile

The overall cost breakdown and funding profile is shown in table 5-2. 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. The estimated figures are based on solid heritage from the Ørsted, Astrid and Champ programmes and thus have a high level of confidence. The estimated total of 70.3 MEUR ensures a margin of approximately12% to the ultimate financial ceiling of 80 MEUR available for a full realisation of an Earth Explorer Opportunity mission. Considering the large responsibility of the Lead Investigator to ESA and to the participating institutions this seems a reasonable margin to allow for possible uncertanties in the circumstances that may still exist at this preliminary stage. The funding profile assumes a launch in Dec. 2002 using a Eurockot launcher.

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, GeoForschungsZentrum Potsdam,	ESA
	Campaigns	Not Applicable	-
System engineering and assembly integration and test		Swedish Space Corporation	ESA
Space segment	Instrument(s)	Danish Technical University, Danish Space Research Institute	ESA
	Platform	Swedish Space Corporation, RST in Rostock, Germany (boom),	ESA
	Launcher	Eurockot, Germany	ESA
Ground segment facilities	Command and acquisition stations	German Space Operation Center	ESA
	Operations centre	German Space Operation Center	ESA
	Processing and archiving	Champ Science Data Center, GeoForschungsZentrum Potsdam,	ESA
Mission control and data exploitation	Mission Control	German Space Operation Center	ESA
	Data utilization	Danish Space Research Institute	ESA

Table 5-1: *Mission elements and activities: implementation and funding source assumptions*

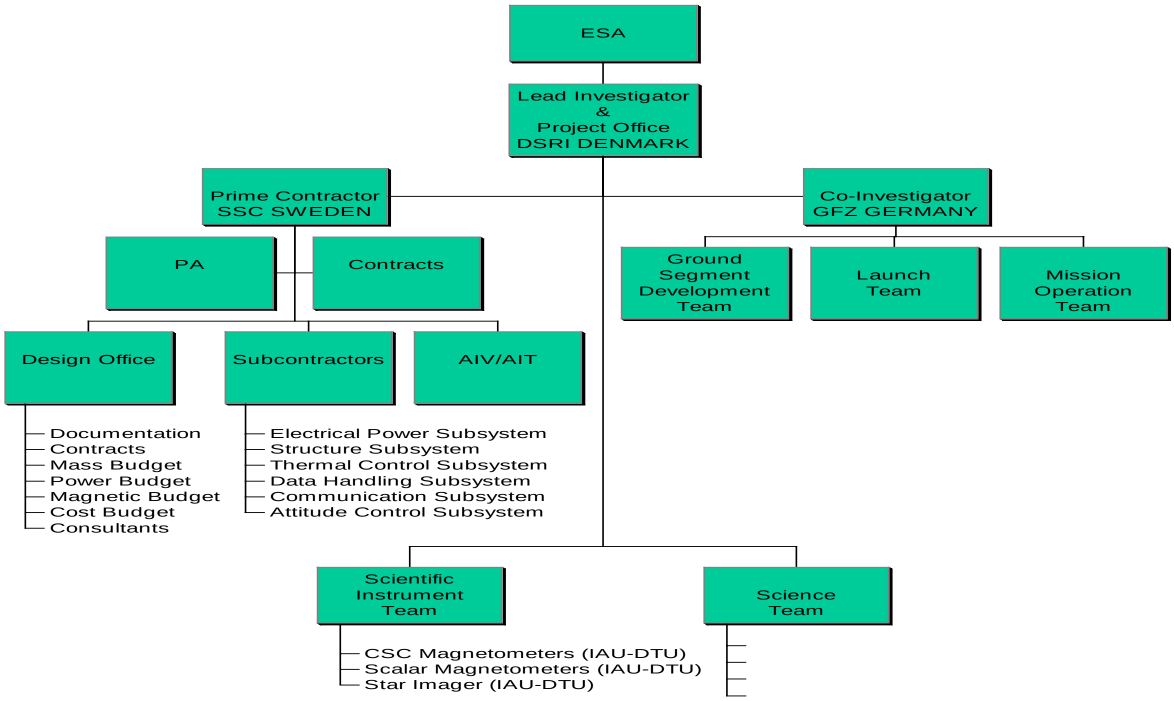
Mission element		Cost estimate 1999-2000	Cost estimate 2001-2002	Cost estimate 2003-	Total cost estimate
		MEUR	MEUR	MEUR	MEUR
Lead Investigator and Project Office		0,50	0,50	0,50	1,50
Science preparation	Scientific definition studies	1,00	1,00	0,00	2,00
	Campaigns	0,00	0,00	0,00	0,00
System Engineering and AIT/AIV		1,50	3,50	0,00	5,00
Space Segment	Instruments	4,50	3,20	0,80	8,50
	Platform	10,00	13,00	0,00	23,00
	Launcher	0,00	12,10	0,00	12,10
Ground segment facilities	Operations centre incl. command & data acquisition	2,40	3,60	8,20	14,20
	Processing and archiving		0,20	0,80	1,00
Mission control and data exploitation	Mission control		0,20	0,80	1,00
	Data utilization		0,40	1,60	2,00
Total		**19,90**	**37,70**	**12,70**	**70,30**

Table 5-2: *Overall Cost Breakdown and Funding Profile*

6.0 Implementation

6.1 Project Organisation

Organizationally the structure shown below is proposed which emphasizes 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, namely Swedish Space Corporation, SSC, who is proposed to be the Prime Contracter on the satellite platform, and GeoForschungsZentrum Potsdam, GFZ, who will take care of the launch team and the ground segment including mission operations and archiving. The science payload and analysis will be coordinated from 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 and SAC-C, Astrid-1 and -2, and the CHAMP mission, respectively.

6.2 Management Approach

This section describes the management and development approach for the *swarm* mission. The discussions have been based on the experiences from the Ørsted project, the Swedish Freja mission and on the Astrid 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.

6.2.1 Engineering Approach and Methodology

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 the Ørsted satellite 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 cognizant 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 verbalized 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 CDR's. 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 minimized 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 six small satellites are to be built only one CDR should be held during the mission design phase.

6.2.2 Design Guidelines

The following brief list of design guidelines and policies summarizes 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. Derating of parts should be in accordance with [pss-01-301].
- Test the hardware design and interfaces whenever possible, provided that the test is quick, easy, and dirt-cheap. 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 reduce the cost of ground support, and the utilization of valuable labor resources, and to minimize ground-to-space contact and command-and-control complexity
- Use cost effective systems which still meet mission goals and graceful degradation instead of full systems redundancy.
- 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.
- Adhere to local quality assurance (PA) standards and procedures as much as possible, to ensure familiarity and prevent retraining of PA personnel.
- Use common software for satellite ground testing and control center operation, as much as feasible, by using the same software platform/database and co-location of the involved software and operation engineers.

6.2.3 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 minimized to the extent feasible, keeping in mind that some level of duplication is necessary for clarity.

High-level specifications initially developed during Phase A/B should be contained in a Project Document Book, and distributed to everybody working on the project. Interface control documents, 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 organization 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.

6.2.4 Parts and Materials Selection

The project shall maintain a list of preferred flight parts and materials including, but not limited to, [PSS-01-603], throughout the subsystem design and fabrication phase. The lists serve as a baseline in the component and material selection process. Use of other components and materials shall be justified individually, assessing the effect on the overall satellite performance and reliability. Special tests and/or analysis may be required to justify the use of non-listed parts and materials. A complete list of all parts and materials within each subsystem is maintained by each subsystem.

Usually the parts and materials form a significant part of the cost on a normal ESA project. In order to keep the cost at a reasonable level, the selection of materials and parts should be based on previous experience, ensuring that the parts and materials will survive the thermal, vibration and radiation environments, which they will be exposed to. The parts and materials used shall not necessarily, be formally space qualified, but shall fulfil the outgassing requirements set by ESA. Other means such as military standards are sufficient to qualify the items.

6.2.5 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.
- Minimize/eliminate special hardware performance and test requirements and buy off-the-shelf equipment whenever feasible.
- Minimize/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.

Annex A: Scientific Team

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***Eigil Friis-Christensen* (efc@dsri.dk, 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, planned for launch in January 1999. He was leading the Danish research and instrument teams and established an International Science team consisting of more than 50 research groups from 14 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 Program, 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, 1995 and was elected Associate of the Royal Astronomical Society, London, in 1996. He was a member of the ESA Solar System Working Group 1995 to 1997, of ESA's Earth Explorer Surface and Geophysics Peer Group, 1996, of ESA's Explorer Magnetometry Mission Working Group, 1996, and he joined ESA's Science Programme Committee, SPC, in 1998.

Therese Moretto (moretto@dsri.dk), D.Phil., University of Oxford, 1993. Senior Scientist at the Danish Space Research Institute, working on magnetospheric and ionospheric current systems. Co-Investigator on The Danish Geomagnetic Mapping Ørsted Mission and on the Swedish Astrid-2 Satellite. International representative on the Geospace Environmental Modeling steering committee. Author of several papers in refereed journals.

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Fritz Primdahl (fp@iau.dtu.dk), M.Sc. EE. and Physics, Technical University of Denmark, 1964. Currently Senior Scientist at DSRI and DTU, working with space magnetometry instrumentation. Co-Investigator on FREJA and Cluster, PI for the magnetometer on the Danish Geomagnetic Mapping Ørsted Mission, coordinator for the magnetic experiments onboard Astrid-2 and CHAMP satellites and for the MMP on the SAC-C Mission. Has participated in a large number of magnetometer experiments on NASA and Scandinavian suborbital sounding rocket missions, and has published over 60 papers on space plasma physics and magnetometers.

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Gauthier Hulot (gh@ipgp.jussieu.fr), Ph.D. in Geophysics, Université Denis Diderot (Paris 7), 1992. Assistant Professor in Geophysics at the Ecole Polytechnique (Palaiseau) and Senior Scientist at the CNRS within the Laboratoire de Géomagnétisme of IPGP, where his main interests are the modelling and the interpretation of the main field. His work involves contributions to potential theory, to the understanding of the dynamics of the core (mapping of the core flows at the Core-Mantle Boundary, Core-Mantle Interactions) and to the characterization of the behaviour of the main field at all time scales (From Jerks, to archeomagnetism and paleomagnetism). He is PI of an Oersted Proposal, and leads an INTAS/CNES project on the future of magnetic satellite missions. Author of 25 articles in Geomagnetism.

Jean-Louis Le Mouël (lemoue@ipgp.jussieu.fr), Director of IPGP, Director of the french magnetic observatories, former president of the international group for study of the Earth deep interior (SEDI, 1993-1995), member of the executive committee of the INTERMAGNET programme (International magnetic observatory network), Chairman of the scientific programme committee of CNES, Chairman of the “Bureau des Longitudes”, member of the French Académie des Sciences, member of Academia Europea, associate member of the Royal Astronomical Society, corresponding member of the International Academy of Astronautics. His has made major contributions in all aspects of Geomagnetism: Aeromagnetic maps, main field modelling, core flow at the CMB, Core-Mantle Interactions, dynamo theory, potential theory. He was recently awarded the John Fleming Medal of AGU for recognition of his work in Geomagnetism.

Mioara Alexandrescu (mioara@ipgp.jussieu.fr) is currently Head of the French National Magnetic Observatory of Chambon-la-Foret. She received her state thesis at University of Bucharest in 1993 and her thesis at IPGP in 1996, both dealing with main geomagnetic field and secular variation. She has more than 10 years experience in observing and analysing the geomagnetic field. Her research currently deals with main field and secular variation analysis and modelling, with particular interest to geomagnetic jerks studies using new mathematical tools, such as the wavelet technique. She is the author of more than 15 refereed publications.

Pascale Ultre (ultre@ipgp.jussieu.fr) Post-doc with CNES at IPGP, Main research in geomagnetic field modelling, separation of internal and external sources of the field, reduction of the Backus Effect. Author of 5 refereed articles.

University of Brest
UMR ' Domaines Oceaniques '
Place Nicolas Copernic
F-29280 Plouzane

Pascal Tarits (tarits@univ-brest.fr). State Thesis in Geophysics, 1989 IPG Paris. Chairman of the Department of Marine Geology and Geophysics at the Institute Universitaire Europeen de la Mer (IUEM) at UBO vice-chairman of the IUEM Current research: electromagnetic studies of the earth mantle by mean of long period electromagnetic data from seafloor magnetotelluric stations, from land observatories and satellite magnetic data. Also applicatiom of electromagnetic imaging to environmental problems (water ressources, pollution). Development of forward and inverse techniques for EM modelling Co-I of the Ørsted Mission. PI of AMPÈRE french satellite mission Co-I on Mars exploration.

Jerome Dyment (jerome@univ-brest.fr) PhD in Marine Geophysics, Univ. Strasbourg, 1991. Post Doc at Lamont Doherty Geological Observatory and at McGill University, Montreal, 1992-1994. CNRS Researcher position in Brest since 1993. Research interests: Marine magnetic anomalies, satellite magnetic anomalies, structure and properties of the oceanic lithosphere, mid-ocean ridge processes.

Centre d'Etude des Environments Terrestre et Planetaires, CEPT
4 Avenue de Neptune,
94107 Saint Maur des Fosses Cedex

Michel Menvielle (michel.menvielle@cetp.ipsl.fr) Professor at the Université Paris Sud. He received his state Thesis at IPGP in 1984 on electromagnetic induction. His work deals with (1) the study and characterisation of the transient magnetic activity of external origin, (2) the application to planetary exploration of magnetic and electromagnetic techniques developed in the case of the Earth, PI of the magnetic portion of the OPTIMISM/Mars'96 experiment and participatant in the Netlander project of a network of stations at the surface of Mars, as Co-PI of the magnetometer experiment. He is Participating Scientist on the MAG/ER experiment on Mars Global Surveyor 1. In the frame of the Oersted program, he is in charge of providing longitude sector geomagnetic activity indices. He is the author of more than 50 refereed publications.

UNITED KINGDOM:

British Geological Survey
Global Seismology and Geomagnetism Group
Murchison House
West Mains Road
Edinburgh EH9 3LA, Scotland

David R Barraclough (d.barraclough@bgs.ac.uk) D.Sc. Co-investigator, Magsat; member of Magnetometry Working Group, ESA's ARISTOTELES Project; member of Ørsted International Science Team and Oersted Science Advisory Committee; member of ESA's Explorer Magnetometry Mission Working Group; involved in global modelling of the geomagnetic main field and its secular variation since 1969.

Toby D. G. Clark (t.clark@bgs.ac.uk) Ph.D. Member of Ørsted International Science Team. With BGS since 1990. Has worked with POGS data. Primary interest: external geomagnetic field.

David J Kerridge (d.kerridge@bgs.ac.uk) Ph.D. Phone number: +44 131 650 0220 e-mail address: With BGS since 1983. Has worked with Magsat data. Member of Oersted International Science Team. Group Manager, Global Seismology & Geomagnetism Group.

Susan Macmillan (s.macmillan@bgs.ac.uk) Ph.D. With BGS since 1989. Has worked with Magsat and POGS data. Member of Oersted International Science Team. Primary interests: global modelling of the main geomagnetic field and its secular variation; modelling the crustal anomaly field.

Alan W. P. Thomson (a.thomson@bgs.ac.uk) Ph.D.With BGS since 1991. Has worked with Magsat & POGS data. Primary interests: external geomagnetic field; global main-field modelling.

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

Andrew Jackson (jackson@earth.leeds.ac.uk) Ph.D. University of Cambridge, 1989.Royal Society University Research Fellow. Member of Ørsted International Science Team. Geomagnetic interests focus on historical secular variation (from c.1500), crustal magnetism, retrieval of core fluid flow and its implications for Earth rotation. Other research interests in fluid mechanics and geophysical inverse theory.

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 Modeling steering committee. Author or co-author of over 80 refereed publications corning the solar wind, magnetosphere ionosphere and thermosphere.

SWEDEN:

Kungliga Tekniska Högskolan
Alfvén Laboratory,
Valhallavägen 79
100 44 Stockholm

Göran T. Marklund (marklund@plasma.kth.se), Ph.D. Plasma Physics, Royal Institute of Technology, Stockholm, 1983. Currently Professor of Space Plasma Physics at the Alfvén Laboratory of the Royal Institute of Technology. Principal Investigator of the Freja and Viking double probe electric field experiments, Project Scientist for the Astrid-2 micro satellite, Co-Investigator of the double probe electric field experiments onboard the Cluster and Polar satellites and on the proposed NASA/MIDEX mission Auroral Lites. Co-Investigator on the proposed Langmuir probe experiment on Mars Express. Project reponsible for the double probe electric field experiments on 7 sounding rocket experiments. Author or co-author of 90 scientific publications.

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.

ITALY:

Istituto nazionale geofisica (ING)
V. Vigne Murata 605
Roma 00143

Angelo De Santis (desantis@ing750.ingrm.it) PhD. in Physics, Rome University,1984. Researcher (1987) and First Scientist (1991) at the Istituto Nazionale Geofisica. Main interests: mathematical models in Geomagnetism and Aeronomy; studies of the inner crust and upper mantle conductivity structure; investigations in magnetometry and riometry. Obtained a Royal Society Grant (5 months, 1987) at British Geological Survey. Member of the Scientific Committee of ING; Vice-Responsible for the Space Weather Project; Member of PNRA (Italian National Project of Research in Antarctica, 1996-1999); Participated in several Italian antarctic expeditions, Responsible Projects: Riometry, PNRA (1993-96), and "Mathematical models of the Geomagnetic Field in Europe", Italy-Spain Bilateral Protocol, (1994-96); Temporary Professor (Lecce, 1996; Bologna, 1997). He is author of about 90 scientific papers (50 intern.).

SPAIN:

Observatori de l’Ebre
Horta Alta, 38,
43520 Roquetes

Joan M. Torta (ebre.jmtorta@readysoft.es) Researcher at Observatori de l'Ebre. PhD. in Physics, University of Barcelona, 1991. His main expertise is on global and regional analyses of the geomagnetic field, including main and crustal field, studies on secular variation and on variations of external origin; as well as on by-products of those analyses, as the dynamics of the upper atmosphere and the earth's electrical conductivity. Observatory practice and magnetic studies on volcanoes are also of his interest. He is author or co-author of 36 scientific papers.

Annex B: Technical Team

Swedish Space Corporation (SSC)
Albygatan 107
P O Box 4207
S-171 04 Solna
(www.ssc.se)

The Swedish Space Corporation (SSC) is a government-owned limited company with activities covering the entire range of space-related work from feasibility studies to operational applications of space technology. Systems engineering and management are the major activities of the company, but SSC also designs and develops high-technology hardware and software in-house, especially for use in space vehicles and in satellite ground stations. SSC's experience in space technology goes back to 1961. In 1997 the company had a total turnover of 286 million Swedish Crowns (about 36 MUSD) and 358 employees. The Science Systems Division is located in Solna, Sweden and designs and build systems and subsystems for space research and other space projects. The largest customers are the Swedish National Space Board and ESA.

The principal business areas of SSC are design and development of small satellites, sounding rocket and balloon systems for space and application, the technical implementation of Sweden's space and remote sensing programmes; and the system management and engineering for complex high-technology projects. This includes overall project responsibility for the Viking, Freja and Astrid scientific satellite projects, for the national Tele-X (Direct Broadcasting and Business Communications) programme, and commercialization of telecommunications services on the Tele-X and Sirius satellites.

The Space Systems Engineering and Management Support comprising feasibility studies, systems engineering and specification, technical project management, procurement assistance, design, manufacture and test of equipment, commissioning including launch, positioning and in-orbit test and acceptance and applications and market studies for communications and scientific satellite systems, satellite launch services, satellite control systems as well as for sounding rockets and microgravity.

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 Research. 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 producing flight hardware for the Russian Spectrum Röntgen Gamma (X-ray telescopes and detectors) and 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 has recently been asked to host and manage 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. This experiment will be followed by a project that is going to be selected in the spring of 1999. Eight experiments were proposed and after the first screening, four candidates are remaining for final selection. The Small Satellite Programme Office at DSRI works closely together with the Danish Research Councils regarding the technical issues that must be considered in the selection process.

Danish Technical University (DTU/IAU)
Institute of Automation
Building 327
DK-2800 Lyngby
(www.iau.dtu.dk)

The Department of Automation is a part of the Technical University of Denmark (DTU) in the sector concerning Communications, Computer Science, and Mathematics. The Department works in a number of research areas relating to industrial automation. The teaching and research areas of the department are control engineering and instrumentation. 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 instrumention and control. The space instrumentation group has delivered top-class scientific instruments to a large number of international rocket and satellite eksperiments, including the Astrid-2, Ørsted, SAC-C, and CHAMP 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 (Bodenstation) 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
Att.: Tuncer Miski
P.O. Box 28 61 46
Hünefeldstraße 1-5
D-28 199 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.

RST Rostock Raumfahrt und Umweltschutz GmbH
Richard-Wagner-Strasse 31
D-18119 Warnemünde
(www.rst-rostock.de)

RST, a subsidiary of Daimler-Benz Aerospace AG, Munich, has 20 years of experience in system engineering and system development. Today the staff comprises about 60 people engaged in various space services including subsystems and components, software systems and sensor systems. Beside the space market RST concentrates in all these areeas on technology transfer for terrestrial applications.

Annex C - Letters of Endorsement

Agencies:
Centre National D'Etudes Spatiales (CNES)
National Aeronautics and Space Administration (NASA)
International Association of Geomagnetism and Aeronomy (IAGA)
United States Department of Commerce, National Oceanic and Atmospheric Adm. (NOAA)
Swedish National Space Board
World Data Center A for Solar-Terrestrial Physics (Boulder/CO, USA)
World Data Center A for Solid Earth Geophysics (Boulder/CO, USA)

Institutions directly involved:
GeoForschungsZentrum Potsdam (GFZ)
Université de Bretagne Occidentale
University of Leeds
Observatori de l'Ebre
Royal Institute of Technology (KTH)
Istituto Nazionale Geofisica (ING)
Institut de Physique du Globe (IPGP)
Danish Meteorological Institute (DMI)
Danish Technical University (DTU)
The following Letters of Endorsement are sent directly to ESA:
British Geological Survey, Edinburgh
Centre d'Etude des Environments Terrestre et Planetaires (CETP)
Swedish Space Corporation (SSC)
University of Copenhagen (KU, NBI)
British Antarctic Survey (BAS)
Rostock RST

Institutions with scientific interest:
NASA Goddard Space Flight Center
National Center for Atmospheric Research High Altitude Observatory (HAO)
Technische Universität Braunschweig
Universität Göttingen

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cnes

Paris, November 27, 1998
ref DP/EOT 98.224 JLC/JLC

DIRECTION DES PROGRAMMES

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

Dear Dr Friis-Christensen,

Dr Pascal Tarits from UBO has informed CNES that you are preparing a proposal called "SWARM" based on seven geomagnetic satellites in response to ESA's "Call for Earth Explorer Opportunity missions

As you know, the French scientific community has been involved for many years in the definition and implementation of space missions devoted to the Earth magnetic field monitoring and several French laboratories such UBO, IPG and CETP are associated to the SWARM initiative.

In the framework of the prospective seminar organised by CNES in March 98, a proposal, entitled AMPERE has been submitted (leader P. Tarits) that has been recognised as a possible candidate mission to pursue the monitoring of the magnetic field after the already decided missions Oersted, CHAMP and SAC-C. As AMPERE was proposed in the 2004/2006 timeframe, it has not been selected as one of the two first missions of the CNES « micro-satellite program » planned for launch in 2001/2. Nevertheless, performing a long-term monitoring of the Earth magnetic field through a series of satellites remains a priority of the French Earth Sciences community.

I am confident that the SWARM proposal is capable to ensure the continuity of high quality geomagnetic data acquisition initiated with Oersted and that its original concept of measuring simultaneously from a number of micro-satellites will be a major contribution to the decorrelation of the spatial and temporal variations of the Earth magnetic field.

Sincerely,

JEAN-LOUIS FELLOUS

ASSISTANT DIRECTOR
EARTH SCIENCES AND APPLICATIONS

CENTRE NATIONAL D'ETUDES SPATIALES
AGENCE FRANÇAISE DE L'ESPACE
Siège
2 place Maurice Quentin - 75039 Paris Cedex 01
Tél. : (1) 44 76 75 00 / Téléfax 44 76 76 76 / Télex 214674
SIRET 775 665 912 00082
Centre de Toulouse
18, avenue Edouard Belin - 31055 Toulouse Cedex
Tél. : 61 27 31 31 / Téléfax : 61 27 31 79 / Télex : 531081
SIRET 775 665 912 00033
RCS PARIS B 775 665 912 - CODE APE 731 Z - N° d'identification TVA : FR 49 775 665 912

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

y to Attn of: YO

November 24, 1998

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

Dear Eigil:

I am writing as NASA Program Scientist for Geodynamics and Geopotential Fields to endorse your proposal for SWARM, a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field. The selection of the SWARM proposal would allow continued cooperation between NASA and Denmark in the area of geomagnetism. Denmark's leadership has already made a substantial contribution to the NASA and US geomagnetic science communities, and this proposal is clearly important in continuing that tradition.

In our space mission planning efforts over the past six months, the need for international partnerships in earth observations has been an important theme. Magnetic field studies, in particular, have been recognized within the Office of Earth Sciences as important candidates for such partnerships. Thus, the NASA geopotential fields program will support scientific collaboration of US Scientists with the SWARM mission, using competitive proposals, just as for the Oersted mission over the past several years. There may be possibilities for other forms of NASA cooperation in the planning and execution of the SWARM mission, as well.

The SWARM multi-satellite constellation will provide the key space-time sampling needed to separate the various contributors to the magnetic field, and will be an important step forward in understanding both terrestrial and space sources of the magnetic field. I wish you success in your efforts to obtain this important set of measurements.

With best regards,

Clark R. Wilson
Program Scientist for Geodynamics and Geopotential Fields

cc: IY/ Herberger

** TOTAL PAGE.02 **

98-11-27; 7:09PM;東京大学(理)地球惑星 ;03-3818-3247 # 1/ 1

Department of Earth and Planetary Physics, University of Tokyo
Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan
fax: +81-3-3818-3247 tel: +81-3-5802-2738 (direct) email: mkono@geoph.s.u-tokyo.ac.jp

27 November 1998

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

Dear Eigil,

I gather that you are going to propose a "swarm" of seven geomagnetic satellites to ESA with the main aims of observing the magnetic field simultaneously at different points in space – i.e. to address the space-time aliasing problem. In addition, the possibility of long term measurements in space is also sought by this mission.

This is quite interesting mission to the space science as well as the study of geomagnetism, and I would like to express the support for this proposal. Such a mission will be quite useful in understanding various sources which contribute to the near-Earth magnetic field, particularly for the determination of the dynamics of the external sources, which both acts as a source of noise for the determination of the main field and is an important parameter of the Earth space environment. The mission will also provide important data to determine the secular and solar cycle variations of the geomagnetic field.

Although we did not have time to discuss such project in International Association of Geomagnetism and Aeronomy (IAGA), I am sure that IAGA scientists will benefit from this mission, if the measurement data are made public.

Sincerely yours,

Masaru Kono
Professor of Geophysics
(also President of IAGA)

CC:
JoAnn Joselyn Secretary-General, IAGA

NOV 24 '98 11:03AM P.2/2

UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories
325 Broadway
Boulder, Colorado 80303-3328

November 24, 1998

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. SWARM's data will fill a void in our understanding of one of Earth's basic physical properties. In addition, your innovative concept of an armada of microsatellites and instrumentation on a flexible cable is of interest in itself.

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,

Ernest Hildner

Ernest Hildner, Director
Space Environment Center

cc: ESTEC

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RYMDSTYRELSEN
Swedish National Space Board

November 30, 1998

Our ref:
255/98

ENDORSEMENT

" SWARM – A Small Multi-Satellite Mission to Observe the Dynamics of the Earth's Magnetic Field "

In the response to the ESA Announcement of Earth Explorer Opportunity Mission for the Living Planet Program a proposal **SWARM** is submitted by Dr E Friis-Christensen from the Danish Space Research Institute, Copenhagen, Denmark.

The Swedish National Space Board (SNSB) has received a description of the proposed **SWARM** project, which aims at a new mission to investigate features of the geomagnetic field, especially concerning its dynamics. It is a multisatellite mission using micro or even nano satellite technology.

The Swedish National Space Board endorses the **SWARM** proposal. However, a final commitment, should the proposal be selected, is subject to the availability of appropiate funds.

Sincerely yours,

Per Tegnér
Director General

Postadress Box 4006, S-171 04 SOLNA | Besöksadress Albygatan 107, 7 tr, Solna | Telefon 08-627 64 80 | Telefax 08-627 50 14 | E-mail rymdstyrelsen@snsb.se

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

TELEPHONE: (303) 497-6324
TELEX: 592811 NOAA MASC BDR
IN REPLY REFER TO:

December 1, 1998

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 a number of space-based magnetometers. Your effort to separate the magnetic contributions from each of four components is to be commended, i.e., the main field, lithospheric fields, fields from external currents, and fields from induced mantle currents. I would like to focus my scientific comments on the external current, or solar-terrestrial, component.

As you know, the space community in the USA is embarked on a National Space Weather Program (NSWP). The NSWP program seeks to significantly improve space weather specification, climatologies and forecasts; especially those events that effect technology in space and on the ground. The NSWP has logically focused on the development of robust and accurate physical models that describe in space and time the space environment from the sun to the Earth. This extremely large volume of electrically charged space has with very few observations. As a result all models are "data starved", so we must take full advantage of remote sensing technology, especially measurements of the ambient magnetic field, from as many satellites as possible. From the US scientific perspective, data from the "SWARM" program are desperately needed and would be of great value to the NSWP.

A review should also include an evaluation of the Principle Investigators. It is with great pleasure that I highly recommend the "Swarm" program proposed by Dr. Friis-Christensen and DSRI. Over the past 25 years, we have used a great deal of their data in our models, tested the information content of their data against that from all other sources worldwide, and found it to always be of the absolute best quality. Without reservation, I recommend this proposal by Dr. Friis-Christensen and DSRI.

We look forward to the opportunity to use your very valuable data.

Sincerely,

Herbert W. Kroehl

Herbert W. Kroehl, Director

WORLD DATA CENTER A

BOULDER CENTERS

SOLAR-TERRESTRIAL PHYSICS
(303) 497-6324

SOLID EARTH GEOPHYSICS
(303) 497-6521

National Geophysical Data Center
National Oceanic and Atmospheric Administration
325 Broadway, E/GC
Boulder, Colorado 80303-3328 U.S.A.
TELEX: 592811 NOAA MASC BDR

MARINE GEOLOGY AND GEOPHYSICS
(303) 497-6487

GLACIOLOGY (SNOW AND ICE)
(303) 492-5171

November 30, 1998

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

Dear Dr Friis-Christensen:

It was with pleasure I read your SWARM proposal to the European Space Agency's "Call for Earth Explorer Opportunity Missions". I say pleasure because you are encompassing in one proposal a method for substantially extending our understanding of Earth's magnetic field and, most importantly, the separation of the magnetic field contributions. The proposal was written with the clear style and strong scientific understanding I have come to expect from any endeavor with which you are associated.

The data from this proposed mission would greatly improve the accuracy of the International Geomagnetic Reference Field (IGRF). By providing data from multiple satellites at the same time, we will finally have an opportunity to separate the various contributions to Earth's magnetic field. We will also have the ability to accurately model the intermediate wave-lengths. This will greatly effect the accuracy and change in a material way the resultant models.

I fully support the DRSI's proposal and look forward to helping with the dissemination of data resulting from the mission.

Sincerely,

Allen M Hittelman
Director, World Data Center-A for Solid Earth Geophysics

30/11/98 11:15 GFZ POTSDAM TELEGRAFENBERG → +4535362475 NUM082 P02

GeoForschungsZentrum Potsdam

Stiftung des öffentlichen Rechts

Vorstand

The Earth Science Division(VR)
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NL-2200 AG Noordwijk ZH
Niederlande

Telegrafenberg, Haus G
D-14473 Potsdam
Germany

Phone:(+49) 331 288 1000
Fax: (+49) 331 288 1002

Potsdam, Nov 26, 1998

Subject: **Proposal of a magnetic field mission SWARM**
Reference: ESA's call for Earth Explorer Opportunity Missions

Dear Sirs,

we are pleased to announce our participation in the proposal "SWARM, a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field" 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 help to better separate the contributions from various magnetic field sources and shed light on the wide spectrum of their variations. We are prepared to take over an appreciable part in the scientific data interpretation.

Prof. Dr. Rolf Emmermann
Executive Scientific Director

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

iuem
INSTITUT UNIVERSITAIRE EUROPEEN DE LA MER
UNIVERSITE DE BRETAGNE OCCIDENTALE

Brest le 26/11/98

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" based on seven geomagnetic satellites 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. Dr 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
Director

INSTITUT UNIVERSITAIRE EUROPÉEN DE LA MER - UNIVERSITÉ DE BRETAGNE OCCIDENTALE
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27-NOV-1998 10:45 FROM EARTH SCIENCES LEEDS TO 9004535362475 P.02

UNIVERSITY OF LEEDS

From the School of Earth Sciences
Head of Resource Centre Professor Bruce W D Yardley

University of Leeds
Leeds LS2 9JT

Direct line +44 (0) 113 233 5200
Fax +44 (0) 113 233 5201
Departmental Fax +44 (0) 113 233 5259
E-mail: b.yardley@earth.leeds.ac.uk

25 November 1998

Re: SWARM, a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field

The Department of Earth Sciences at the University of Leeds enthusiastically endorses the proposed SWARM mission, designed for investigation of the Earth's magnetic field. We consider that this mission represents a well-planned experiment which is operating in a innovative configuration, using state-of-the-art microsatellite technology. As such it presents the opportunity to address many questions of interest to this department, within the fields of deep-earth geophysics and crustal magnetism.

The Department of Earth Sciences has considerable interest in all aspects of geomagnetism, with a total of eight researchers making up our geomagnetism research group. Investigations into the data produced by SWARM will be lead by Dr. Andrew Jackson, who is a Royal Society University Research Fellow in this department, a member of the Orsted Science Team, and who has over 10 years of experience in this research area.

We give our wholehearted backing to this project.

Signed ....
Professor B. W. D. Yardley

TOTAL P.02

OBSERVATORI DE L'EBRE

Universitat Ramon Llull

20 November 1998

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

Dear Dr. Olsen,

In response to your mail sent to one of our scientists (Joan Miquel Torta), requesting our support to the contents of the "SWARM: A Small Multi-Satellite Mission to Observe the Dynamics of the Earth's Magnetic Field" project, the Research Group of Ebre Observatory would like indeed to join your team and be part of the proposing consortium. We would also like to insist in the necessity of these 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, its 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

Luis F. Alberca

Luis F. Alberca Silva
Director

c/ Horta Alta, 38
43520 - ROQUETES (Tarragona). Spain

Letter of Endorsement

SWARM

a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field

as proposed for the Earth Explorer Opportunity Missions

The Alfvén Laboratory at the Royal Institute of Technology, Stockholm, fully supports the participation of Professor Göran Marklund and Drs Lars Blomberg and Per-Arne Lindqvist 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 three 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 such as the Wallenberg Foundation (who provided partial funding for the Swedish participation in the Cluster and Astrid-2 missions) and KTH (who provided partial funding for the Astrid-2 mission).

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.

Stockholm, December 8, 1998

Göran Marklund
Head of the space group

Nils Brenning
Director of the Plasma Physics Division

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

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Istituto Nazionale di Geofisica

Rome, December 9th, 1998

Il Presidente

Prot. n. 2125
ESPRESSO Air-Mail

Dr. Eigil Friis-Christensen
Director, 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 Netherland

Subject: Letter of endorsement for the Project "SWARM, a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field".

Dear Dr. Friis-Christensen,

I am writing in support of the proposed mission "SWARM, A Small Multi-satellite Mission to Investigate the Dynamics of the Earth's Magnetic Field".
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, 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.
Direct involvement of the I.N.G. is subject to availability of appropriate funds.

Yours Sincerely,

Prof. Enzo Boschi

IPGP
INSTITUT DE PHYSIQUE
DU GLOBE DE PARIS

LE DIRECTEUR

December 8, 1998

Dr Eigil Friis-Christensen
Danish Space Research Institute
Juliane Maries Vej 30

DK-2100 COPENHAGEN 0
Denmark

Dear Colleague,

The Institut de Physique du Globe de Paris enthusiastically supports the proposal SWARM of a small multi-satellite mission to investigate the dynamics of the Earth's magnetic field.

IPGP and especially its geomagnetism an paleomagnetism department have been involved for long in the study of the dynamo, secular variation, earth's rotation irregularities due to core-mantle interactions, but also of the crustal field and geomagnetic induction by external sources. We hope that, after Oersted which we have waited for 20 years and Champ, a permanent space observatory will monitor the geomagnetic field.

For continuity of observations, SWARM will be essential. Furthermore, its configuration will allow, to a reasonable cost, to bring a tremendous improvement in the knowledge of the different components of the field (main, crustal, external).

IPGP endorses the proposal SWARM and strongly hopes it will meet success in the selection process.

Sincerely,

Jean-Louis LE MOUEL
Director of IPGP

4, place Jussieu - Case 89 - Tour 24 - 75252 PARIS Cedex 05 - Tél. : (33/1) 44.27.37.77 - Fax : (33/1) 44.27.33.73 - Télex : (42) 202 810

Danish Meteorological Institute
Ministry of Transport

DMI

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NL-2200 AG Noordwijk ZH
The Netherlands

COPY

Our ref.: 98-33-40

8. December 1998

FS/TON/gtj

Letter of Endorsement for SWARM

The Danish Meteorological Institute strongly support the SWARM mission - in our opinion one of the most exciting missions proposed in years. The science is within the core research objectives of our division and fits well with our observational program, which is based on data from the coming magnetic satellite missions, Orsted and SAC-C, and our chains of ground magnetometers and riometers in Greenland.

Sincerely

Torsten Neubert
Head of Solar-Terrestrial Physics Division
Danish Meteorological Institute

cc: Dr. Nils Olsen, Danish Space Research Institute

DEPARTMENT OF AUTOMATION
TECHNICAL UNIVERSITY OF DENMARK

DTU

ESA, ESTEC
Earth Sciences Division-VR
Keplerlaan 1
P.O.Box 229
NL-2200 AG Noordwijk ZH
The Netherlands

7. DECEMBER 1998
KA/ib

Subject: **Letter of Endorsement for participation in the SWARM project.**

The Department of Automation, Technical University of Denmark fully endorses the participation of the Space Instrumentation Group in the exciting SWARM multi-satellite mission for observing the dynamics of the Earth's magnetic field in close collaboration with the Danish Space Research Institute and the Niels Bohr Institute of the Copenhagen University.

The Department of Automation is vitally interested in all aspects of stellar navigation and space magnetometry, and is presently participating with Advanced Stellar Compasses and Magnetometers in the Danish Ørsted satellite, the Swedish Astrid-2 satellite and the Argentine-US SAC-C satellite. The Department is also under contract to deliver stellar compasses and magnetometers for the German CHAMP Earth's geopotentials satellite mission.

The SWARM mission fits well into our plans, and we are excited over the prospects to participate with stellar compasses and with scalar and vector magnetometers.

The main funding for the DTU instrumentation is expected to come via an ESA contract held by the Danish Space Research Institute and following a successful response to an ESA AO. Funding for DTU participation in the science data analysis will also have to come from external sources.

We are looking forward to working with and being part of the SWARM team for this new and exciting mission.

Yours sincerely,

Kurt Andersen
Head of Department

c.c.: Dr. Nils Olsen, Danish Space Research Institute,
Juliane Maries Vej 30, 2100 Copenhagen Ø

DEPARTMENT OF AUTOMATION

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

NASA

ıly to Attn of: Code 921 November 24, 1998

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

Dear Dr. Friss-Christensen;

We are writing in support of your proposed mission (SWARM), A Small Multi-Satellite Mission to Observe the Dynamics of the Earth's Magnetic Field. Since we have mainly worked on interpreting the crustal magnetic field we believe that your proposed mission will significantly aid our studies of the crustal magnetic anomalies. While your proposed mission altitude is not optimal for crustal studies the fact that you will be measuring the field with multiple satellites in more than one orbit will allow us to remove both the external and core fields to an unprecedented accuracy. We can, therefore, isolate the crustal field with a greater signal to noise level than previously accomplished. A better description of external and core fields will also allow us to better utilize existing, lower altitude, magnetic field data sets. SWARMs multipoint aspect will be especially helpful over the Arctic and Antarctic, where our attempts to construct accurate crustal anomaly maps are now hampered by the dynamic nature of the large-scale external fields in those regions.

We know, from your success in assembling and calibrating the instrumentation for the Orsted mission that you and your group will do a similarly excellent job with the instruments for the SWARM mission. In view of the above we wish you success in your efforts in securing the SWARM project.

Respectfully,

Patrick T. Taylor
Geodynamics Branch

Michael E. Purucker
Raytheon ITSS

HIGH ALTITUDE OBSERVATORY 58 Years • 1940 - 1998
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November 24, 1998

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

Dear Eigil:

Thank you for the information about the proposed SWARM project. This is indeed a very exciting project that would make a major contribution not only to the accurate determination of lithospheric magnetic fields and of secular variations of the main field, but also to the understanding of variable electric currents in space that contribute to the measured signal. It is especially because of the variable nature of these external currents that the multiple-spacecraft nature of the SWARM mission is crucial: multiple spacecraft will permit a large reduction in the errors inherently involved in separating the temporal and spatial variations of the magnetic field, and therefore in separating the effects of ionospheric and magnetospheric currents from those of crustal magnetization. The expertise that has been developed in several European countries based on the Ørsted, CHAMP, and other satellite magnetic missions, constitutes an exceptionally strong base on which to build the ambitious but very feasible SWARM project.

I heartily endorse the SWARM proposal, and would be glad to contribute to the scientific analysis of the data when the mission is in operation.

Sincerely,

Arthur D. Richmond

TU BS Inst.Geophysik +49 531 3915220 26/11 '98 14:30 NO.329 01/01

Technische Universität Braunschweig
Institut für Geophysik und Meteorologie

Univ.-Prof. Dr. Karl-Heinz Glaßmeier
Fax: 0531 391 5220
Tel: 0531 391 5214
Handy: 0172 9086077

Braunschweig, 25. November 1998

Dr. Eigil Friis-Christensen

Danish Space Research Institute
Juliane Maries Vej 30
DK-2100 Copenhagen

Fax 0045 3536 2475

Dear Eigil,

with great interest I read the proposal "Swarm" for a small multi-satellite mission to observe the dynamics of the Earth's magnetic field.

I like to indicate that our group be prepared to support you in this proposal both via scientific and experimental contributions. As you are aware our group has vast experience in building, calibrating and operating space magnetometers. Our recently developed very small fluxgate magnetometer might be a very interesting contribution for the proposed small-satellite mission. Also, contributions for the required magnetic-cleanliness considerations and sensor calibration aspects can be offered.

Furthermore, I like to point out that I am currently trying to organize a larger German research project concerning the analysis of Earth magnetic field variations, their causes and consequences on the system Earth. A mission as proposed would certainly be in the spirit of this programme. Thus, I like to support your proposal as much as I can. Please, keep us informed.

Sincerely yours

K.H. Glaßmeier

Karl-Heinz Glaßmeier

Institut für Geophysik
Universität Göttingen

Herzberger Landstrasse 180
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Prof. Ulrich Christensen

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November, 25, 1998

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

Fax: 0045-3536-2475

Re: Proposal for Magnetometer Mission SWARM

Dear Dr. Friis-Christensen,

Hermann Lühr (GFZ Potsdam) has sent me the proposal outline for the SWARM mission and invited me to participate in the scientific interpretation of the results.

As you know, the theoretical understanding of the processes in the liquid outer core that generate the Earth's magnetic field has entered a new stage. Realistic and detailed computer models of the geodynamo are within reach. Several groups worldwide now pick up on the pioneering work of Gary Glatzmaier and Paul Roberts. The results of various models are similar in the sense that dipole-dominated magnetic fields are generated. In order to discriminate between competing models and to develop of full understanding of the geodynamo, predictions concerning the detailed spatial field structure up to high-order multipole components and its variation with time must be compared with precise observations of the geomagnetic field. There is a clear need for improved data that allow to separate external field components and possibly components from crustal magnetisation from the core field.

./.

In collaboration with Peter Olson (Johns Hopkins University, Baltimore) and Gary Glatzmaier (now at UC Santa Cruz), I have recently joined the quest for a realistic model of the geodynamo. We obtained results that look quite promising concerning the field morphology including the non-dipolar terms. I would definitely be interested in the improved geomagnetic field data that the SWARM mission promises and would like to participate in their scientific interpretation.

Sincerely yours

U. Christensen

Ulrich Christensen
Professor of Geophysics