

EarthCARE	- Earth Clouds, Aerosols and Radiation Explorer
SPECTRA	- Surface Processes and Ecosystem Changes Through Response Analysis
WALES	- Water Vapour Lidar Experiment in Space
ACE+	- Atmosphere and Climate Explorer
EGPM	- European Contribution to Global Precipitation Measurement
Swarm	- The Earth's Magnetic Field and Environment Explorers



REPORTS FOR MISSION SELECTION
THE SIX CANDIDATE EARTH EXPLORER MISSIONS

Swarm – The Earth's Magnetic Field and Environment Explorers

***European Space Agency
Agence spatiale européenne***

ESA SP-1279(6) – Swarm – The Earth's Magnetic Field and Environment Explorers

Report prepared by: Mission Experts Division
Scientific Co-ordinator: R. Haagmans

Published by: ESA Publications Division
c/o ESTEC, Noordwijk, The Netherlands
Editor: B. Battrick

Copyright: © 2004 European Space Agency
ISBN 92-9092-962-6
ISSN 0379-6566

Price (6 vols): € 50

Contents

1.	Introduction	1
2.	Scientific Background	3
2.1	Internal Magnetic Fields	5
2.1.1	Core Field and Secular Variation	5
2.1.2	Lithospheric Field	6
2.1.3	Mantle Conductivity	8
2.1.4	Ocean Circulation	8
2.2	External Magnetic Fields	9
2.2.1	Magnetospheric and Ionospheric Current Systems	10
2.2.2	Atmospheric Studies	11
2.3	The Present Situation	11
3.	Swarm Research Objectives	13
3.1	Primary Research Objectives	13
3.1.1	Core Dynamics and Geodynamo Processes	13
3.1.2	Lithospheric Magnetisation	15
3.1.3	3-D Electrical Conductivity of the Mantle	15
3.1.4	Magnetospheric and Ionospheric Current Systems	16
3.2	Secondary Research Objectives	16
3.2.1	Ocean Circulation and its Magnetic Signature	16
3.2.2	Magnetic Forcing of the Upper Atmosphere	17
4.	Observational Requirements and Measurement Principle	19
4.1	Specification of Observational Requirements	20
4.1.1	Space-Time Sampling Requirements	20
4.1.2	Multiple-Satellite Constellation Requirements	21
4.1.3	Single Satellite Requirements	23
4.1.4	Measurement Principle	24
4.1.5	Time Sampling Requirement	25
4.2	Proposed Constellation	25
4.3	Timing of the Mission	27
4.4	The Need for Observations from Space	27
4.5	Target and Threshold Requirements	28

5.	Data Processing Requirements	29
5.1	Scientific Data Processing	29
5.2	Scientific Data Calibration and Validation	31
6.	Performance Estimation	33
6.1	Single Satellite Performance	33
6.1.1	Magnetic Field Products	34
6.1.2	Electric Field Products	35
6.1.3	Air Drag Product	35
6.1.4	Performance Summary for Level 1b	36
6.2	Constellation Performance	37
6.2.1	Performance Related to Internal Fields	38
6.2.2	Performance Related to External Fields	43
6.3	Constellation Performance	44
7.	User Community Readiness	47
8.	Global Context	49
9.	Application Potential	51
9.1	Possible use in Other Scientific Studies	51
9.2	Modelling and Operational Aspects and Other Applications	52
	References	55

1. Introduction

The ESA Living Planet Programme includes two types of complementary user driven missions: the research-oriented Earth Explorer missions and the operational service oriented Earth Watch missions. These missions are implemented through the Earth Observation Envelope Programme (EOEP) and the Earth Watch Programme, where the Earth Explorer missions are completely covered by the EOEP.

Earth Explorer missions are divided into two classes, with Core missions being larger missions addressing complex issues of wide scientific interest, and Opportunity missions, which are smaller in terms of cost to ESA and address more limited issues. Both types of missions address the research objectives set out in the Living Planet Programme document (ESA SP-1227 1998), which describes the Agency's new strategy for Earth Observation in the post-2000 time frame. All Earth Explorer missions are proposed, defined, evaluated and recommended by the scientific community.

Following a call for Core mission ideas in 2000 and selection of five of the ten proposals for pre-feasibility study, three of the candidates, EarthCARE, SPECTRA and WALES, were chosen for feasibility study in November 2001. In response to a call for Opportunity mission proposals in 2001, which resulted in 25 full proposals being submitted by early 2002, three mission candidates, ACE+, EGPM and Swarm, were also chosen for feasibility study. The Phase-A studies for all six Earth Explorer candidate missions are being finalised by early 2004, forming the basis for the Reports for Mission Selection for all six candidate missions.

The Swarm candidate mission is based on the mission proposal co-written and submitted in 2002 by a team lead by Eigil Friis-Christensen, Hermann Lühr, and Gauthier Hulot. This Report for Mission Selection for Swarm was prepared based on contributions from the Mission Advisory group (MAG) consisting of: Angelo De Santis, Eigil Friis-Christensen, Andrew Jackson, Gauthier Hulot, Hermann Lühr, Michael Purucker, Markus Rothacher, and Pieter Visser. Parts of the Report have been prepared by the Executive based on input provided by the industrial Phase A contractors. Nils Olsen, Mioara Mandea, Susanne Vennerstrøm, Terence Sabaka, Stefan Maus, Alexei Kuvshinov, Alan Thomson and all others, who participated in the supporting studies during Phase A, are acknowledged for their direct or indirect contributions to this report. A special expression of gratitude goes to John LaBrecque who made a vital contribution by supporting the studies performed by NASA scientists Michael Purucker and Terence Sabaka.

The Report for Mission Selection for Swarm, together with those for the other five Earth Explorer candidate missions, is being circulated within the Earth Observation research community in preparation for a User Consultation Meeting at ESRIN, Frascati, Italy, in April 2004.

2. Scientific Background

On 25 October 2003 the Japan Aerospace Exploration Agency (JAXA) reported that their Earth Observation Satellite “Midori-2” (ADEOS-II) had ceased operation. The malfunction occurred above the Pacific Ocean a little westward of Peru, and the effect may have been related to the huge geomagnetic storm at that time. This region in the southern hemisphere is known to be the place of many spacecraft failures (Webb 2003) due to the reduced magnetic field intensity (Heirtzler et al. 2002).

This was the latest in a series of radiation-induced satellite failures in recent years, mainly in the so-called South Atlantic Anomaly, where the intensity of the Earth’s magnetic field is particularly low (Fig. 2.1). The magnetic field created deep inside our planet protects us from the continuous flow of charged particles, the solar wind, before it reaches the atmosphere. It is being produced and sustained by a dynamo process involving turbulent motions of molten iron in the outer core. Its dominant axial dipole component, however, is currently decreasing at a rate presumably ten times faster than the one at which it would naturally decay, were the dynamo to be switched off. It has decreased by nearly 8% over the last 150 years (Jackson et al. 2000), a figure comparable to that seen at times of magnetic reversals (Hulot et al. 2002). However, in some regions, as the South Atlantic Anomaly, the field has decreased by up to 10% during the last 20 years (Fig. 2.1).

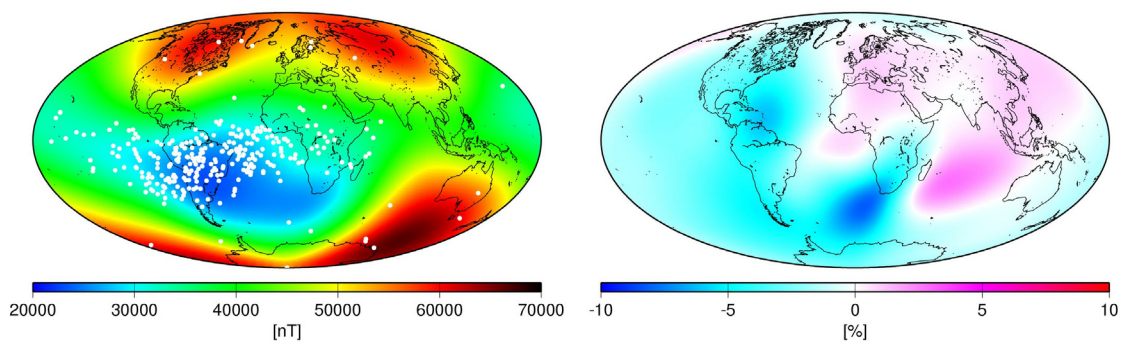


Figure 2.1: The geomagnetic field intensity at the Earth’s surface with the South Atlantic Anomaly defined by the low values of the field. The white dots indicate positions where the TOPEX/Poseidon satellite experienced single event upsets (left). The change in field intensity over 20 years (from MAGSAT to Ørsted) is shown in percentage (right).

Understanding how this weakening shield is going to evolve in the future is a very important issue that will have to be addressed with new and unique satellite measurements. Other universal issues could then also be addressed:

- In conjunction with recent advances in numerical and experimental dynamos, better mapping of the time-variable geomagnetic field will provide new insights

into field generation and diffusion, and mass and wave motions in the fluid core. Progress in geomagnetic research calls for moving beyond simple extrapolation of the time-variable field to forecasting that field, via data assimilation and a better understanding of the underlying physics.

- The magnetism of the lithosphere, which tells us about both the history of the global field and geological activity, could be determined with much increased resolution. The increase in resolution will serve as a bridge between our knowledge of the lower crust from previous satellite missions, and our knowledge of the upper crust from aeromagnetic surveys. As the history of the field may also have affected the climate (by modulating atmospheric escape), other issues related to the global history of our planet could then be investigated.
- Global 3-D images of the electrical conductivity in the mantle could be constructed for the first time. These images provide insight into chemical composition and temperature, fundamentally important for understanding mantle properties and dynamics.
- Finally, the magnetic field is of primary importance for the external environment of the Earth, providing information about the coupled Sun-Earth system.

Magnetic sensors at or near the Earth's surface measure a superposition of the core field along with other fields caused by magnetised rocks in the crust, by electric currents flowing in the ionosphere, magnetosphere and oceans, and by currents induced in the Earth by time-varying external fields. The scientific challenge is the difficult **separation of the magnetic field from various sources**, each having specific spatial and temporal characteristics.

The core field and, in particular, its temporal changes are among the very few means available for probing the **properties of the liquid core**. The secular variation directly reflects the **fluid flows** in the outermost core and provides a unique experimental constraint on **geodynamo** theory. But a serious limitation regarding the investigation of internal processes at time-scales of months to years is the effect of external magnetic sources, which significantly contribute on time-scales up to the 11-year solar cycle. All this clearly demonstrates the need for a **comprehensive separation and understanding of external and internal processes** (Langel 1987, Sabaka et al. 2002).

Recent studies have greatly enhanced our global and regional knowledge of the magnetisation of the crust and uppermost mantle, with attendant geodynamic implications. However, fundamental unresolved questions remain about the **lithospheric field** and the **electrical conductivity of the mantle**. The key to answer these questions is an adequate determination of the time-space structure of the geomagnetic field on global and regional scales (Olsen et al. 2002).

The geomagnetic field is not only an issue related to scientific research regarding the origin and the evolution of our planet. The magnetic field is also of primary importance

for the **external environment** of the Earth. While it is well-known that the air density in the thermosphere is statistically related to geomagnetic activity, recent results (Lühr et al. 2004) have indicated that the **air density** is locally affected by the **geomagnetic activity** in a very specific way that is still to be explored and understood. Furthermore, the magnetic field acts as a shield against high-energy particles from the Sun and from outer space. It controls the location of the **radiation belts**, and also the trajectories of incoming **cosmic ray particles**, which reflect the physical state of the heliosphere. The interplanetary medium controls the energy input into the Earth's magnetosphere and the development of magnetic storms, in short: **Space Weather**. Numerous reported, but still poorly understood, correlations between various solar activity parameters and **climate variations** (Friis-Christensen 2001) have recently been related to the flux of high-energy cosmic ray particles from Space and from the Sun (Marsh and Svensmark 2000, Yu and Turco 2001).

In summary, no other single physical quantity may be used for such a variety of studies related to our planet. Highly accurate and adequately sampled measurements of the magnetic field will provide new insights into the Earth's formation, dynamics and environment, stretching all the way from the Earth's core to the ultimate source of life, the Sun.

2.1 Internal Magnetic Fields

2.1.1 Core Field and Secular Variation

The essence of the core field lies in electromagnetic induction: its creation associates currents and fields through the motion of a conducting fluid across magnetic field lines. The Earth's core is a highly conductive medium where convection takes place with characteristic velocities of a few tens of kilometres per year, that is five orders of magnitude larger than the assumed mantle convection (Stacey 1992). On time scales shorter than a decade, and for medium to large spatial scales the core may be considered to behave as a perfect conductor. The main consequence is that the magnetic field appears as frozen in the material of the core. Consequently, the evolution of the core field with time, known as secular variation, can be used to derive the **flow at the top of the core**, under specific assumptions concerning the dynamics of fluid motion.

The evolution of the core field between 1980 and 2000 observed by the MAGSAT and Ørsted missions, respectively, was used to derive 20-year averaged small-scale flows (Hulot et al. 2002). These flows proved to be very useful in providing insight into the geodynamo mechanism. Although dramatic advances have recently been made in the field of numerical simulations of the **geodynamo** (Kono and Roberts 2002), observationally driven studies are still critically needed to understand the processes in the fluid core. High-accuracy and well-sampled observations, in particular snapshots at short intervals, are needed to derive sufficiently small-scale flow models.

Other studies rely on those fluid flow models. For example, the core **axial angular momentum** can be estimated and shown to account for the **length-of-day** variation on decadal time scales through exchange of axial angular momentum between the solid mantle and the core (Jackson et al. 1993). More generally, the core is a place where many phenomena occur on decadal and shorter time scales, for example the so-called **torsional oscillations**, which play a central role in **core dynamics**. These oscillations carry the core angular momentum (Jault et al. 1996), and could also be responsible for geomagnetic jerks, sudden changes occurring from time to time in the secular variation (Bloxxham et al. 2002). The dynamics of **geomagnetic jerks** have so far only been studied from ground-based observations (Mandea et al. 1999), because none has yet occurred during a magnetic mapping mission. By ensuring that the evolution of the core field is also observed beyond the end of the current satellite missions, and by improving accuracy and resolution in space and time, it will be possible to better understand each of those phenomena and how they relate to one another.

The detailed mechanism, through which core and mantle exchange angular momentum, could then also eventually be better identified. Three such mechanisms have been proposed: gravitational, arising from density anomalies in the mantle and in the core, including the inner core (Ponsar et al. 2003), electromagnetic, arising from Lorentz force in the electrically conducting lower mantle (Holme 2000), and topographic, arising from non-hydrostatic pressure acting on the core-mantle boundary topography (Jault 2003). Current and planned gravity missions such as CHAMP, GRACE and GOCE lack sensitivity for extracting direct information on the core-mantle boundary dynamics, leaving magnetic field observations as the primary source for studying those processes, in combination with seismic data.

Finally, and most importantly, some understanding could be gained with respect to the way the core field is currently evolving, making it possible to predict the evolution of some of its remarkable features, such as its global intensity, or the reverse patch at the core surface responsible for the South Atlantic Anomaly at the Earth's surface.

2.1.2 Lithospheric Field

Plate tectonics successfully describes the Earth's oceanic lithosphere in terms of rigid body motions of a small number of plates, although sparse data coverage hinders even this level of understanding in the southern oceans. Deformation in the continents behaves differently and is not confined to plate boundaries. Current thinking relates the diffuse character of continental deformation to the thickness of its constituent parts. However, the thermal regime, thickness, and **deep structure of the lithosphere** below continents are still poorly known (Langel and Hinze 1998).

The lithospheric magnetic anomaly field is produced by spatial variations in the magnetisation carried by crustal and some mantle rocks. This magnetisation is partly **induced** by the ambient field, and is therefore proportional to its strength, and to the

susceptibility of the rock. It can also be a remanent magnetisation acquired during the formation of the rock, which may be reset by thermal or chemical alteration, or by metamorphic phase changes. The magnetic stripes on the sea floor are an example of remanent magnetisation. Until recently, **remanent** magnetisation in continental crust was thought to have little or no expression in the longer wavelengths of the anomaly field, which can be measured from satellites (Purucker et al. 2002a). This changed with the recent discovery of large-scale remanent magnetisation on the planet Mars, showing intensities an order of magnitude larger than anything seen over the Earth (Acuña et al. 1999, Langlais et al. 2004).

In spite of this caveat, induced magnetisation or viscous remanent magnetisation is likely to be the dominant type of magnetisation in the deeper layers of the crust as well as in the upper mantle. Predominantly associated with the presence of magnetite, the distribution of induced magnetisation depends on gradually changing parameters such as mineralogical composition or in-situ temperature and pressure conditions.

Recent satellite data have enhanced our knowledge of the global and regional magnetisation of the crust and uppermost mantle, with attendant geodynamic implications. The magnetic field originating from the lithosphere appears globally weaker in the oceanic domain than above continental areas, reflecting a difference of factor of five in thickness between continental and oceanic crust. The field from the Earth's core masks the lithospheric field at degrees less than 14. Hence the resolved lithospheric field contains only wavelengths less than 2800 km. Maps of the observed field can be interpreted as edge effects from even longer wavelength fields (Cohen and

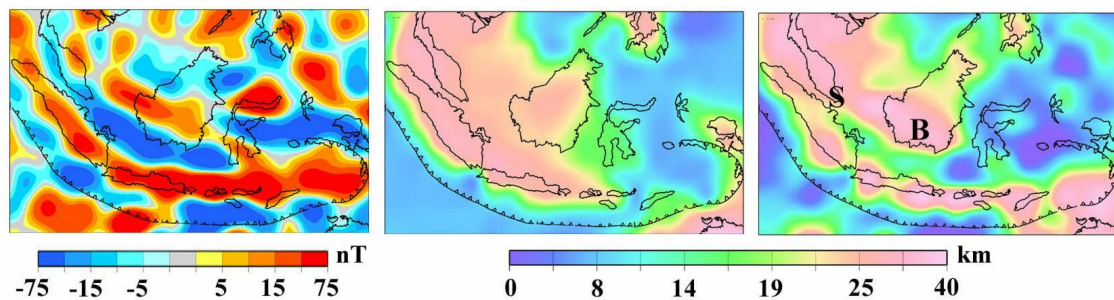


Figure 2.2: Radial magnetic field of lithospheric origin (left) and magnetic crustal thickness (right) in the Java trench region. It is based on joint inversion of magnetic (MF-3) (left) and seismic/thermal (3SMAC) models (centre), with long-wavelength control from 3SMAC (Nataf and Ricard 1996) and short-wavelength control from MF-3 (Maus et al. 2004). The enhanced magnetic thickness north of the trench (barbed line; Hamilton 1979) probably reflects the down going slab, with the southern boundary defined by a steepening of the dip of the slab, while the northern boundary may correspond to the depth at which the slab reaches the Curie temperature. The sharp linear crustal thickness boundary extending from Singapore (S) to the southern boundary of Borneo (B) has not been previously recognised, and may provide insight into the earlier history of tectonics and subduction in this region (right).

Achache 1994). The resolution of present day satellite data is sufficient to resolve only the widest sea-floor stripes, those associated with the Cretaceous quiet zones, although the satellite data are also capable of resolving the enhanced magnetisation associated with spreading ridges. Measurements of the lithospheric field have been used for structural interpretations, for example to show that the European Tornquist-Teisseyre Zone is a first-order feature characteristic of both the upper and lower crust (Ravat et al. 1993), and for delineating the thermo-mechanical properties of the lithosphere, as for example, in the Java trench (Fig. 2.2).

2.1.3 Mantle Conductivity

A parameter of importance for improving our knowledge of the physical and chemical properties of the mantle is the **electrical conductivity**. This is generally estimated in two ways. It can be probed ‘from below’ using signals originating in the core and observed at the surface (Mandea Alexandrescu et al. 1999). 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 the fluid motion at the top of the core. Mantle conductivity can also be probed ‘from the top’ by the analysis of geomagnetic variations at various frequencies (Olsen 1999). This method requires a good knowledge of the space-time dependence of the magnetic field of external origin.

The electrical conductivity of the mantle is very sensitive to small changes in the fluids content and partial melting in the mantle and, to a lesser extent, to changes in mineralogy. Studies of lateral variability in the physical properties of Earth’s mantle using geophysical methods is a hot subject of modern fundamental science since it provides insight into geodynamic processes such as mantle convection, the fate of subducting slabs, and the origin of continents. Recent advances in seismic tomography (Bijwaard and Spakman 2000) provide unprecedented views of subducting slabs, cratonic roots, and mantle plumes. While seismological data give information about mechanical bulk properties, electrical conductivity reflects the connectivity of constituents as graphite, fluids, partial melt, and volatiles, all of which may have profound effect on rheology and, eventually, mantle convection and tectonic activity.

Present insights are based upon analysis of observatory data that are biased towards continental conditions, which allowed mainly construction of 1-D conductivity models. True global estimates can only be obtained from space. However, single-satellite results do not allow the determination of conductivity inhomogeneities. This would require simultaneous measurements at different local times.

2.1.4 Ocean Circulation

In the oceans, the motion of the electrically conducting seawater generates electromagnetic fields. Recently, it has been shown that the flow makes a detectable

contribution to the geomagnetic field signal, of the order of a few nT at satellite altitude (Tyler et al. 2003). The opportunity for remote sensing of the ocean using magnetic observations is attractive because the ocean-motion generated magnetic signals directly relate to the baroclinic flow component. Currently, we are limited to a description of only the barotropic component of ocean flow using satellite radar altimetric measurements of sea-surface topography. First attempts to indirectly derive a large-scale baroclinic signal are foreseen, once sufficiently accurate time-variable gravity fields become available from GRACE, together with satellite altimetry and operational numerical weather prediction model analyses (GRACE 1998). Such improved knowledge would contribute to a better understanding of global ocean circulation (Stammer et al. 2003).

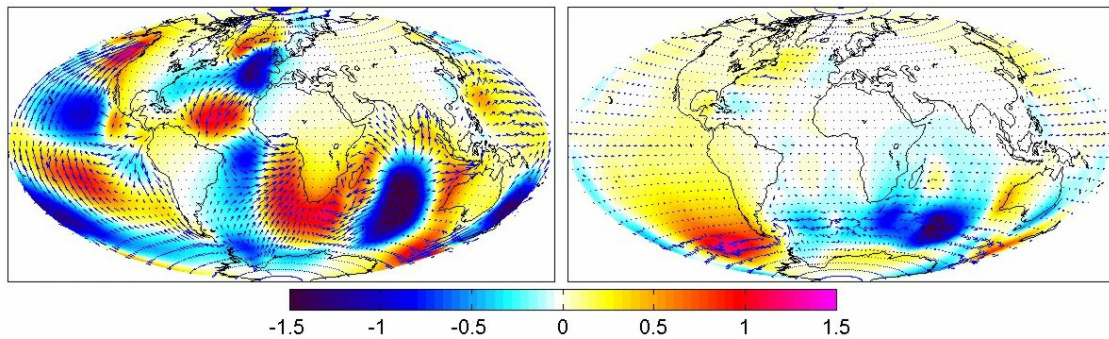


Figure 2.3: Radial magnetic field (in nT) at satellite altitude produced by ocean flow, for the lunar M2 tide (left) and the stationary ocean circulation according to ECCO model (right). ECCO is not eddy resolving and fails to capture the most energetic parts of the ocean flow to its full extent, which indicates that more signal can be expected.

2.2 External Magnetic Fields

During recent years, society has become aware of the limitations of our planet and of our dependence on advanced technological systems. The distinction between man-made and natural causes of ‘Global Change’ has become an important issue, and the concept of a steady Sun, expressed for example in the term ‘the solar constant’, has gradually been abandoned and transformed into a broadly accepted concept of a constantly varying external environment dominated by processes in the Sun.

The external environment is characterised by large electrical currents providing the coupling between the solar wind input and the different regions around the Earth. The measured magnetic field and its temporal variations provide crucial information about the coupling currents, and hence about the physical processes that contribute to form the Earth’s system.

In addition, the geomagnetic field itself also plays an important role in controlling many of the physical processes in the Earth’s environment that directly affect our daily

life, in particular those that are related to our increasing utilisation of highly technological systems in space.

2.2.1 Magnetospheric and Ionospheric Current Systems

The geomagnetic field is an effective shield against charged particles impinging from outer space onto the Earth. The magnetosphere forms a kind of cocoon, diverting most of the solar wind around the Earth. The particles that do enter the magnetosphere are guided by the magnetic field and form fundamental structures like the **radiation belts** and the **ring currents**. The motion of charged particles causes electric currents, which can be traced by the magnetic fields, thus presenting the opportunity to identify the activity state of the magnetosphere.

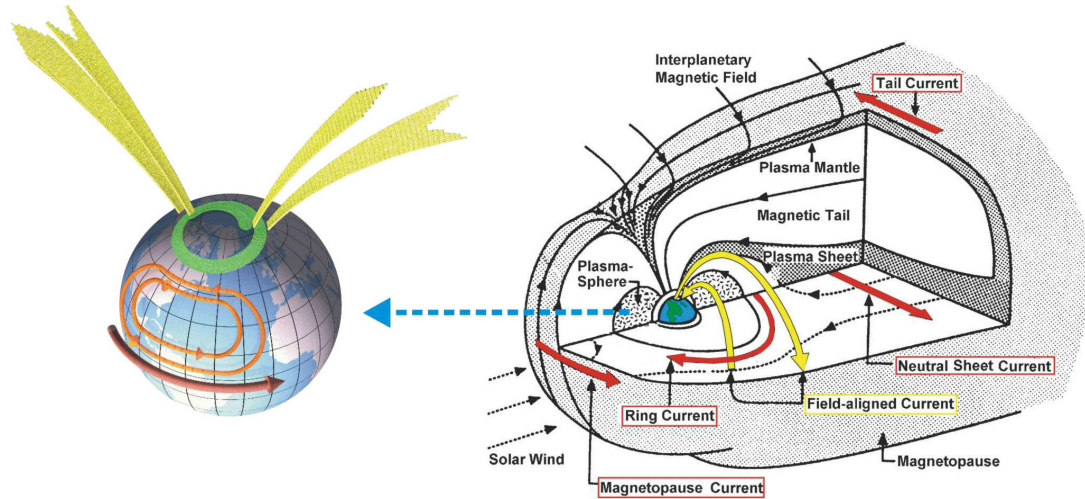


Figure 2.4: Schematic of major current systems in the ionosphere (left) and magnetosphere (right). The field-aligned currents (yellow) coupling the two spheres cause toroidal magnetic fields at satellite level.

Radiation damage to spacecraft and radiation exposure to humans in space is a matter of increasing concern. In particular, over the South Atlantic Anomaly, the low magnetic field strength allows high-energetic particles from the radiation belts to penetrate deep into the upper atmosphere, creating intense radiation. Recent instrument failure statistics suggest (Heirtzler et al. 2002) that this anomaly has shifted to the Northwest. Recent geomagnetic models derived from satellite data have confirmed this. Accurate and timely geomagnetic field models clearly play a pivotal role for space mission planning and operation.

Any charge separation built up in the magnetosphere can only be neutralized through currents routed along the field lines and closed in the ionosphere. With its finite conductivity perpendicular to the field lines, the ionosphere forms the load in the current circuit. **Field-aligned currents** are a major link for transferring energy from the solar wind into the upper atmosphere. Our present day knowledge of these currents is

limited to statistical studies. Quantitative measurements have not been possible either from ground-based or from single-satellite measurements.

In addition, horizontal current systems are forming in the ionosphere. Confined bands of intense currents are found both at high (the **auroral electrojets**) and at low latitudes (the **equatorial electrojet**). The energy dissipated by these currents makes an important contribution to the heating of the upper atmosphere. The highly anisotropic conductivity in the ionosphere results in a combination of different kinds of currents. Multipoint measurements of the electric and magnetic fields are required to distinguish between them (Vennerstrøm et al. 2004).

2.2.2 Atmospheric Studies

The upper atmosphere is a highly coupled system. With its neutral and ionised constituents, the particle motion is governed both by thermodynamics and electrodynamics. Only recently it has been noticed that there is a steady decrease in air density at this altitude (Emmert et al. 2004), which may be related to the global warming of the troposphere. Simultaneous observations of the forces acting on either the neutral or the ionised particles is needed to improve our understanding of the coupling between the ionosphere, the thermosphere, and the magnetosphere. With a high-accuracy magnetic mapping mission, many of the quantities of interest can be observed, directly or indirectly. A few additional key parameters have to be observed in order to obtain a coherent picture. With a better knowledge of the upper atmospheric dynamics, more reliable nowcasts and forecasts of space weather phenomena can be made.

2.3 The Present Situation

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

However, these three missions have been conceived as single-satellite missions, with different instrumentation, satellite designs and orbits. Recent progress in geomagnetic research indicates that the main limiting factor in the accuracy of present field models is the dynamic behaviour of the external current configuration. Models derived from existing single-satellite data have been obtained with accuracy no better than a few nT and a rather coarse resolution. Hence, single-satellite missions are not able to take advantage of the impressive instrument improvements that have been achieved during the last couple of years. Multiple satellite missions measuring simultaneously over different regions of the Earth offer the only way to take full advantage of this new generation of instruments. It enables capture of the **time-variability of the**

geomagnetic field, which is a great advancement over the extrapolation based on statistics and on ground observations at selected sites. At the same time magnetic field measurements are important for **Space Weather** applications. Preliminary results of combining Ørsted, CHAMP and SAC-C observations from a few suitable periods indicate the great potential of a constellation. More extensive analyses are hampered by the fact that the orbital parameters of the various missions, as well as the differences in instrumentation, do not yield an optimal configuration (Purucker et al. 2002b).

Another limiting factor on the advance of geomagnetic research concerns the requirement for measurements during a **full solar cycle**. This is needed to properly distinguish between solar activity and secular variation effects. Numerous important aspects of the secular variation can be addressed over a time span of decades. Some of the fastest changes, the geomagnetic jerks, occur relatively frequently, but unfortunately at times without adequate satellite measurements of the magnetic field. It would be a tremendous scientific benefit to achieve data suitable for a proper characterisation of such an event.

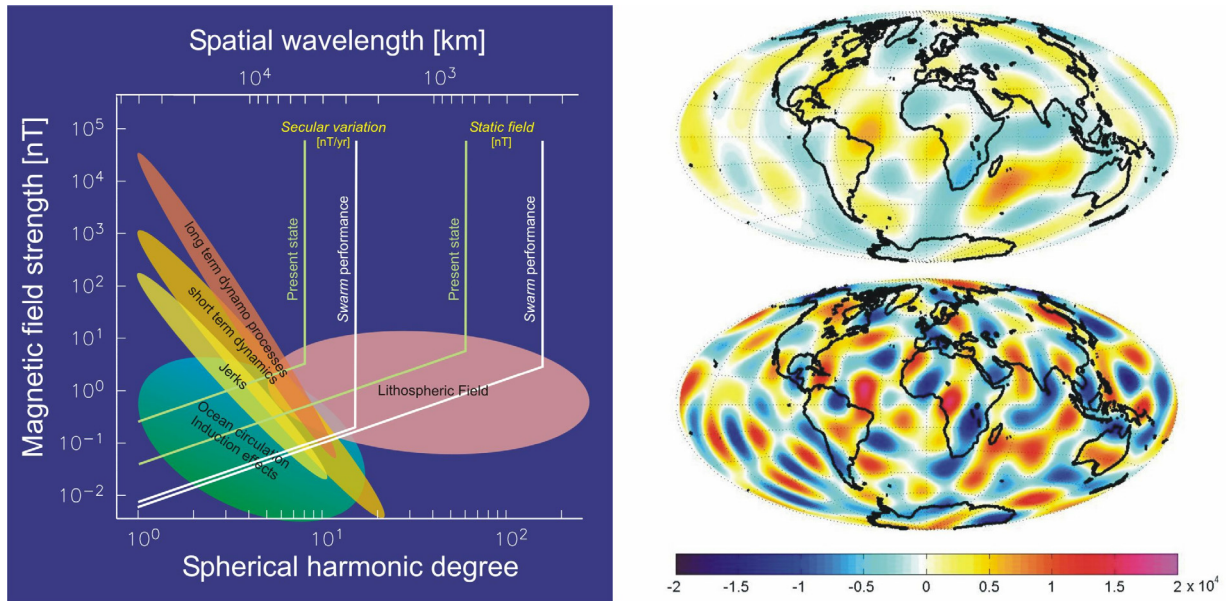


Figure 2.5: Present-day resolution and accuracy of secular variation and lithospheric models (valid at the Earth surface) and expected performance from the Swarm constellation. The secular variation of the radial component (in nT/yr) at the core-mantle-boundary from ground data only (top right) and from Swarm (lower right).

Recently scientists in the various geomagnetic research disciplines have been exploring the available data with increasingly sophisticated methods. It is becoming more and more evident, however, that real scientific progress requires an interdisciplinary approach based on a concerted effort integrating all aspects, from the magnetosphere to the deep core, and involving new observations, theory and modelling efforts. The research goal is to synthesise various scientific issues into a coherent and unified picture of the coupled Sun-Earth system.

3. Swarm Research Objectives

The primary aim of the Swarm mission is to provide the best survey ever of the geomagnetic field and the first global representation of its variations on time scales from an hour to several years. The more challenging part, however, is to separate the contributions from the various sources. Swarm, a proposed constellation mission, will simultaneously obtain a space-time characterisation of both the internal field sources in the Earth and the ionospheric-magnetospheric current systems.

The primary research objectives assigned to this mission are:

- studies of core dynamics, geodynamo processes, and core-mantle interaction,
- mapping of the lithospheric magnetisation and its geological interpretation,
- determination of the 3-D electrical conductivity of the mantle,
- investigation of electric currents flowing in the magnetosphere and ionosphere.

In addition to the above sources, the ocean currents produce a contribution to the measured magnetic field. But the magnetic field is not only used as evidence of the evolution of the planet, it also exerts a very direct control on the dynamics of the ionised and neutral particles in the upper atmosphere, and possibly even has some influence on the lower atmosphere. This leads to the identification of the secondary research objectives of:

- identifying the ocean circulation by its magnetic signature,
- quantifying the magnetic forcing of the upper atmosphere.

Analysis of the Swarm data will greatly improve existing and provide new models of the near-Earth magnetic field of high resolution and authenticity compared with a single-satellite mission. This will provide the prospect of investigating hitherto undetected features of the Earth's interior.

3.1 Primary Research Objectives

3.1.1 Core Dynamics and Geodynamo Processes

Ørsted and CHAMP have recently demonstrated the capability of satellite missions to increase the spatial resolution with which secular-variation models can be determined, compared to observatory-only solutions (see Fig. 2.5). By ensuring long-term space observations with an even better spatial resolution, Swarm will further improve models of the core field and its secular variation.

These models will open new science opportunities. **Core surface flow** models will be obtained with much greater detail than is currently possible. These flow models will be used to investigate **torsional oscillations** and **core-mantle interactions**. If, by any chance, and as is very likely to be the case, a **geomagnetic jerk** occurs during the course of the mission (the two last occurred around 1991 and 1999), its nature and possible connection with torsional oscillations could be investigated in much more detail than was previously possible with just ground-based data. Combining existing Ørsted, CHAMP and future Swarm observations will more generally allow any magnetohydrodynamic phenomena affecting the core on sub-annual to decadal scales to be investigated down to length scales of about 1000 km. Three particularly important scientific issues could then, for the first time, be addressed in detail.

The first deals with **diffusion** in the core. The signal produced by diffusion of the magnetic field in the not-so-perfectly-conducting core is likely to be small compared to that produced by advection of field lines. Nevertheless, diffusion produces a signal that is significant, in particular when small length scales are considered. Furthermore, it is quite clear that the reverse patch currently seen below the South Atlantic (Fig. 2.1) must have been created with significant contributions from diffusion. Swarm models will include details on small-scale structures, which will allow the evolution of this reverse patch to be tracked. The role of diffusion will thus be identified.

A second major issue is the question of whether **wave motion** is detectable in the core. Wave motion could be responsible for the propagation of magnetic features on the core surface, whilst the underlying fluid has no net translation and hence no momentum transfer. This classic dichotomy between the picture of mass motion and that of wave motion remains largely unresolved. Recently, attention has been focused on the equatorial belt, which appears to be particularly unusual from an observational point of view (Jackson 2003, Finlay and Jackson 2003). Coupled with theoretical arguments for the equatorial wave-guide (Zhang 1993) being a location for instabilities, the time is ripe for a thorough study of this region and its dynamics. The higher accuracy and resolution provided by Swarm will allow analysis of the secular variation with respect to dispersion and the dependence of propagation speed on wave number. One benefit from a proper identification of wave motion would be a strong constraint on the strength of the toroidal magnetic field at the top of the core, which is otherwise largely unknown. This strength most likely forces the selection of waves and constrains the way they propagate.

Finally, by making it possible to access the detailed evolution of the field at the core surface over a significant time period, data assimilation approaches of the type pioneered by Kuang et al. (2004), ‘feeding’ a dynamo code with real data, could be used to **predict the future behaviour of the Earth’s magnetic field**, and of the South Atlantic Anomaly in particular.

3.1.2 Lithospheric Magnetisation

Knowledge of lithospheric magnetisation is important for the insights it can provide into identifying geological provinces, for structural interpretations, and for the thermo-mechanical properties of the lower crust and mantle. With previous satellite missions, impressive results have been obtained about the magnetisation of the crust and uppermost mantle and their geodynamic implications. However, the resolution of previous satellite missions was insufficient to image the entire crust, and there remains a spectral ‘hole’ between spherical harmonic degrees 60 and 150, corresponding to the middle crust. Degrees higher than 150, corresponding mainly to the upper crust, are accessible from high-quality airborne surveys. The higher resolution provided by the Swarm satellites, in combination with more comprehensive approaches to characterizing the field sensed by aeromagnetic surveys, will allow for global compilations of lithospheric fields at scales from 5-3000 km, and provide our first ever, top to bottom view of the crust.

In the oceans, the increased resolution of the Swarm satellites will allow, for the first time, the delineation of oceanic magnetic stripes laid down during times of reversing polarity. This is important because the sparse data coverage in the southern oceans, and poor control of all long-wavelengths, limits our first-order understanding of plate tectonics in the oceanic lithosphere. In addition, two of the three largest ocean basins are dominated by north-south trending magnetic anomaly stripes, and along-track features such as these have proven difficult to extract from a single polar-orbiting satellite. The side-by-side (east-west) separation of the lower two satellites of the Swarm constellation is designed to solve this problem (Olsen et al. 2004).

3.1.3 3-D Electrical Conductivity of the Mantle

The goal of induction studies is to identify large-scale spatial variations and 3-D structures in upper mantle electrical conductivity. Traditionally, land-based data have been used for such 3-D studies; however, due to the sparse and inhomogeneous distribution of geomagnetic observatories, with only few in oceanic regions, and with varying data quality, a true global picture of mantle conductivity can only be obtained from space (Olsen 1999, Constable and Constable 2004). Until now, it has been difficult to map the 3-D electrical conductivity structure of the deep Earth accurately, because of poor spatial data coverage and highly uncertain estimates of the electrical response of the mantle over long periods. Both of these difficulties can be overcome by using magnetic data from satellites when they operate in constellation mode. The Swarm mission, providing simultaneous observations over different regions, will offer a unique opportunity to derive 3-D models of the mantle electrical conductivity. These models will provide information about the dynamics of the mantle, and furthermore allow interpretation of the 3-D images in terms of thermal and compositionally generated heterogeneity.

3.1.4 Magnetospheric and Ionospheric Current Systems

For studies of the Earth's interior, it is essential that the magnetic field models be contaminated as little as possible by fields originating from the ionosphere and magnetosphere. Recent investigations have shown the great advantage of modelling the Earth's core field and its secular variation simultaneously with ionospheric and magnetospheric contributions in a comprehensive approach by means of a joint inversion of ground-based and satellite magnetic field measurements (Sabaka et al. 2002, Sabaka et al. 2004). The ability of Swarm to obtain measurements at different latitudes and local times simultaneously will allow a better separation of internal and external sources, thereby improving geomagnetic field models (Olsen et al. 2004).

The magnetospheric and ionospheric currents vary in intensity depending on the degree of magnetic activity. Some of these currents cause poloidal magnetic fields, others toroidal ones. Due to their dynamics, the latter are very difficult to characterise from a single satellite, but with a constellation it will be possible to distinguish between these two types of fields. The local time distribution of simultaneous data will foster the development of new methods of co-estimating the internal and external contributions (Olsen et al. 2004). Such methods can also take advantage of complementary data acquired by other planned (space environment) missions and ground facilities in polar regions.

The Swarm constellation of spacecraft will allow, for the first time, the unique determination of the near-Earth field aligned currents, which connect various regions of the magnetosphere with the ionosphere and might be regarded as a complement to ESA's Cluster mission. Ionospheric currents are particularly strong at auroral latitudes. At these latitudes solar wind-magnetosphere interaction is causing, for example, geomagnetic storms and substorms. At mid- and low latitudes, ionospheric currents are driven primarily by high-altitude wind systems. Investigating these currents will add to the understanding of the upper atmospheric dynamics. A constellation mission like Swarm will allow the ionospheric current systems to be characterised by combining the electric and magnetic field measurements, and also the local time distribution of the currents to be obtained.

3.2 Secondary Research Objectives

3.2.1 Ocean Circulation and its Magnetic Signature

The ocean flow makes a substantial contribution to the geomagnetic field at Swarm's altitude. This encourages attempts to observe ocean flows from space. A comparison of observed and simulated magnetic fields at satellite altitude produced by the lunar oceanic M2 tide revealed consistent results (Tyler et al. 2003). Complementary to most other methods for measuring ocean flow, the magnetic signal senses the transport, i.e. depth-integrated velocity, which is a crucial parameter for, for example, ocean-climate

modelling. Furthermore, the magnetic signal due to ocean circulation can also be sensed in regions covered by ice. Correcting magnetic data for ocean flow signals strongly improves the accuracy of lithospheric field models. With the improved separation capabilities of Swarm, and using statistical methods, signals from other flow types might also be recovered (Olsen et al. 2004, Vennerstrøm et al. 2004).

3.2.2 Magnetic Forcing of the Upper Atmosphere

The dynamics of the upper atmosphere results from a complex interaction between the charged particles and the neutrals in the ambient magnetic field. With a dedicated set of instruments, each of the Swarm satellites will be able to acquire the needed high-resolution and simultaneous *in-situ* measurements, which are the key to understanding the system. The plasma density measurements will yield the structure of such ionospheric phenomena as the mid-latitude trough and the low-latitude Appleton anomaly. In addition, the plasma density significantly perturbs the local magnetic field measurement through the diamagnetic effect, and this effect has to be taken into account in magnetic field modeling (Lühr et al. 2003). Another topic to be investigated is the density variation in the neutral upper atmosphere. Local density maxima, encountered in the auroral regions, are believed to occur in response to Joule heating in the ionosphere (Lühr et al. 2004). By combining air drag with electric and magnetic field measurements, the physical mechanism causing the density variation can be elucidated.

4. Observational Requirements and Measurement Principle

Specific observational requirements are linked to each of the research objectives concerning the internal and external contributions to the magnetic field. This allows the derivation of a set of overall observational requirements that contain the most stringent ones for all models in terms of signal content and accuracy. For illustration, the magnitude of the internal and external sources related to their spatial scales is presented in Figure 4.1.

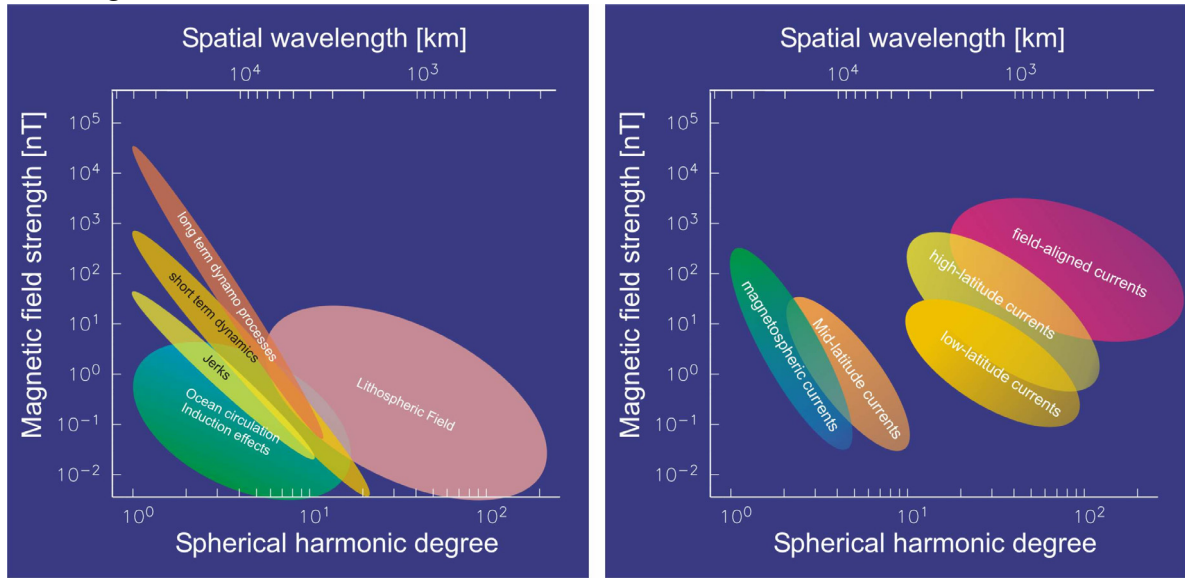


Figure 4.1: Signal amplitude at orbit altitude of the contributions from processes contributing to the magnetic field as a function of spatial scale. Source terms from within the solid Earth and the oceans (left), and contributions from external sources (right).

The first impression one may get from this figure is that just an increase in instrument sensitivity towards the smallest signal magnitude per scale is required to sense the lumped magnetic signal at 400 km altitude. This alone is not, however, sufficient to reach the envisaged goals due to contributions from the external sources. At certain spatial wavelengths, the external fields are much larger than the internal fields and they can easily mask them. Progress in modelling performance can only be achieved by co-estimation of internal and external field sources. The various field sources exhibit different temporal and spatial characteristics, which may help to distinguish between them. Typically, the external current systems are ordered primarily by local time, unlike the Earth-fixed internal sources. A dedicated space-time sampling strategy is needed to obtain reasonable coverage of the various systems within a time period compatible with the time scales of the variations.

4.1 Specification of Observational Requirements

The expected internal field characteristics at 400 km altitude based upon current knowledge are shown in Table 4.1 (upper). Also indicated are the types of measurements that are needed for the analysis. The aim is to recover the finest scales of this table with sufficient accuracy. In Table 4.1 (lower) the expected signals of the external contributions are given. These values correspond to the same altitude.

Research Objectives	Time Range	Spatial Range	Signal Range	Signal at Certain Wavelength (wl)	Measurement (B= magnetic)
Core dynamics and geodynamo processes	static	3000 km to global	± 65000 nT	0.8 nT @ 3000 km wl	B-field vector, altitude and position
	3 months to decades	2500 km to global	± 200 nT/yr	0.025 nT/3 months @ 2800 km wl	
Lithospheric magnetisation	decades to static	300 km to 3000 km	± 25 nT	0.8 nT @ 3000 km wl 0.009 nT @ 360 km wl	B-field vector, altitude and position
3-D mantle conductivity	1.5 hours to 11 years	300 km to global	± 200 nT	n.a. (modelled as conductivity)	B-field vector, altitude and position
Ocean circulation	12 hours to 2 years	600 km to 10000 km	± 5 nT	0.5 nT @ 10000 km wl 0.01 nT @ 600 km wl	B-field vector, altitude and position

Research Objectives	Time Range	Spatial Range	Singal Range	Measurement (E = electric)
Ionosphere - magnetosphere current systems	0.1 sec to 11 years	1 km to global	B-field: ± 1000 nT E-field: ± 0.2 V/m	B-field and E-field vector, attitude and position
Magnetic forcing of the upper atmosphere	10 sec to 2 years	200 km to global	Elect. density $1 \cdot 10^9$ m ⁻³ to $1 \cdot 10^{13}$ m ⁻³ Air drag: $\pm 1 \cdot 10^{-5}$ m s ⁻²	B-field and E-field vector, acceleration attitude and position

Table 4.1: Expected signals related to internal field (upper) and external field (lower) objectives at 400 km altitude.

4.1.1 Space-Time Sampling Requirements

Single-satellite magnetic missions do not allow full scientific advantage to be taken of currently obtainable instrument precision because the sequential data sampling causes a time-space ambiguity. In the case of the magnetic field, this results in an inadequate capability for separating the contributions from various sources. In principle, the field modeling algorithms require a well-distributed global and instantaneous data set. Since this is not feasible, temporal variations occurring during the sampling process have to be accounted for in a proper way. A major difficulty in this respect is the fact that

internal sources are Earth-fixed, while external contributions are ordered primarily in a local time frame. A single satellite in a polar orbit can obtain a reasonably dense sampling of the internal field components within a few days, but it fails to provide adequate spatial coverage of the external contributions, because of the slow orbital precession through local time. Designing a mission with several spacecraft simultaneously orbiting the Earth at different local times will solve this problem. As an example, a constellation of three satellites is considered in Figure 4.2. In the left frame night-side ground tracks for a period of 5 days are shown. This period of time may be regarded as the 5 quietest days of the month. The sampling obtained is sufficient for a snapshot main-field model. The right frame shows the coverage in the local time frame. Even with three satellites there are large unsampled sectors. The local time distribution is worst around the equator, but is much better at higher latitudes and it changes during the lifetime of the mission. Fortunately, the magnetospheric contributions are large-scale and can be described sufficiently well by spherical harmonics up to degree 2. The intensity of the associated currents varies, however, on time scales of hours. A better sampling of these effects is required. The thick lines show the tracks of one orbit. As can be seen, it is possible with this constellation to obtain a full degree 2 characterisation of the large-scale external field at a rate of once per orbit. For a single satellite the coverage reduces drastically.

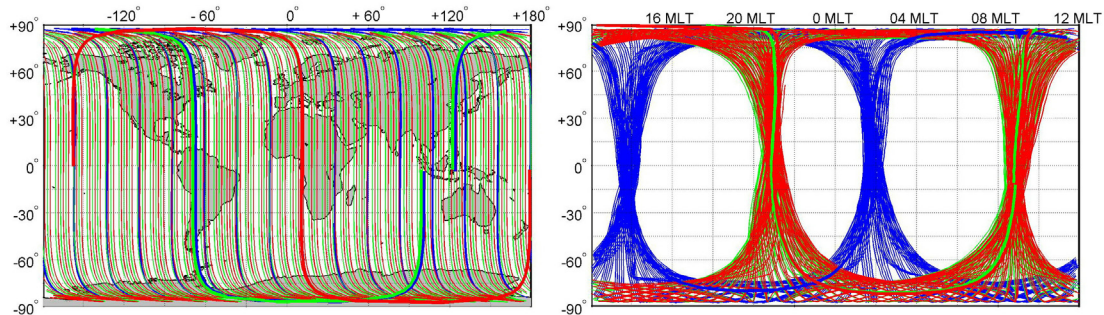


Figure 4.2: Orbit tracks of the 3 Swarm satellites (red: Swarm A; green: Swarm B; blue: Swarm C), for 5 days in an Earth-fixed frame (left), and in magnetic local time (MLT) against magnetic latitude (right). For each satellite, one orbit has been highlighted with a thicker line. Those are best seen on the left panel.

4.1.2 Multiple-Satellite Constellation Requirements

The scientific return for each of the research objectives can be considerably enhanced when optimised spacecraft constellations are obtainable. An important task is to find an orbit configuration that is a viable compromise for all objectives. The selected constellation reflects an attempt to optimise the primary research objectives: the investigation of the core magnetic field and its secular variation, the mapping of the lithospheric magnetisation with high resolution, and the determination of mantle conductivity. This actually implies that the effects of the remaining sources should be either modelled or reduced. From the research objectives, it follows that the orbit inclination must be near polar, primarily to obtain a good global coverage. Recent

dynamo simulations and observations suggest the existence of specific signals of internal origin near the poles in the “shadow of the inner core” (Hulot et al. 2002). Also the other research objectives demand that the unsampled areas around the poles be kept small, to obtain complete maps of lithospheric magnetisation and mantle conductivity. On the other hand, orbits right across the poles (90° inclination) are not favoured, since they result in a fixed synchronisation of the local time and season for the orbit. In this case scanning all local times will take one year. This would prohibit a distinction between signatures corresponding to the two different effects.

For core field modelling, the larger scales are of importance. Improved results are obtained when the orbital planes of the spacecraft are separated by 3 to 9 hours in local time (cf. Fig. 4.5). This allows for an adequate sampling of internal and external field contributions. This is also desirable for deriving the 3-D conductivity of the mantle since this relates to the interaction between the fields (Olsen et al. 2004).

For improving the resolution of lithospheric magnetisation mapping, the satellites should fly at low altitudes. The selected altitude ranges should, however, be compatible with a multi-year mission lifetime. Once the minimum possible altitude is selected, further improvement in the retrieval of the high-degree magnetic anomalies field can be achieved by considering gradients in the inversion algorithm, in addition to the full magnetic field readings. This concept for emphasising the small-scale anomalies by partially counteracting the attenuation effect with altitude has already been accepted and applied in gravity missions (cf. GRACE 1998, ESA SP-1223 (1) 1999). Optimal spacecraft separations for deriving the gradients are dependent on signal spectrum and instrument resolution. An additional consideration is the definition of the smallest scales that should be resolved during the mission. As can be seen in Figure 4.3, spacecraft separations in longitude between 1° and 2° are favourable. A further advantage is that signals from large-scale external contributions that predominantly change in north-south direction are suppressed by the gradient method applied in the east-west direction (Olsen et al. 2004). Another advantage of using the east-west gradient as opposed to the originally proposed pair of following spacecraft (Friis-Christensen et al. 2002) is that, for short time intervals (approximately within 10 seconds), gradients along both neighbouring tracks can still be used.

Two satellites flying side-by-side closely spaced in the east-west direction is also a favourable constellation for the determination of ionospheric currents. The estimation of field-aligned currents, for example, will be based on the curl-B technique (Vennerstrøm et al. 2004). At auroral latitudes, where these field-aligned currents are most prominent, field lines are almost vertical. It is proposed to use measurements taken almost simultaneously, i.e. within 10 seconds, at the four corners of a rectangle to calculate the radial current density. The Swarm constellation will allow, for the first time, a unique determination of these very important coupling currents, routing the energy input from the solar wind into the upper atmosphere. With a constellation of satellites, the response of the upper atmosphere to influences from outside can be traced

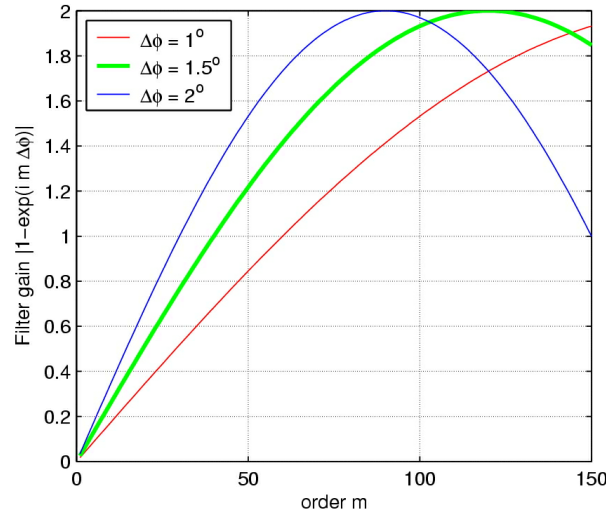


Figure 4.3: Relative sensitivity of the gradient method versus spatial scales. Three examples with different spacecraft longitudinal separations (Olsen et al. 2004).

with increased accuracy. The multi-point measurements also taken at different altitudes allow the determination of the shape of thermospheric density structures or ionospheric plasma enhancements. In addition, the propagation direction and velocity of such features can be obtained. All of these items are necessary pieces of information for a systematic understanding of the atmosphere.

4.1.3 Single Satellite Requirements

From the expected signals listed in Table 4.1 and experiences from Ørsted and CHAMP (Olsen et al. 2003, Reigber et al. 2003), the overall accuracies of the data products at Level 1b for the various quantities can be summarised for each single satellite:

- magnetic field magnitude: 0.15 nT 1σ -accuracy for signals of up to 20 km wavelength, with a stability in time accurate to 0.05 nT per 3 months for the slow variations,
- magnetic field vector: 0.5 nT 1σ -accuracy for signals of up to 2 km wavelength, with a stability in time accurate to 0.5 nT per year for the slow variations,
- electric field vector: 1.5 mV/m 1σ -accuracy for signals of up to 20 km wavelength, with a stability in time accurate to 0.5 mV/m per month for slow variations,
- electron density: $0.5 \cdot 10^{10} \text{ m}^{-3}$ RMS precision for signals of up to 20 km wavelength,
- air drag: $2.5 \cdot 10^{-8} \text{ m s}^{-2}$ 1σ -accuracy for signals of up to 200 km wavelength in all directions.

All listed requirements must be met for each satellite¹ of the proposed configuration.

¹The GNSS radio occultation is no longer part of the baseline mission for several reasons. The radio occultation is a proven concept that is currently flying on Ørsted, CHAMP, GRACE, and SAC-C and has an operational character. This will be expanded in the near future with six COSMIC satellites, MetOp, TerraSAR-X, etc. The scientific analysis requires a combination of data from several satellites and ground stations, which can most likely be achieved by means of the other available satellites during the Swarm mission. In case the capability needs to be enlarged for operational reasons at the time of the Swarm mission, radio occultation equipment could easily be accommodated in the current satellite and ground segment design, which follows from the analysis during Phase A (Technical and Programmatic Annex).

4.1.4 Measurement Principle

The most important quantities to be measured during this mission are the vector components of the magnetic field. A dedicated magnetometer package is required for this task. The primary instrument is the vector magnetometer. To ensure the accuracy of the measurements throughout a multi-year mission, the calibration requires an absolute scalar magnetometer, which may be used for the field magnitude data product also. Another demanding task is to determine the orientation of the vector components in a defined coordinate system. This requires a dedicated attitude sensor. High-quality instruments for such packages have been developed in the context of the Ørsted and CHAMP missions and are readily available for Swarm. The desired accuracy for the magnetic field products is significantly higher than that of existing missions. This demands precise attitude transfer to the vector magnetometer and a magnetically clean or controlled environment. Furthermore, a continuous record of precise orbit information is needed for the interpretation of the data, which can be obtained from a high-quality GNSS receiver.

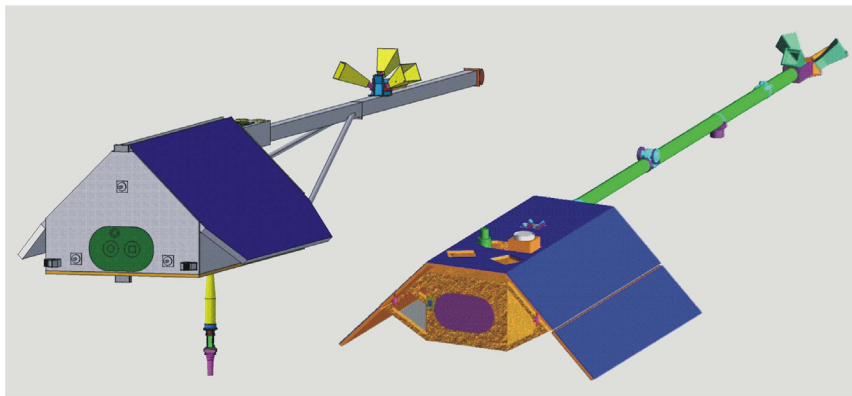


Figure 4.4: *Spacecraft designs proposed by the industrial consortia during Phase A*

For the determination of the electric field, an ion drift meter will be used. The electric field is estimated from the relation between the ion velocity and the magnetic field (Technical and Programmatic Annex). In addition, this instrument measures the plasma density and temperature. This technique has been applied successfully in several low-Earth orbiting missions.

The air drag, needed for deriving the thermospheric density, can be obtained by observing the non-gravitational forces. Suitable instruments, i.e. tri-axial accelerometers, are presently used in gravity missions. Precise orbit information is needed for calibration purposes and for complementing the air drag obtained from an accelerometer at long wavelengths.

In summary, it can be stated that the instruments needed to fulfil the Swarm measurement requirement are available and have in most cases proven their

performances in space. For the magnetic field data products, stronger requirements are needed than for existing missions. This puts increased demands on the spacecraft design.

4.1.5 Time Sampling Requirement

Requirements on sampling rates for the magnetic measurements are driven by the spatial scales and the temporal variations of the ionospheric current systems. The most stringent demands come from the intense fine-scale field-aligned current filaments at auroral latitudes. These have wavelengths down to a kilometre (Neubert and Christensen 2003). At orbital velocities, such structures appear as variations of about 10 Hz. To measure these signals properly, the vector magnetic field has to be sampled faster. An adequate measurement of this high-frequency signal is of scientific interest, since these fine-scale currents seem to play a crucial role in thermospheric heating (Lühr et al. 2004). The in-flight cross-calibrations between the vector and scalar magnetometers (Olsen et al. 2003) also benefit from a high sampling rate because the best results are obtained when both magnetometers sample the signal over the full spectral range. From the science objectives, the following sampling requirements result:

- uninterrupted sampling of the geomagnetic field vector components,
- compatible measurement of the absolute scalar magnetic field for calibration purposes,
- continuous measurement of the electric field vector,
- continuous probing of the local electron density and temperature,
- measuring the non-gravitational forces for air density determination,
- precise measurement of the attitude compatible with the requirements of the vector components,
- uninterrupted tracking of the satellite position in three spatial dimensions.

To take full advantage of a constellation requires that all the satellites can be regarded as part of a single system. Therefore, the following features have to be supported by the spacecraft:

- synchronisation of all measurements to a common external time reference ,
- common calibration of all instruments and capability of in-orbit verification,
- capability to change/maintain the spacecraft separation during the mission.

4.2 Proposed Constellation

As part of an End-to-End Mission Performance Simulation (Olsen et al. 2004), several orbit constellations have been checked for their suitability, including the one originally

proposed (Friis-Christensen et al. 2002). Focussing on the primary research objectives, an optimal configuration of three satellites was identified (Olsen et al. 2004). Although optimal conditions cannot be provided for all the research objectives at the same time, a dedicated mission design makes it possible, thanks to a differential orbital evolution, to experience favourable conditions during parts of the mission. Key features of the orbit evolutions are shown in Figure 4.5. During the first part and at the end of the mission, it is primarily the lithospheric recovery that will benefit. Periods of all three satellites being close together within a radius of a few thousand kilometres are very favourable. The most important contribution, however, comes from the closely spaced lower pair of satellites flying side-by-side. A separation of 1-1.5° in longitude is optimal according to Figure 4.3 for mapping crust signals up to degrees 150. The best conditions for core field, secular variation, and induction studies are obtained in the middle part of the mission when the two orbital planes are separated by 3 to 9 hours in local time.

The identified three-satellite orbit constellation that can be achieved through a single launch (Technical and Programmatic Annex), comprises the following parameters:

- One pair of satellites (Swarm A+B) flying side-by-side in near-polar, circular orbits with an initial altitude and inclination of 450 km and 87.4°, respectively. The east-west separation between the satellites will be between 1-1.5° in longitude, and the maximal differential delay in orbit will be approximately 10 seconds.
- One higher satellite (Swarm C) in a circular orbit with 86.8° inclination at an initial altitude of 530 km with right ascension of the ascending node close to that of the two other satellites.

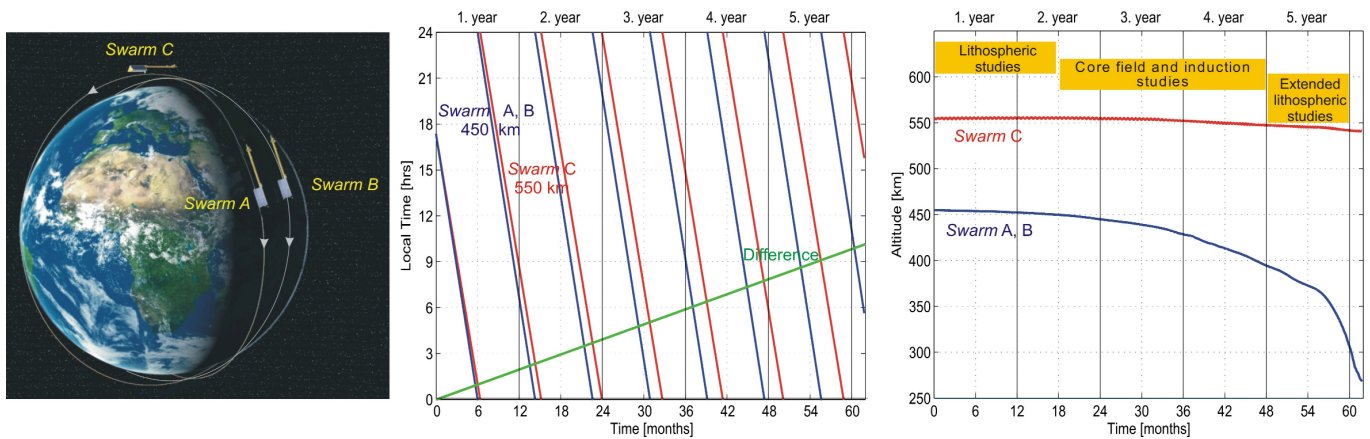


Figure 4.5: Impression of the proposed three satellite constellation (left) and mission scenario. Local time evolution for the satellites in the two orbital planes (centre); change in altitude versus time (right).

The research objectives associated with the study of high-latitude current systems would benefit significantly from a fourth spacecraft in the higher orbit plane at a phase difference of 180°, sampling the antipodes simultaneously. Many of the processes in the polar regions of the two hemispheres are related to each other. Existing

measurements do not allow analysis of the differences between them. The impact on the primary research objectives of the fourth satellite in various orbit planes was analysed (Olsen et al. 2004) and is discussed in Chapter 6.

4.3 Timing of the Mission

A launch in 2008 is optimal for several reasons. It will make the Swarm mission an important element in the *International Decade of Geopotential Research* programme, continuing directly the series of the Ørsted, CHAMP and SAC-C magnetic field missions. One of the prime objectives of the programme – obtaining satellite measurements of the geomagnetic field over a full solar cycle (1999 – 2010+) – can thus be achieved. Covering this basic period of solar activity provides the opportunity to experience the full range of variability of the external field components. Although the occurrence of a geomagnetic jerk cannot be predicted, its typical recurrence rate is once per decade (cf. Fig. 4.6 left). We would thus, for the first time, have the chance to investigate globally such a sudden magnetic change, and to study its temporal and spatial evolution. Reconstructing the core dynamics at its smallest observable temporal and spatial scales will provide important constraints for geodynamo studies.

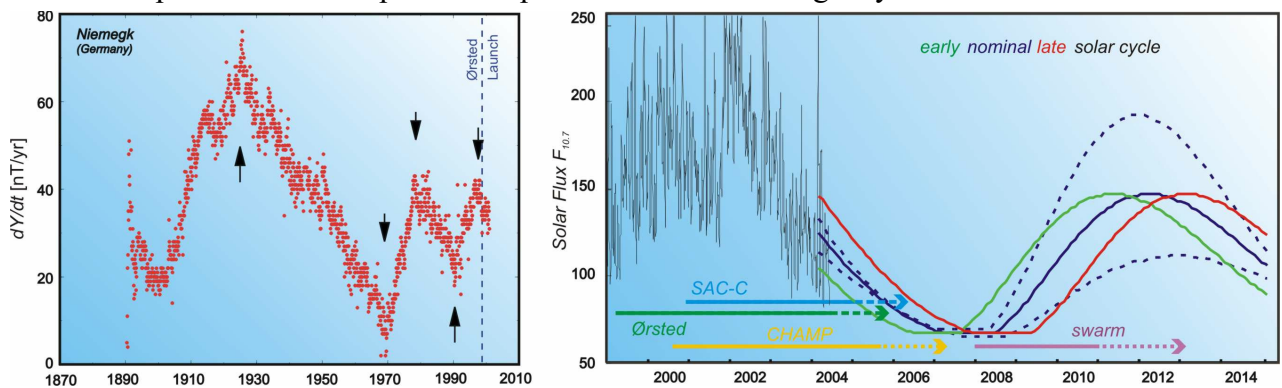


Figure 4.6: Sudden changes of the secular variation in the east components are termed jerks (left); observed and predicted variation of solar activity reflected by the $F_{10.7}$ index. Uncertainties of the prediction are indicated (right).

The year 2008 falls, as shown in Figure 4.6 (right), into a solar minimum. It is known that the early years of the slowly rising solar activity are magnetically very quiet. The Swarm mission thus would take advantage of the most suitable period for internal field studies. The scientific return in terms of internal field modelling efforts, using data sampled during magnetically quiet periods, would be particularly high in that case.

4.4 The Need for Observations from Space

Most of the research objectives outlined in Chapter 3 require a dense global coverage of magnetic field observations within a short time span. Sampling points shall not be separated by more than 200 km. This cannot be achieved from ground-based stations.

We may conclude that there is no viable alternative to a space-based magnetic field mission when it comes to global, high-resolution geomagnetic field mapping. Nonetheless, the data obtained by magnetic observatories are also of great value for the resulting scientific products, the magnetic field models. This is because observatories lie below the ionosphere and record the magnetic field in a continuous manner at fixed locations. Some of the scientific objectives, in particular those concerned with ionosphere and thermosphere phenomena, can only be accomplished by space-borne measurements. For example, the field-aligned currents, which are an important means for routing energy and momentum from outer space into the upper atmosphere, are virtually invisible in ground-based magnetic field measurements. Similarly, there are no reasonable alternatives to mapping the global electric field, detecting thermospheric density structures, and retrieving the 3-D conductivity of the mantle.

For a successful accomplishment of the Swarm mission, the following elements are required: a space segment, consisting of 3 satellites carrying a suite of instruments, and a ground segment, consisting of the data reception and mission control centre, as well as a data processing and archiving centre.

4.5 Target and Threshold Requirements

The level of performance reached by currently available space instruments is already fairly high. For the Swarm mission, it is anticipated to basically rely on instrument performances of the sort achieved with Ørsted and CHAMP. However, higher accuracy demands are put on the final data products, based on experience gained from the existing missions. The improved quality of the derived information is expected to rely on coordinated measurements at the dedicated spacing provided by the controlled constellation of spacecraft. An important requirement regarding the Swarm mission is thus that the complement of all spacecraft is treated as a single system. This implies that all readings from the three satellites must be directly comparable. A desirable mission target would be to achieve the overall mission requirements listed above at Swarm system level. Such a performance would contribute to improving our knowledge significantly in several areas of geomagnetism.

As a minimum, each of the spacecraft should perform as well as existing magnetic field missions. In particular, if the direct comparability between the different spacecraft is no longer available, e.g. due to instrument problems, the value of the constellation concept could be reduced, depending on the instrument. The advantage of a multi-satellite mission could then be limited to the larger number of measurements, but still with a better performance than at present. If one of the satellites fails, reductions in some of the anticipated scientific results are expected. In case of failure of the higher satellite, mainly the core field studies would suffer, while in case of a lower satellite failure, the performance of the lithospheric recovery would be significantly reduced. This indicates that a reduction to less than three satellites would result in possible non-compliance with the primary research objectives (Olsen et al. 2004).

5. Data Processing Requirements

For the Swarm mission, the main data products up to Level 1b will be provided as time series along the different satellite tracks. Only between Level 1b and Level 2 will data from different Swarm satellites be combined and, if necessary, data from other sources added. For Level 1b and specific Level 2 data products the processing chains will be explained. Some of the products/models that require dedicated computing centres to serve the user community will be discussed in more detail, based upon today's experiences from the Ørsted and CHAMP missions,

5.1 Scientific Data Processing

The processing of the scientific data follows several steps, data-products outputs at increasing levels. For the prime Swarm mission objectives, the processing can be done in a self-contained manner by using the satellite data. Based on the requirements of the scientific community and experience gained with the present satellite missions Ørsted and CHAMP, the data may be distributed to the scientific community as daily files in CDF² data format.

Level 0: Spacecraft and instrument housekeeping data, attitude sensor (ASC), 1Hz; Instrument science raw data from absolute scalar magnetometer (ASM); vector flux-gate magnetometer (VFM), 50Hz; electric field instrument (EFI), up to 16Hz; accelerometer (ACC), 1Hz; Global Navigation Satellite System receiver (GNSS), at least 0.1Hz position.

Level 1a: Time series of merged relevant housekeeping, instrument and auxiliary data needed for processing and calibrating the measurements; post-processed orbit and attitude data.

Level 1b: Time series of relevant quantities as observed along the orbit, corrected, calibrated and converted to physical units. Magnetic field magnitude (1Hz), field vector in the spacecraft frame and in the geophysical north, east, centre (NEC²) frame (50 Hz) and coarser sampling rate (e.g. 1Hz)⁴; ion drift vector and electric field in NEC frame electron density and temperature (all 2Hz); acceleration vector, linear and rotational, in spacecraft frame at 1Hz; position, velocity and attitude of spacecraft (all 1Hz) derived from Precise Orbit Determination (POD) system.

Level 2: Global models of all the sources of the geomagnetic field; regional models of ionospheric current systems; improved global ionospheric and plasmaspheric models;

² NSSDC's CDF Homepage: <http://nssdc.gsfc.nasa.gov/cdf/>

³ The NEC (north, east, centre) frame is a local frame with the origin in the geometric centre of the vector feedback magnetometer (VFM). The radial component points from the centre of the VFM towards the centre of the Earth (defined in ITRF). The north (N) and east (E) components point from the centre of the VFM towards north and east, i.e. along the local tangent to the meridian, respectively, the parallel, of the sphere (defined in ITRF) with radius from the centre of the Earth to the centre of the instrument.

⁴ Down-sampling may be done using approaches developed for the Ørsted mission by Philip B. Stark from the University of California, Berkeley (<http://128.32.135.2/~stark/Preprints/Oersted/writeup.htm>).

improved parametrisation of atmospheric models; thermospheric density and cross track winds; quality assessment of the products.

The flow from the observations of the different instruments (Level 0), through calibrated data (Level 1), to achieve the scientific objectives (up to Level 2) is schematically shown in the flowcharts below; further details can be found in (Technical and Programmatic Annex, Olsen et al. 2004; Vennerstrøm et al. 2004).

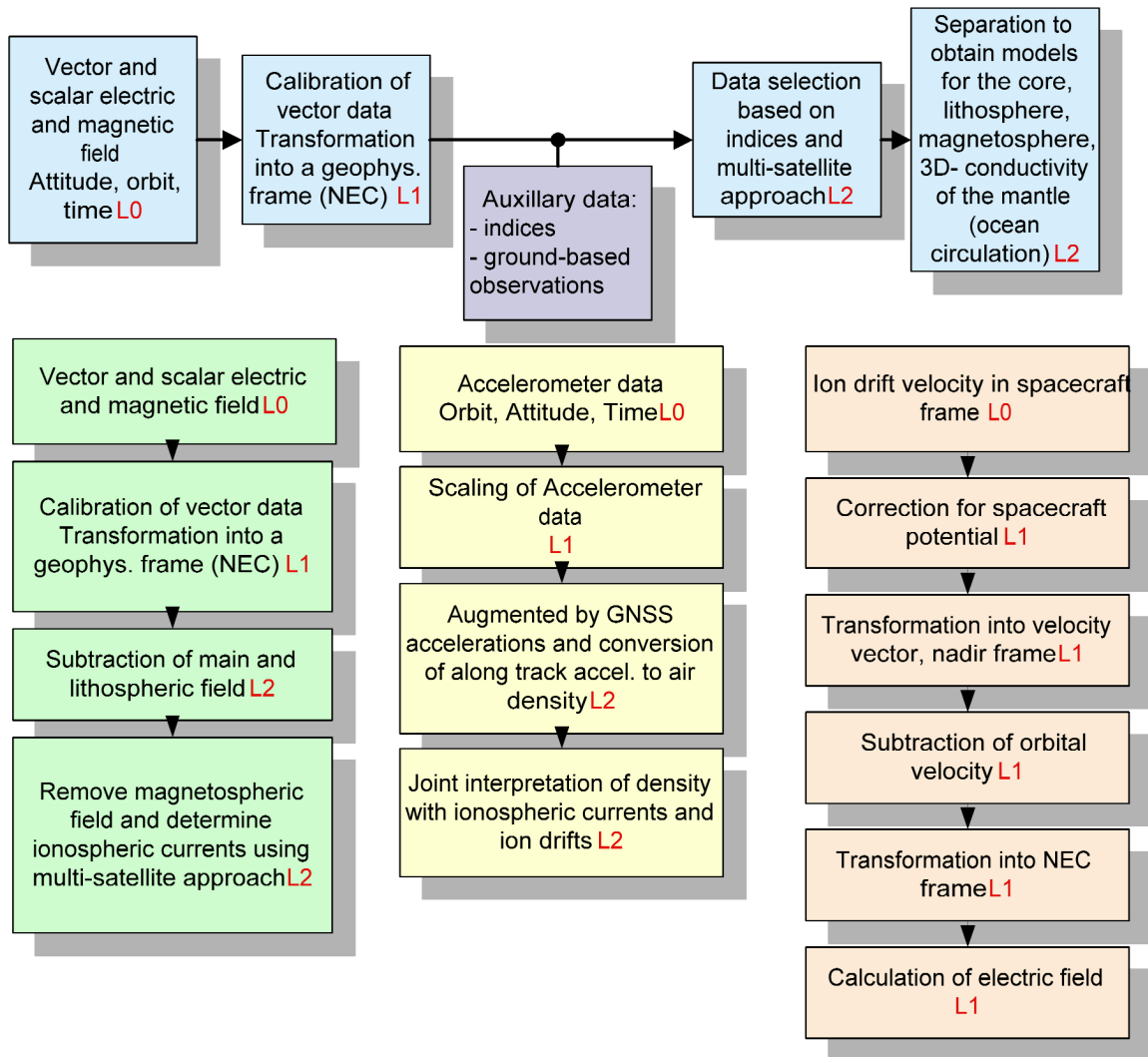


Figure 5.1: Determination of magnetic contributions (top), ionospheric current systems (left), magnetic forcing of thermospheric density (centre), and determination of the electric field vector (right). (L0 is Level 0, L1 is Level 1, and L2 is Level 2)

At Level 3 scientific value-added products can be derived, for example, for modelling related to space weather, solid-Earth physics and exploration, for studies related to continental heat flux, and as international reference models. These will be discussed in more detail in Chapter 9.

Most algorithms for the Level 0 to Level 1 and Level 1 to Level 2 processing are mature and build upon the heritage of Ørsted and CHAMP. For Level 1, the algorithms have been implemented during the Phase A studies in the industrial system simulator and extensive performance analysis was done (Technical and Programmatic Annex). Regarding the Level 1 to Level 2 processing, existing approaches have been modified to cope with a constellation instead of a single satellite during the end-to-end mission performance simulator study. Some refinements and optimisation of algorithms are foreseen. Also, tools for a quality assessment for the Level 2 products need to be further elaborated beyond the simulator environment. The new aspects of the mission related to the 3-D conductivity of the mantle, the estimation of field aligned currents, the improved data selection related to better knowledge of the disturbing effects from external currents and ocean flow, resulted in development of methods and algorithms during the Phase A (Olsen et al. 2004, Vennerstrøm et al. 2004). In these new fields further developments can be expected in the near future to optimise procedures and retrieval algorithms.

5.2 Scientific Data Calibration and Validation

The calibration activities for the magnetometer package follow the procedures that have been developed and successfully applied to the present single-satellite missions (cf. Olsen et al. 2003). In addition, the multi-satellite aspect will be considered by comparing the observed field during close encounters and by joint inversion of the data from all satellites and ground observatories (e.g. Sabaka et al. 2002). In addition, dedicated multi-satellite methods (for instance based on those developed for the ESA Cluster mission; Paschmann and Daly 1998) will be used. The calibration activities for the magnetometer package consist of:

- ground calibration of scalar and vector magnetometers and attitude sensor at instrument, package and satellite level,
- in-flight calibration of vector magnetometer at satellite level (by comparison with the scalar magnetometer); verification at mission level (as a by-product of magnetic field modelling using all Swarm satellites),
- in-flight estimation of vector instrument-attitude sensor alignment at mission level (as a by-product of magnetic field modelling using all Swarm satellites),
- taking measurements with the vector magnetometer pointing cross-track (for better separation of magnetometer parameter combinations, like non-orthogonalities and offsets) and/or with all spacecraft close together at the beginning of the mission (proposed as an option after launch during the industrial studies; see Technical and Programmatic Annex).

The satellite inter-calibration is new and its possible merits need to be studied in more detail to arrive at an optimal procedure for reducing relative errors between the individual satellites even further.

The calibration activities for the electric field instruments consist of:

- ground calibration at instrument level,
- in-flight calibration at satellite level requiring attitude manoeuvres during the commissioning phase for the determination of overall alignment and measurement biases.

Calibration of the accelerometer can be achieved by:

- ground calibration at instrument, and satellite level,
- in-flight calibration by estimation of biases and scale factors in the precise orbit determination (Reigber et al. 2003) and/or by comparison with GNSS-based accelerations obtained from the best available gravity field and tide models from CHAMP, GRACE and/or GOCE (IJssel and Visser 2004).

The accuracy and reliability of the various data products has to be validated. The basic concept for that is a consistency check between results obtained by different instruments or comparison with models:

- the electrical field instrument data will be verified during passes over incoherent scatter radars like EISCAT,
- an inter-comparison between the individual spacecraft during close encounters will be performed routinely (see Purucker et al. 2003, for examples of close encounters of the Ørsted/CHAMP/SAC-C satellites),
- comparisons with data from other missions that are (still) operational will also be performed,
- the Swarm magnetic field models (Level 2 data) will be validated through comparison with data from magnetic observatories and independent models.

The different steps that are required in the data processing have been identified and described. The derivation of all variables (Level 0 and Level 1 processing) that form the basis for the recovery of the magnetic field, and other Level 2 products, is well understood. It has been demonstrated how the various instrument and sensor combinations at the specific locations in the spacecraft can be merged to provide the necessary information for this derivation, including ancillary data such as calibration parameters (Technical and Programmatic Annex; Friis-Christensen et al. 2002). It has also been demonstrated by a full-scale end-to-end mission performance simulator (Olsen et al. 2004) that already mature algorithms and software exist for the production of the products and the quality assessment under controlled circumstances. The tools for quality assessment of the final real-world models need some further development, but it is known what should be implemented.

6. Performance Estimation

The success of the mission will depend on the success in implementing new and advanced models of the static and dynamic part of the Earth's magnetic field. Based on a data set that is unique in accuracy as well as in spatial and local time coverage, these models will provide new insight in our system Earth, including its interior and environment. Meeting the research objectives requires a complex analysis where the constellation of satellites is crucial for separating the various contributions from the Earth and its continuously changing environment. The analysis of mission performance includes:

- single satellite performance based on the industrial Phase A studies (Technical and Programmatic Annex),
- constellation performance based on the end-to-end mission performance studies (Olsen et al. 2004, Visser and IJssel 2003, Vennerstrøm et al. 2004).

A full mission simulation has been performed for the constellation. The four-year simulation was set exactly one full solar cycle before the planned mission, in order to use realistic indices of the Earth's environment. The magnetic field models used for the system simulator study of the industrial Phase A studies were made compatible, so that a similar realism was built into the performance analysis at the system level. The errors of the system simulator for the magnetic field products were fed back into the multi-satellite mission performance simulator and the error models generated a priori from CHAMP experiences were reviewed. The synthetic magnetic field values were generated based upon a combination of existing and simulated models for all relevant contributions. Measurements and errors for a total of six different satellites were generated for the complete mission lifetime (190 million satellite positions), which amounted to 10,950 files (2.42 MB each), requiring 26.5 GB per constellation run. Out of these six satellites, different constellations of 1, 2, 3 and 4 satellites were selected and the success in recovering the original models was analysed for each constellation. The starting point was the 4-satellite constellation from the original proposal (Friis-Christensen et al. 2002). Modified 3- and 4-satellite constellations provide significantly improved scientific return, as already addressed in Chapter 4 and explained below (Olsen et al. 2004, Vennerstrøm et al. 2004).

6.1 Single Satellite Performance

Each satellite carries a payload package for observing the magnetic field, the electric field and the non-gravitational acceleration changes. An error analysis is done considering the relevant error budgets that play a role in expressing the overall performance of the Level 1b products. The total error for a product contains contributions from each of the categories specified in Figure 6.1. Instrument errors contain all elements of the instrument itself that impact directly on the raw

measurement. Instrument-satellite coupling errors contain all effects from the satellite, including other payloads, on an instrument under consideration. Satellite errors are directly related to the satellite. Post-flight errors include processing and in-flight calibration errors, which themselves can include other Level 1b product errors for example.

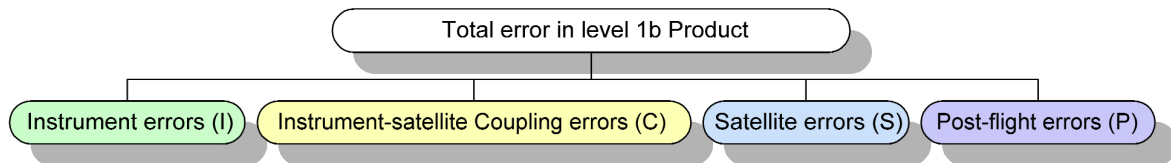


Figure 6.1: Error sources contributing to the final Level 1b product error.

6.1.1 Magnetic Field Products

The error budget for the **magnetic field magnitude** product at Level 1b contains the following error contributions (the letters refer to Figure 6.1):

- measurement accuracy of scalar instrument (I),
- magnetic disturbance from vector instrument, attitude sensor units, and optical bench; magnetic disturbance from the satellite platform, including boom; uncertainty resulting from timing errors (C),
- uncertainty resulting from position determination errors (S) (P),
- uncertainty with respect to instrument calibration parameters (P).

The error budget for the **magnetic field vector** product at Level 1b contains the following main error contributions:

- measurement accuracy of vector instrument (I),
- magnetic disturbance from scalar instrument, the attitude sensor unit, the optical bench; magnetic disturbance from the satellite platform, including boom; uncertainty resulting from timing errors (C),
- uncertainty of the vector/scalar instrument inter-calibration; uncertainty of the vector instrument/attitude sensor inter-alignment; uncertainty of attitude knowledge, including attitude jitter uncertainty resulting from boom dynamics (P),
- uncertainty resulting from position determination errors (S) (P).

Most of these error estimates have been generated in the system simulator based upon the designs proposed for Swarm and experience from existing missions like CHAMP and Ørsted. Some parts were assessed using an analytic approach, however, based upon current procedures and knowledge from the existing missions. Those effects are covered in more detail in the technical description (Technical and Programmatic Annex).

6.1.2 Electric Field Products

The error budget for the **electric field vector** product at Level 1b contains the following main error contributions:

- measurement accuracy of instruments (I),
- accuracy of sensor apertures pointing in the spacecraft ram direction; obstruction within the required field of view; uncertainty resulting from timing errors (C),
- uncertainty of spacecraft potential (S),
- uncertainty of attitude knowledge; uncertainty of magnetic field vector; calibration errors (P).

The error budget for the **electron density** product at Level 1b consists of the following main error contributions:

- measurement accuracy of instruments; uncertainty in electrical surface property of probe (I),
- spacecraft potential close to instrument accommodation higher than 1V; obstruction within the required field of view; uncertainty resulting from timing errors (C).
- uncertainty resulting from derived plasma drift velocity (P).

6.1.3 Air Drag Product

The error budget for the **air drag** product at Level 1b consists of the following main error contributions:

- measurement accuracy of instruments (I),
- uncertainty in optical properties of surfaces affecting the radiation pressure; uncertainty resulting from timing errors (C),
- uncertainty of instrument position with respect to spacecraft centre of gravity; uncertainty of attitude knowledge; uncertainty of combination / inter-calibration with GPS (P).

The observations of the Swarm accelerometers can be used to their full extent only after proper calibration and validation. The CHAMP mission has proved that accelerometer biases and scale factors can be estimated with high precision in a precise orbit determination based on GNSS (or GPS) satellite-to-satellite tracking observations (supported by a ground network), provided a high-quality gravity field model is available (Reigber et al. 2003, Visser 2003). At the time when the Swarm satellites will fly, the CHAMP and GRACE missions will have resulted in improved and high-

precision gravity field and tide models. This will allow an even better calibration of space-borne accelerometers than is currently possible.

In addition, improved gravity field modelling opens the possibility to derive non-gravitational accelerations from the GNSS observations. In principle, the total satellite accelerations can be derived from such observations. After subtracting the gravity contribution, the non-gravitational accelerations can be derived indirectly. This concept has been proved by a supporting study of the Swarm end-to-end simulator (IJssel and Visser 2004). CHAMP along-track and cross-track non-gravitational accelerations were derived from the GNSS observations that match very well the observations made by the accelerometer instrument, especially at the longer wavelengths. This way, the accelerometer observations can be validated independently at these longer wavelengths, and accelerometer biases and scale factors can be derived. Moreover, a possible degraded performance of the accelerometers at very low frequencies (or long wavelengths) can be compensated by the strong performance of GNSS in the long wavelength domain. Although it is not possible at present to derive non-gravitational accelerations from GNSS observations with a precision and resolution in accordance with the Swarm requirements, this technique provides a certain level of redundancy and partial backup for the accelerometers, thereby enhancing the robustness of the Swarm baseline mission concept.

The accelerometer Level 1b products in orbit can be cleaned of relevant non-air drag accelerations due to solar radiation pressure, the Earth's albedo and IR radiation (Bruinsma and Biancale 2003). This provides the required air drag products. The following step is the conversion of air drag values into air density figures, with an expected precision of 10% of the air density signal, following approaches as proposed in Lühr et al. (2004). Also air drag, electric field and magnetic field values from the individual satellites need to be combined to investigate the physical mechanism responsible for the density variations.

6.1.4 Performance Summary for Level 1b

Table 6.1 provides an overview of the required measurement performance at Level 1b as specified in Chapter 4, in comparison with the results of the analytical assessment and the numerical simulation results from the system simulator, both derived from the industrial Phase A studies. The numerical simulation results have been obtained for different types of orbits and environments to analyse any possible impact on the products. The predicted performance generally includes worst-case scenarios, so that the simulations may lead to more optimistic results for more general circumstances. For the electric field vector product, the magnetic field vector product, and the electron density, the numerical simulations were carried out in a simplified way (see Technical and Programmatic Annex).

	Requirement (1σ)	Predicted Performance #	Numerical Simulation Results
Scalar magnetic field down to 20 km scales	Random: 0.15 nT	0.13 nT	0.11 nT
	Stability: 0.05 nT per 3 months	compliant	n.a.
Vector magnetic field down to 2 km scales	Random: 0.5 nT	0.49 nT*	[0.245, 0.155, 0.22] nT
	Stability: 0.5 nT per year	0.49 nT	n.a.
Vector electric field down to 20 km scales	Random: 1.5mV/m	1.35 m V/m**	[0.22, 0.345, 0.20] mV/m
	Stability 0.5 mV/m per month	compliant	n.a.
Electron density down to 20 km scales	$0.5 \cdot 10^{10} \text{ m}^{-3}$ RMS precision	compliant	$0.6 \cdot 10^{10} \text{ m}^{-3}$ RMS***
Air drag down to 200 km scales	Random $2.5 \cdot 10^{-8} \text{ m s}^{-2}$	$1.5 \cdot 10^{-8} \text{ m s}^{-2}$	$[0.9, 1.6, 1.85] \cdot 10^{-8} \text{ m s}^{-2}$

In the case of a vector, one value is given that is representative for each of the three components.

* Predicted value from analytic assessment is higher because this also includes the expected calibration errors. The latter are considered realistic because they are based upon what is currently possible for single-satellite missions like Ørsted and CHAMP.

** Predicted value from the analytical assessment is higher because it includes worst-case values for effects that were not included in the simulator (Technical and Programmatic Annex).

*** Results based on a simplified model (Technical and Programmatic Annex).

Table 6.1: Overview of required and expected measurement performance at Level 1b.

6.2 Constellation Performance

Each of the satellites has a better single-satellite performance related to the magnetic field products than existing missions such as Ørsted and CHAMP. Also, the Level 1b data accuracy (1σ) of each Swarm satellite, which is 0.5 nT for the vector components and 0.15 nT for the field intensity, will be superior to that of any previous or present satellite missions, which have a vector component accuracy of approximately 2-5 nT. The main reason for this is the unique triple-head attitude sensor concept of Swarm in combination with the ultra-stable optical bench that connects attitude sensor and vector magnetometer, and the improved in-flight inter-satellite calibration possibility.

This increased data accuracy already leads to improved magnetic field models. Moreover, analysing data from two instead of one satellite will double the number of data points, and from that one might expect an improvement in the results by a factor of $\sqrt{2}$, and by factor of $\sqrt{3}$ if data from 3 satellites are combined. This, however, is only the case if the data are statistically independent; the improvement can be much less if unmodelled large-scale magnetospheric contributions are present. Nevertheless, the

actual improvement obtained with the Swarm mission will be much higher than these values, indicating that advantage has been taken of the specific constellation. Such a specially designed multi-satellite observational system is new for Earth Observation in this field and opens up possibilities for scientific advancement that cannot be obtained from a single-satellite mission. Two dedicated studies (Olsen et al. 2004, Vennerstrøm et al. 2004) were performed during Phase A to optimise the choice of a constellation for the Swarm satellites that would best achieve the scientific objectives of the mission. The performance of the finally selected constellations in relation to the recovery of models and the links to the science objectives are described below.

Several independent methods were applied in the simulation environment to analyse various aspects of the model estimation in relation to different numbers of satellites, different constellations, and realistic noise sources. The comprehensive inversion (Sabaka et al. 2002, 2004), which contains parameterisation of all relevant sources, has been chosen as the primary approach for field recovery and error analysis. However, independent approaches for improved lithospheric modelling and field aligned currents (Maus et al. 2004, Vennerstrøm et al. 2004) show potential for further exploitation of the satellite.

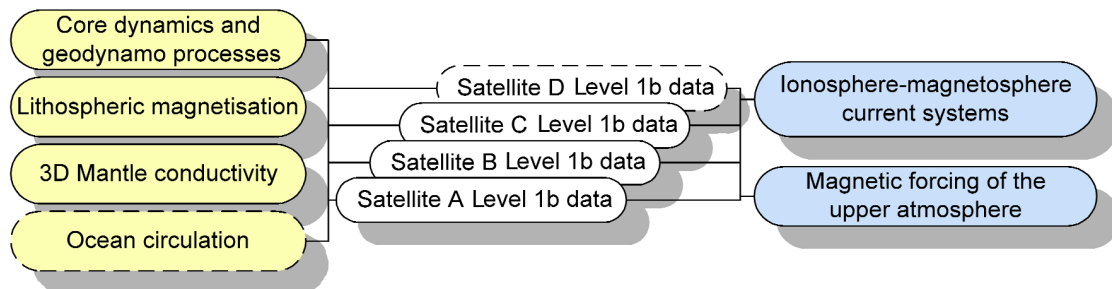


Figure 6.2: The satellites A, B and C are described in Chapter 4.2. Satellite D has a 530 km initial altitude at 86.8° inclination, a node 12° westward of C, and 180° out of phase with the latter. Level 1b vector and scalar products and auxiliary products are used to determine the field models.

6.2.1 Performance Related to Internal Fields

6.2.1.1 Lithosphere

The black curve of the left panel of Figure 6.3 shows the degree signal, i.e. the square root of the degree variance, of the lithospheric vector field at ground. The relation between a certain spherical harmonic degree and spatial wavelength can be read from Figure 4.1. The degree errors of models derived from MAGSAT and CHAMP, combined with Ørsted, are included (dashed blue lines). The error exceeds the signal beyond degree 30 for MAGSAT, and beyond degree 60 for the present CHAMP model. The difference between CHAMP and MAGSAT models is due to significantly improved data accuracy and the longer observational period. Future CHAMP data collected at 300 km altitude will probably allow this model to be extended to degree 70 or so.

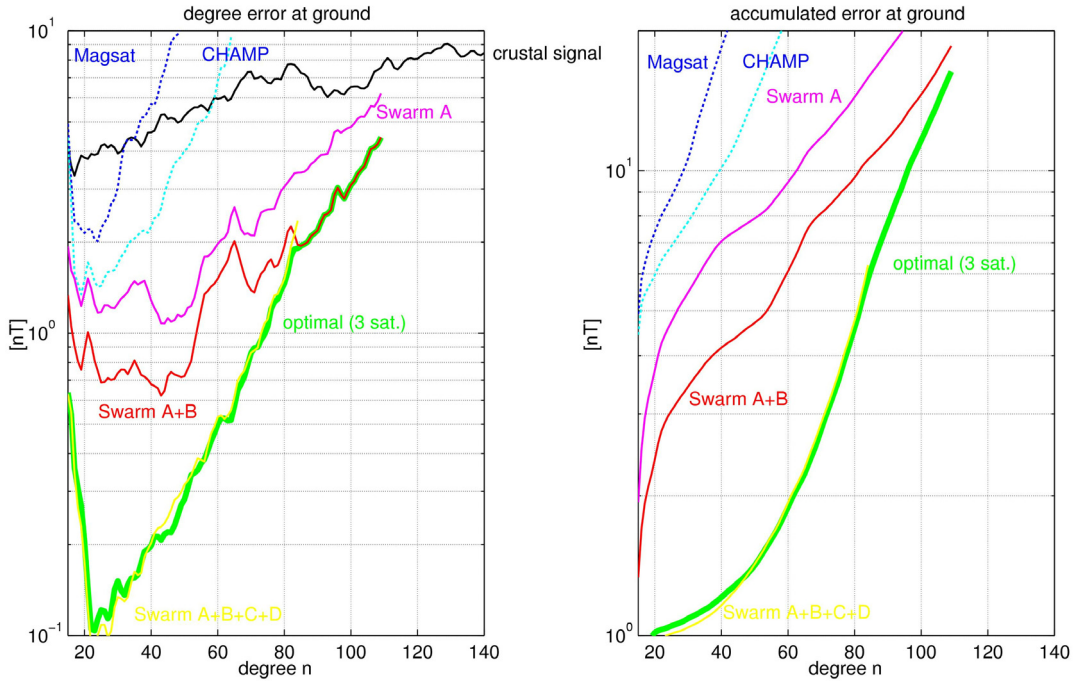


Figure 6.3: Degree error (left) and accumulated error (right) of the lithospheric field recovery for different satellite combinations and approaches against spherical harmonic degree. Black curve presents the crustal signal.

The magenta curve shows the error in a model derived from single Swarm satellite data observed at an altitude of about 300km towards the end of the mission. Compared to present state-of-the-art models, this curve indicates the improvement that one will get from the higher accuracy of the Level 1b products of the Swarm mission. Combining data from the two side-by-side flying lower Swarm satellites A and B significantly improves field recovery at higher degrees (Olsen et al. 2004). The green curve shows the three-satellite solution (Swarm A, B and C) that can be obtained using existing approaches (Sabaka et al. 2002, Maus et al. 2002) that have been optimised for model recovery from gradient data (Olsen et al. 2004). The co-estimation of external and induced fields results in much improved crustal field recovery for degrees below 80. The fourth satellite (yellow curve) does not improve crustal field recovery significantly. Figure 6.4 shows the lithospheric radial magnetic component at ground derived from a state-of-the art crustal model up to degree 60, left panel, and the improvement (field models up to the range between degree 110 and 150) that Swarm will provide, right panel. This will bridge the existing gap between satellite models and data from ground, airborne and marine surveys.

6.2.1.2 Core Field and Secular Variation

Without Swarm satellite data, models of the time change of the magnetic field have to be based on magnetic ground data. This allows for deriving field models only up to degree 8 (Alexandrescu et al. 1994), indicated by the magenta curve in Figure 6.5.

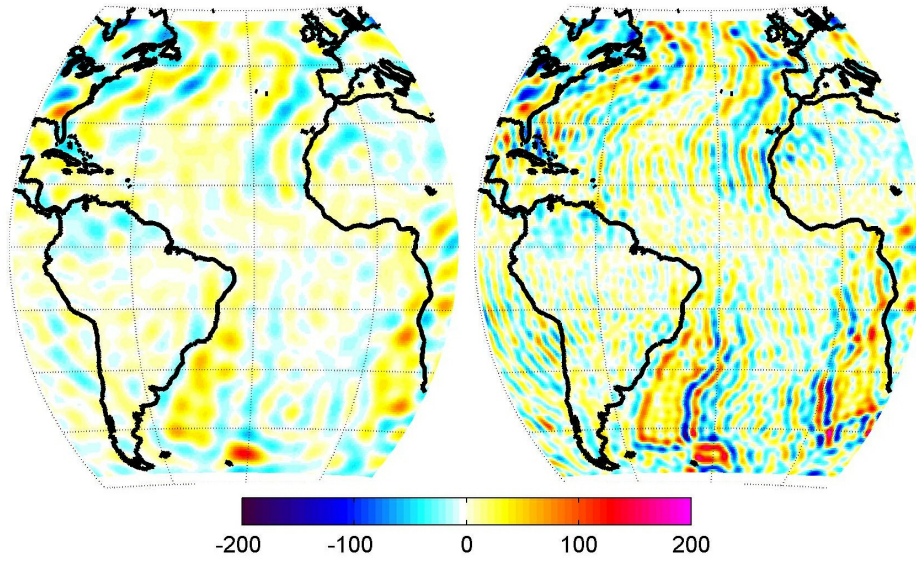


Figure 6.4: Radial magnetic component of the lithosphere (in nT) at ground, up to degree 60 (present state, left panel) and up to degree 133 (anticipated Swarm result, right panel).

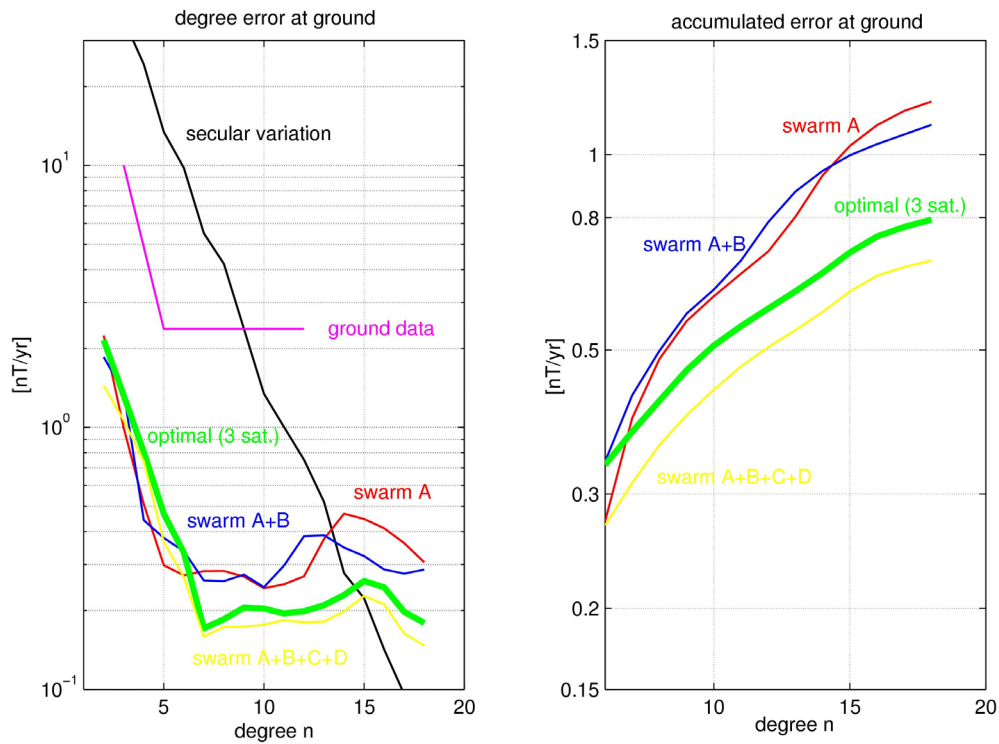


Figure 6.5: Degree error (left) and accumulated error (right) of the secular variation for different satellite combinations and approaches. Black curve presents secular variation signal.

Models derived from single-satellite missions will reduce the degree error typically by one order of magnitude. The proposed constellation with 3 Swarm satellites allows determination of secular variation models up to degree 15, with half the degree error obtainable with a single satellite. The short-time fluctuations in the secular variation can be improved with data from a constellation. Models derived from Ørsted data, over two-month intervals, show that secular variation cannot be directly obtained on this short time scale, due to the limited geographical distribution of a single satellite (Langlais et al. 2003). However, the increased geographical coverage available from the proposed satellite constellation will allow the recovery of core field and secular variation simultaneously up to degree 14 (Olsen et al. 2004).

6.2.1.3 3D Mantle Conductivity

Magnetic field variations with periods of a few hours to 30 days are indicators of mantle conductivity in the depth range between about 400 and 1000 km. Swarm will allow global determination of 3D structures in the electrical conductivity of the mantle for the first time. Key for this is the simultaneous observation of the magnetic field variations at different local times, resulting in models of the time-space structure of inducing magnetospheric and ionospheric fields. This can be achieved in the important period range of a few days down to a scale of 8000 km, corresponding to degree 5.

The C-response (Schmucker 1985) of a location is a transfer function that connects the vertical component of the magnetic field variation and the horizontal derivatives of the horizontal components; its frequency dependence contains information on the variation of conductivity with depth in the surrounding of that location. The real part of the C-response indicates the depth of the induced currents; regions with reduced real parts indicate shallower induced currents, as shown in the left part of Figure 6.6, which shows the true value of the real part that has been used as input for the simulation. The centre part of the figure demonstrates a successful detection of a conductivity anomaly beneath the Pacific with 3 Swarm satellites; a detection using single satellites (right panel) is not possible. This demonstrates the ability of Swarm to detect regions of enhanced conductivity at 400 km depth, the boundary of which is indicated by the thick black curve. External field variations of 7-day period induce currents that are normally flowing at about 800-900 km depth; they will, however, be shallower beneath the Pacific since they tend to flow in regions of higher conductivity.

Three specific locations, marked in green in Figure 6.6, have been selected because they represent different regimes for the mantle environment. The frequency-dependence of the C-response for these locations is shown in the left part of Figure 6.7; as expected, the real part increases with the period, since variations at longer periods penetrate deeper into the mantle. The right panel shows the error in the recovered C-response from 1 and 3 satellites, respectively. The recovery is shown in relation to the original model responses for these locations in Figure 6.6. The relative errors in the right panel of this figure show a drastic improvement for three satellites, down to

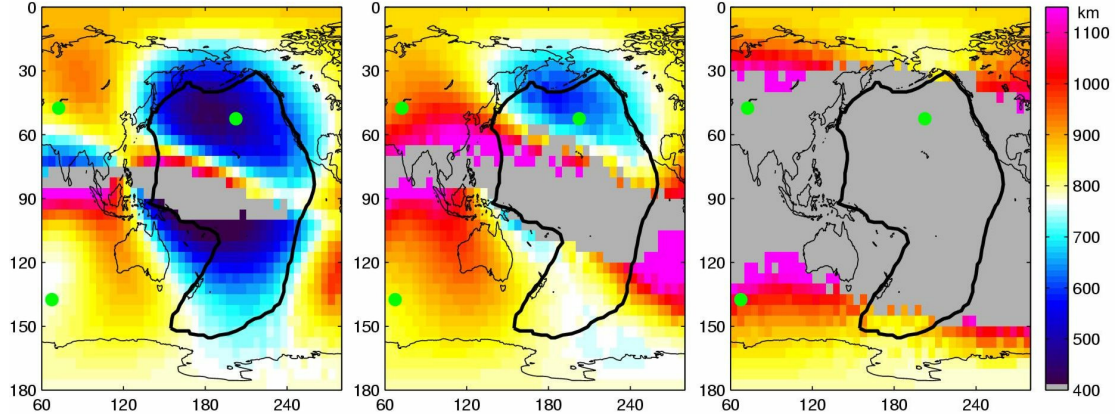


Figure 6.6: Maps of the real part of the C -response for a period of 7 days. The thick black curve indicates the boundaries of a hypothetical conductivity anomaly at 400 km depth. True values (left); estimated ones using 3 satellites (centre); and estimated ones from one single satellite (right). Regions in which squared coherency is below 0.6 are excluded and shown in grey.

approximately 10% of the expected responses, whereas the single-satellite solutions perform poorly. Since the model does not contain inhomogeneities in the lower mantle, the error with the single satellite solution is less at longer periods, but still larger than the 3-satellite solution by a factor of at least 2.

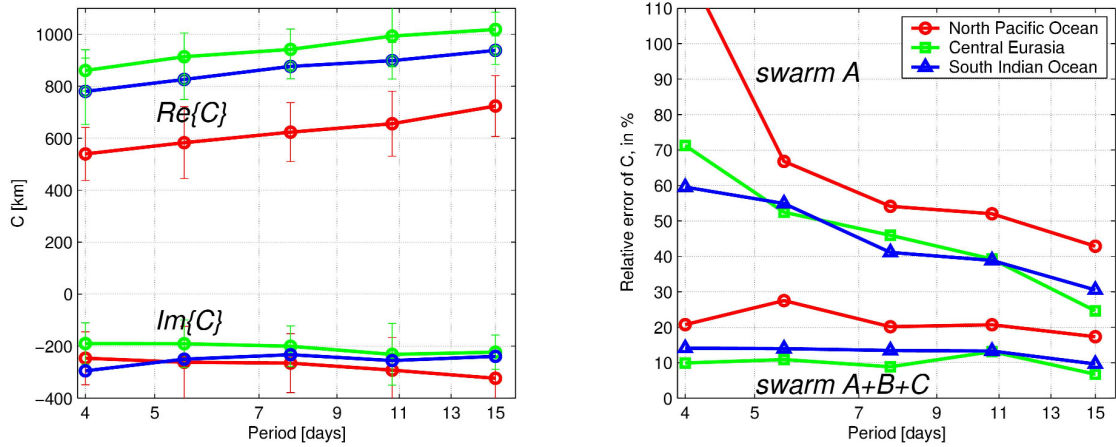


Figure 6.7: Single site C -response estimation using 3 satellites against true values and error bars (left). The locations of these sites are shown by the green dots in Figure 6.6. The relative error of C -response estimation for a single satellite and the proposed 3 satellite constellation solutions are also shown (right).

6.2.1.4 Ocean Circulation

It has already been demonstrated that the prominent tidal signals present in the CHAMP magnetic field data can be recovered (Tyler et al. 2003). The first attempts to recover simulated tidal signals from a constellation indicate a significant improvement from the one- or two-satellite to the three-satellite solutions (Olsen et al. 2004). The

gain with the fourth satellite is marginal. Although ocean-tide models are rather well known Swarm could possibly contribute to the improvement of some weaker lunar-solar components. However, this needs further analysis. The magnetic signature of general ocean circulation and its seasonal variations is derived from the global ECCO model (Stammer et al. 2003) at Swarm altitude (Fig. 2.3). In addition to these larger scale effects, specific energetic phenomena like El Niño and a western boundary current using the fine scale OCCAM model are presently being analysed (Vennerstrøm et al. 2004). To first order, these signals, and also those derived from existing state-of-the-art global tide models, can be used to adjust Swarm magnetic Level 2 products. Currently, the methods for extracting signals due to ocean circulation are being analysed and tested for the proposed Swarm constellation.

6.2.2 Performance Related to External Fields

6.2.2.1 Currents in the Ionosphere and Magnetosphere

With its multi-point measurements Swarm will allow specific current components in the near-Earth space to be uniquely determined for the first time. This capability will not only help to separate the various external magnetic field components, but also to study the characteristics of these currents, which are an important element of space weather.

In a dedicated study associated with the End-to-End Mission Performance Simulator the UCLA ‘Geospace General Circulation Model’ has been used to generate the external current systems for various activity levels. Figure 6.8, centre and right panels, shows the horizontal (arrows) and vertical (colour coded) current components in the ionosphere, for low and medium activity. These currents were used to calculate consistent magnetic and electric fields at satellite levels (Vennerstrøm et al. 2004). From these fields, the current systems were calculated, in order to estimate to which degree the original current systems can be recovered from the Swarm electric and magnetic field measurements. Of specific interest is the recovery of the field-aligned currents coupling the ionosphere and the magnetosphere (Fig. 2.3). Taking advantage of the closely spaced satellite pair, Swarm A and B, the horizontal field gradients are determined, and the vertical currents are calculated from the radial component of the curl of the magnetic field. As can be seen in Figure 6.8 (left), the estimated currents reproduce very well the simulated vertical current distribution (centre), demonstrating the capability of the selected constellation and the developed technique.

The calculated field-aligned currents may also be used to select passes of low magnetic disturbance suitable for providing data for internal field modelling. The current selection criteria, based on the planetary index Kp, are not optimal at high latitudes. By means of the simultaneously measured electric field, the various constituents of the current can be separated and the associated magnetic signal estimated.

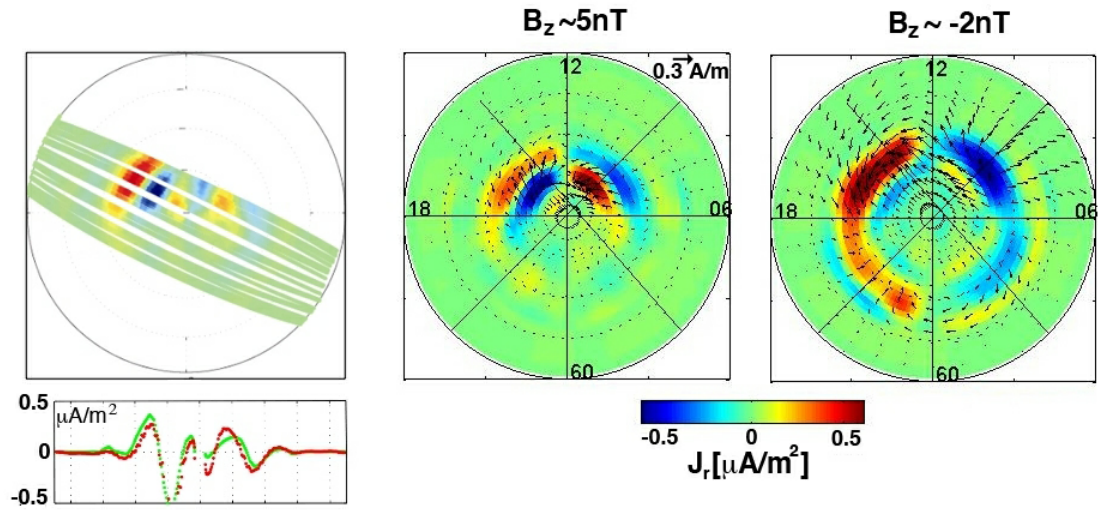


Figure 6.8: Synthetic ionospheric currents for low and medium activity (centre and left), recovered vertical currents using one day of data (left), direct comparison of one track (below) green: model, red estimate.

6.3 Constellation Performance

The main findings related to the primary objectives are summarised in the table below. Given the fact that the single-satellite performance requirements are met, the proposed three satellite constellation will lead to a drastic improvement in the desired models. The relative improvement with the fourth satellite appears to be marginal in relation to these objectives. However, specific scientific investigations related to the external field could benefit from such a fourth satellite, but this was not studied during Phase A, in the End-to-End Mission Simulator. From the analysis of the results for three satellites, it appears possible to recover the signals up to the finest scales as indicated in Table 4.1(upper), which is necessary to achieve the Swarm research goals. The performance of the models at ground level and satellite level is shown in Table 6.2. Overall, the two-satellite performance does not meet these requirements.

The experience gained from the existing missions and the extensive detailed scientific studies of various constellation scenarios, which were performed in parallel with the Phase A studies, have demonstrated very convincingly that a dedicated mission like Swarm is bound to bring significant advances in many science fields, from the Earth's deep core to its external environment. Furthermore, the Swarm constellation concept will provide measurements that can be used for completely new investigations and methodology developments. Some of the most promising new science areas within the field of geomagnetism include studying the fine-scale of the core and lithospheric field, determination of the 3-D conductivity of the mantle, the fine-structure of the field aligned currents and their surprisingly large effect on the density variations in the neutral atmosphere.

			without Swarm*	1 satellite (A)	2 satellites (A+B)	3 satellites (A+B+C)	4 satellites (A+B+C+D)
Lithospheric Field	At ground	Degree error, $n=60$ [nT]	6.8	2.0	1.5	0.50	0.50
		Accumulated error, $n=14-60$ [nT]	23.2	11.3	8.5	2.0	2.0
		Degree error, $n=110$ [nT]	N/A	6.3	4.4	4.4	4.4
		Accumulated error, $n=14-110$ [nT]	N/A	29	20	16	16
	At 400 km altitude	Degree error, $n=110$ [nT]	N/A	0.0072	0.0052	0.0052	0.0052
		Relative error, $n=110$ [%]	N/A	67	47	47	47
		Accumulated error, $n=14-110$ [nT]	3.80	2.91	2.58	0.41	0.39
	Altitude independent	Relative error, $n=60$ [%]	117	34	26	4.1	4.1
		Degree correlation, $n=60$	0.58	0.94	0.97	0.996	0.996
		Relative error, $n=110$ [%]	N/A	67	47	47	47
		Degree correlation, $n=110$	N/A	0.74	0.87	0.88	0.88
Secular Variation	At ground	Degree error, $n=8$ [nT/yr]	2.3	0.28	0.26	0.18	0.17
		Accumulated error, $n=5-8$ [nT/yr]		0.52	0.50	0.42	0.36
		Degree error, $n=14$ [nT/yr]	N/A	0.47	0.35	0.22	0.20
		Accumulated error, $n=5-14$ [nT/yr]	N/A	0.99	0.94	0.65	0.57
	At 400 km altitude	Degree error, $n=14$ [nT/yr]		0.176	0.132	0.086	0.075
		Accumulated error, $n=5-14$ [nT/yr]	N/A	0.47	0.45	0.34	0.30
	Altitude independent	Relative error, $n=8$ [%]	32	6.7	6.2	4.4	4.1
		Degree correlation, $n=8$		0.996	0.998	0.999	0.999
		Relative error, $n=14$ [%]	N/A	168	126	82	71
		Degree correlation, $n=14$	N/A	0.59	0.69	0.80	0.82

*For lithosphere it means best present day models (CHAMP and Ørsted). For secular variation it is based upon the ground observatory network available at the time of Swarm.

Table 6.2: Expected performance related to mission primary objectives.

7. User Community Readiness

The International Association of Geomagnetism and Aeronomy (IAGA), one of the seven associations of the International Union of Geodesy and Geophysics (IUGG), is concerned with the science and applications related to the electrical and magnetic properties of the Earth's interior, atmosphere, ionosphere and magnetosphere, as well of the Sun, the solar wind, the planets and the interplanetary bodies. In 1999 the IUGG adopted a resolution proposed by the IAGA in order to encourage research into geopotential fields over one decade, making use of the new satellite opportunities that would become available. This effort, the *International Decade of Geopotential Research*, started in 1999 with the launch of the Ørsted satellite and initiated a new era of intensely focussed geomagnetic research, paralleled only by the activity generated by the MAGSAT mission some twenty years earlier. This activity has progressed to the present day and continues due to the launch of two additional magnetic mapping satellites CHAMP and SAC-C.

In Europe, there is ample evidence of the importance ascribed to the geomagnetic community by various funding agencies. The Danish Space Research Institute, along with its national collaborators, has been technically and scientifically involved in all three existing magnetic missions. In Germany, partly motivated by the great success of the CHAMP satellite, the Deutsche Forschungs Gemeinschaft (DFG) has funded a special six-year programme, *Geomagnetic Variations (Erdmagnetische Variationen)*. France has a strong, long-term programme in geomagnetism within the various groups in the Centre National de la Recherche Scientifique (CNRS) and within the Centre National d'Etudes Spatiales (CNES), which provided the scalar instrument for Ørsted and CHAMP. The UK, which has traditionally had a modest research programme in comparison to the aforementioned countries, has recently funded a consortium 'Geospace' (based at the British Geological Survey and several Universities) to exploit new geomagnetic missions. Due to these activities, a number of young scientists in Europe have become well qualified to exploit the future Swarm data. In the USA, NASA has a long heritage in collaborating with university scientists in this area of research. The need for the Swarm mission is attested by the fact that it is now ten years since the US National Research Council published the *National Geomagnetic Initiative* (National Academies Press 1993), calling for "a programme of satellite missions over at least two solar cycles...and magnetic measurements at three equi-spaced longitudes..."(NRC p60). In a similar vein, the Solid Earth Science Working Group recently published their *Living on a Restless Planet*, for NASA Headquarters, calling for a similar constellation.

Coordinated by the IAGA, many of these agencies play a major role in the production of the International Geomagnetic Reference Field (IGRF), which is widely used, also outside the geomagnetic community. Indeed, the user community for the IGRF is very large, with applications ranging from navigation to field line tracing for external field

studies. For this community a considerable amount of software is available, some distributed via the Internet. This includes code for evaluating magnetic fields, so that even neophyte users can evaluate models when presented as standard spherical harmonic expansions based on Gauss coefficients. For the more advanced users, there are also sophisticated forward modelling codes for spherical 3-D mantle conductivity, and codes to solve the inverse problem of finding core motions from models of the core field and its time changes. Many of these efforts are coordinated by the World Data Centres for Geomagnetism, established by ICSU for the International Geophysical Year (1957/1958). In connection with the present satellite missions Ørsted and CHAMP, dedicated data centres have been created, and regular dedicated user workshops are organised (Friis-Christensen and Skøtt 1997, Stauning et al. 2003, Reigber et al. 2003). Through these centres, the most recent data and models are made available and are actively used by a truly global user community. The expertise collected here will be ready for creating products envisioned in the Swarm mission. In preparation for the mission, this expertise has been available during the development of the End-to-End mission performance simulator and related studies for Swarm, under ESA funding. This was a huge coordinated effort between a group of leading European institutes and NASA. By this effort an immeasurable amount of experience has been gained and the processing methodology has been adapted to data from a constellation. Over the next years, this work needs further refinements and furthermore elaboration of quality assessment and multi-satellite calibration beyond the simulator environment.

One can gauge the size of the user community by looking at the membership of various professional bodies, for example, IAGA, the Geomagnetism section of the American Geophysical Union, and the tightly focussed community involved in the Studies of the Earth's Deep Interior (SEDI). It should be noted that a much larger community within IUGG, AGU and the European Geophysical Union (EGU) benefits from the interdisciplinary results of Swarm. The community involved in the direct analysis of the Ørsted satellite data runs to more than 50 groups from 14 different countries. Similarly, the CHAMP project accepted approximately 35 international proposals for magnetic studies. Under the umbrella of IUGG, the International Association of Geodesy (IAG) established a multi-disciplinary Special Bureau for the Core of the Global Geophysical Fluids Centre of International Earth Rotation Service. This bureau is responsible for collecting, archiving, and distributing data related to the properties of the core. It also promotes and coordinates research on the topic.

The unique data set from Swarm will be crucial for various international scientific programmes across a wide range of geophysical disciplines, able to address problems from the very deep Earth's interior to the Earth's environment. For example, in the *International Living with a Star Programme* (ILWS), several communities are preparing a joint exploitation of the available and planned satellite missions, among which the Swarm constellation will provide crucial observations. It is foreseen and extremely desirable to continue the active involvement of the user community in much the same way as for the existing missions, which has proved to be very successful.

8 Global Context

Geomagnetism is a mature field of science and due to its global character the observational and scientific activities have traditionally been strongly coordinated by international organisations. For more than a century, this coordination has been concentrating on creating and maintaining a global network of permanent observatories together with specific international research campaigns like the 1st Polar Year, 1882-1883, the 2nd Polar Year, 1932-33, and the International Geophysical Year, 1957-58. IAGA has been instrumental in ensuring adequate data handling procedures for all of these research campaigns. This coordination was made more effective by introducing various services such as the service of comparisons of magnetic instrument standards, the establishment of the World Data Centres, and the adoption of standardised geomagnetic indices characterising different aspects of the electric and magnetic environment of the Earth. When measurements from space became available, the IAGA became the natural organisation to coordinate the implementation of this new data source into the various research programmes and applications. With the introduction of satellites in geomagnetic research, the IAGA changed its structure considerably to meet the demands and, in addition to its divisions, a number of specific working groups have been established to deal with various aspects of geomagnetic research.

However, the community had to rely on the major space agencies to really achieve such data coordination. Although measurements of the scalar data were performed for several missions at the beginning of the space era, sufficiently accurate vector data were not achievable until 1979 when the MAGSAT satellite was launched and operated for half a year. The importance of new dedicated magnetic field missions was already being addressed in the early nineties (ESA SP-1143 1991), and many of the challenges expressed at that time still remain to be tackled and are part of the goals of ESA's Living Planet Programme (ESA SP-1227 1999). In addition to contributing to the advancement of geomagnetic sciences, Swarm also plays an important role within the larger Earth and space science satellite programme. The mission is an important contribution to the International Decade of Geopotential Research (Fig. 8.1), an initiative of the IUGG. The primary goal of this enterprise is to elucidate the time-variable nature of the terrestrial gravity and magnetic signals. Ørsted was the first satellite launched during this decade, and Swarm will be able to complement it and thereby ensure an uninterrupted series of data over a full solar cycle. A decade-long programme is necessary to capture time variations on a wide variety of scales. Gravity and magnetic fields are the only two remotely sensed fields that can provide constraints on the Earth's deep interior from space in a manner very different from natural seismic analyses.

Terrestrial gravity and magnetic signals can be interpreted in tandem, using Poisson's theorem, and share a wide range of mathematical, physical, and computational

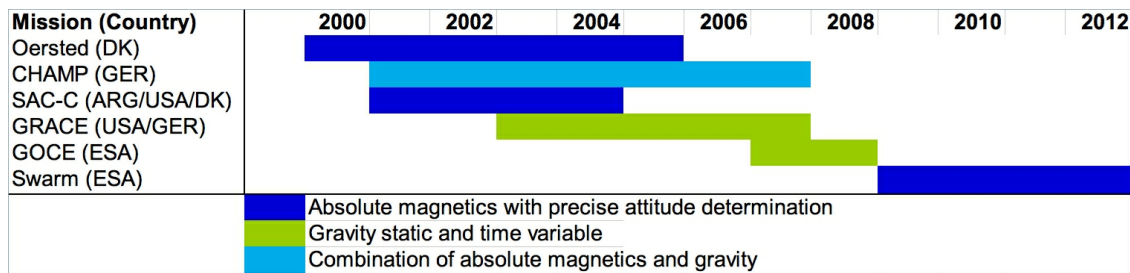


Figure 8.1: Gravity and magnetic missions, part of the *International Decade of Geopotential Research (IAGA 2004)*.

constructs. The objectives of Swarm are also very similar to those outlined by NASA's Solid Earth Science Working Group (SESWG 2003), but Europe is certainly in a position to take the leading role in this international effort, technically as well as scientifically. The Swarm mission can also contribute to obtaining improved models that can be used by large user communities and in several application areas. This is outlined in Chapter 9.

The mission fits within the research programme of the *International Living with a Star* (ILWS) programme. ILWS was formed to stimulate, strengthen, and coordinate space research to understand the governing processes in the connected Sun-Earth system viewed as an integrated entity. The steering committee of the ILWS programme consists of members drawn from the Canadian, Russian, Japanese, European, and American space agencies. Its Ionosphere-Thermosphere task group identified Swarm as an ILWS priority at a meeting held at Nice, France in April 2003. In addition, the various instruments of the Swarm constellation will contribute to the European Space Weather Programme (ESWP and Cost 724).

9 Application Potential

9.1 Possible use in Other Scientific Studies

In solid-Earth geophysics, the Swarm mission will facilitate more synergistic investigations on the topic of density variations in the lithosphere and upper mantle. The goal is an integrated study of magnetic, gravity, and seismic data in order to obtain a well-constrained image of the density variations at these depths (ESA SP-1233(1) 1999). The knowledge of density will then allow precise quantitative modelling of sedimentary basins, rifts, tectonic motion, and vertical deformation.

An exciting development in seismology is the attempt to use thermodynamic properties of minerals, in particular the sensitivities of their compressional and shear wave speeds and densities to variations in temperature and iron and perovskite content, to separate temperature variations from compositional variations in the mantle for the first time. The proposed first mapping of 3-D conductivity in the mantle via the improved accuracy of Swarm will complement this development, by providing evidence of conductivity variations due to the same temperature and compositional variations. Initial work on this (Trampert et al. 2004) confronts conventional wisdom in reporting that the African Megaplume, rather than resulting from high temperatures, results instead from increased iron content, and similarly for the seismically slow Pacific region. Swarm results, coupled with thermodynamic relations relating conductivities to temperature and compositional variations, could support or refute this idea. This would be one of the first instances of joint seismic and geomagnetic studies of the Earth's mantle.

A fine example of the interdisciplinary need for high-resolution models of the core field and secular variation, or equivalently, the core surface flow field, is provided by the synergy between geodesy and geomagnetism. Because the mantle is heterogeneous, the geoid in the core departs from sphericity, resulting in an inner core surface that is aspherical, in fact having a strong degree and order two spherical harmonic pattern. Fluid flow in the core can couple to the mantle via electromagnetic coupling on the inner core (Buffett 1996), and can hence change both the length of day and the gravity field of the Earth. There is an unexplained ~ 6 year variation in the length of day which cannot be explained by changes in atmospheric angular momentum, and it is likely to be due to excitation of a normal mode of the core. The prospect of using a normal mode approach akin to that used in seismology is proposed (Mound and Buffett 2003) to determine the strength of gravitational coupling between the core and mantle, and hence the shape of equipotential surfaces at the core/mantle boundary and the inner core boundary. The gravity changes are estimated to be on the order of 60 nGal, well above the monthly measurement accuracy of the GRACE mission. Thus with a high-resolution magnetic mission like Swarm, all the ingredients are in place for carrying out this study.

9.2 Modelling and Operational Aspects and Other Applications

In addition to the wide range of research topics that can be addressed with geomagnetic data, they are also indispensable for a variety of operational functions and applications. Several Level 3 applications are shown in Table 9.1.

Generic Level 3 product	Specific Level 3 product	Level 2 inputs	Other inputs/requirements	Application potential
Reference field	World Digital Magnetic Anomaly Map (WDMAP) on 5 km grid	Comprehensive magnetic field	Airborne, marine, and ground magnetic surveys. Comprehensive model extension to epoch of survey	Natural resource targeting, Structure, lithology, and tectonic interpretations
Reference field	International Geomagnetic Reference Field	Core contributions	Ground magnetic observatories, and techniques for extrapolations	Multiple, including satellite navigation
Near-real-time models	Directional drilling model	Comprehensive magnetic field model	Real-time observatory data and local magnetic surveys	Precise targeting of natural resources
Core Dynamics Models	Modular, Sealable, Self-consistent, Three-dimensional (MoSST) model	Core contributions and their time variability	Data assimilation of satellite and ground magnetic observations	Earth rotation, core-mantle coupling, and multi-year South Atlantic Anomaly predictions
Lithospheric properties	Oceanic isochron location improvement	Lithospheric magnetic field model	Starting model of isochron location	Improvements in plate tectonics models
Lithospheric properties	Continental heat flux	Lithospheric magnetic field model	Starting model of crustal thickness and heat flux from seismology	Long-term stability of ice caps from regional heat flux under Antarctic Greenland

Table 9.1: Higher level products and applications.

The World Digital Magnetic Anomaly Map (WDMAM) Project, undertaken by the International Association of Geomagnetism and Aeronomy (IAGA), aims to source, collate, and integrate magnetic anomaly data from around the globe onto a 5 km grid (Ravat et al. 2003). Global compilations such as these can help not only in the reconnaissance stage of petroleum and mineral exploration, but also to delineate the composite structure of the crystalline basement and to investigate the chemical and thermal evolution of the lithosphere. Although data gathering for this compilation is still in a preliminary stage, data gaps are evident in the southern oceans. Gaps such as these, survey-to-survey leveling, and long-wavelength control would be the responsibility of Swarm.

For many purposes in the fields of ionospheric, magnetospheric and cosmic-ray physics and in studies of crustal fields, particularly in exploration geophysics, an

internationally produced and agreed global model of the core field and its secular variation, the **International Geomagnetic Reference Field (IGRF)**, is widely used. The IGRF, first developed in 1969, is sponsored by the IAGA. It is a series of mathematical models of the Earth's core field and its annual rate of change. It is a product of a collaborative effort between magnetic field modelling groups and institutes involved in collecting and disseminating magnetic field data from observatories, surveys, and satellites. The IGRF is revised every four years, and the most recent revision was in 2003 (Macmillan et al. 2003). The unprecedented amount of high-quality satellite data available for the latest revision model made it possible for the IAGA to extend the degree of the core field model coefficients to degree 13, and to be quoted to 0.1 nT precision. The data from Swarm are therefore expected to ensure that future revisions, in 2011 and 2015, will be even more accurate.

A navigational use of geomagnetic information, which is assuming increasing importance, is in the **drilling** of deviated (i.e. non-vertical) wells in the **oil and gas industries**. It is common for 50 or more deviated wells to be drilled from a single rig and it is therefore necessary to be able to control the dip and azimuth of the drilling tool to within close tolerances (0.1°). Gyroscopic devices can be used to supply this information, but they are sensitive to vibration, and drilling operations must therefore be suspended whilst measurements are made. This is expensive and the preferred method of navigating the drill string is, in most cases, by using the geomagnetic field as the source of directional reference (Russell et al. 1995). Magnetic sensors are located in a non-magnetic section of the drill string, not far from the drill bit, and it is possible to make navigational measurements whilst drilling is in progress. Accurate and up-to-date geomagnetic field information is essential, and accuracy requirements are much more stringent than in traditional forms of navigation.

The **MoSST (Modular, Scalable, Self-consistent, Three-dimensional) model** of the geodynamo (Kuang and Chao 2003) is currently being upgraded so as to use satellite observations of the magnetic field in a data assimilation scheme in order to forecast the dynamical regime of the core, including the steady or slowly varying background flow and geomagnetic secular variation. The modeling results are now being used in geodynamic studies of Earth rotation, time-variable gravity, and core-mantle coupling. In the future, they may also be used as the IGRF is today, to predict surface fields five or more years into the future.

Solving the heat conduction equation can provide insight into the **regional heat flux**, as recently demonstrated for the Antarctic (Fox Maule et al. 2003). This technique is applicable in **continental areas** where lateral variations in the thickness of the magnetic layer are the dominant source of long-wavelength anomalies. Knowledge of the regional heat flux under ice caps is of considerable societal importance as it provides insight into the ice cap's long-term stability.

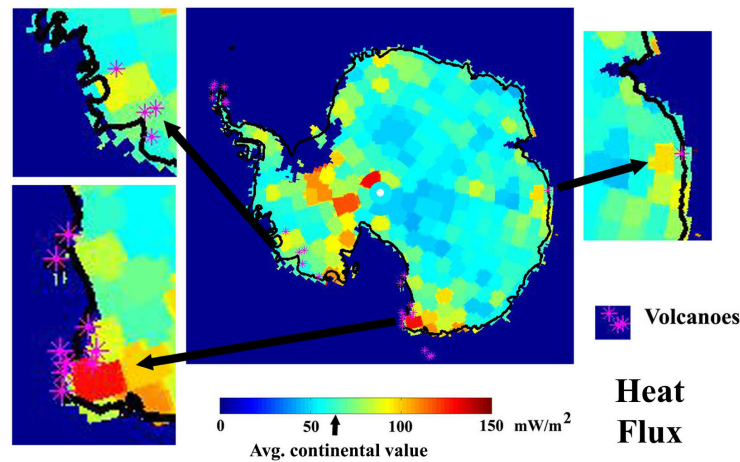


Figure 9.1: Regional heat flux under the Antarctic ice cap estimated using CHAMP data (Fox Maule et al. 2003). Predictions for high-heat flow are in excellent agreement with current active volcanic areas.

Knowledge of the magnetic field and its variations is important for: magnetic compass corrections and **navigation**; orientation of satellites; guidance and detection systems; bio-magnetism and animal navigation.

The magnetic field is the dominant controlling factor regarding the external environment of the Earth, **space weather**. Better understanding of its geographical distribution and its time variations, due to internal dynamics as well as to the changes introduced by solar variability, may help in understanding and mitigating effects regarding damage to satellite systems, disruption of satellite communications, GPS errors, varying orbital drag on satellites, induced currents in power grids, corrosion in pipelines. Of particular interest in this respect is the high spatial resolution of the field-aligned currents, which can be achieved using closely separated satellites. Furthermore, with satellites crossing the auroral electrojets in two orbital planes, there is a large potential for deriving a satellite based index of planetary geomagnetic activity that is more representative for many applications than the existing ground based indices.

In recently published papers, it is suggested that galactic cosmic rays, through their ionisation of the lower troposphere, may affect the production rate of cloud condensation nuclei by ion-mediated nucleation (Marsh and Svensmark 2000, Yu and Turco 2001). The incoming cosmic rays are modulated and controlled by the magnetic field in the heliosphere (the interplanetary field), as well as by the geomagnetic field. This hypothesis was recently highlighted as a particularly promising research area (Editors of Science 2002). If correct, it follows that the geomagnetic field may have a role in **long-term climate changes** since the secular variation will affect the geographical distribution of the incoming cosmic ray flux.

There is growing interest in the effects of magnetic fields on **humans**. In particular, the radiation exposure (see Section 2.2.1) of astronauts and in high-flying aircraft is of increasing concern.

References

Acuña M.H, J.E.P. Connerney, N.F. Ness, R.P. Lin, D. Mitchell, C.W. Carlson, J. McFadden, K.A. Anderson, H. Reme, C. Mazelle, D. Vignes, P. Wasilewski, and P. Cloutier, 1999: Global Distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment, *Science* **284**, 790–793.

Alexandrescu M., C. Ha Duyen, and J.-L Le Mouél, 1994: Geographical distribution of magnetic observatories and field modelling, *J. Geomag. Geoelectr.*, **46**, 891-901.

Bijwaard H. and W. Spakman, 2000: Non-linear global P-wave tomography by iterated linearized inversion. *Geophys. J. Int.*, 110, 251-266.

Bloxham J., S. Zatman, and M. Dumberry, 2002: The origin of geomagnetic jerks, *Nature*, **420**, 65-68.

Bruinsma S. and R. Biancale, 2003: Total density retrieval with STAR, First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, (Eds. Reigber C., H. Lühr, P. Schwintzer), Springer-Verlag, Berlin, ISBN 3-540-00206-5.

Buffett, B. A. 1996: Gravitational oscillations in the length of the day, *Geophys. Res. Lett.*, **23**, 2279-2282.

Cohen Y. and J. Achache, 1994: Contribution of induced and remanent magnetization to long-wavelength oceanic magnetic anomalies, *J. Geophys. Res.*, **99**, 2943-2954.

Constable S. and C. Constable, 2004: Observing geomagnetic induction in magnetic satellite measurements and associated implications for mantle conductivity, *Geochem. Geophys. Geosys.*, **5**, No. 1, Q01006 DOI 10.1029/2003GC000634.

Editors of Science, 2002: Areas to watch in 2003, “ A sun-climate connection”, *Science*, 298, 2298.

Emmert J.T., J.M. Picone, J.L. Lean, and S.H. Knowles, 2004: Global change in the thermosphere: Compelling evidence of a secular decrease in density, *J. Geophys. Res.*, 109(A2) 10.1029/2003JA010176.

ESA SP-1227, 1998: The Earth Explorers: The Science and Research Element of ESA's Living Planet Programme, ESA Publications Division, ESTEC, Noordwijk.

ESA SP-1233(1), 1999: Gravity Field and Steady-State Ocean Circulation Mission, Report for Mission Selection, ESA Publications Division, ESTEC, Noordwijk.

ESA SP-1143, 1991: Report of the Earth Observation User Consultation Meeting, ESA Publications Division, ESTEC, Noordwijk.

Finlay C.C. and A. Jackson, 2003: Equatorially dominated magnetic field change at the surface of Earth's core, *Science*, **300**, 2084-2086.

Fox Maule C., M. Purucker, and N. Olsen, 2003: Magnetic crustal thickness and heat flow in Antarctica, *Eos Trans. AGU*, 84 (46), Fall meet. Suppl., Abstract GP21D-05.

Friis-Christensen E., 2001: Solar activity and possible effects on climate, *Space Storms and Space Weather Hazards* (Ed. I.A. Daglis), Kluwer Acad. Publish., 231-250.

Friis-Christensen E. and C. Skøtt (Eds), 1997: Ørsted Compendium, DMI Scientific report 97:1, ISBN: 87-7478-359-9, ISSN: 0905-3263, Copenhagen, 219pp.

Friis-Christensen E., H. Lühr, and G. Hulot, 2002: Swarm - a constellation to study the dynamics of the Earth's magnetic field and its interaction with the Earth system, *Proposal for ESA Earth Explorer Opportunity Missions*, January 2002, ISSN 1602-527X, DSRI Report 1/2002.

GRACE – Gravity Recovery and Climate Experiment, 1998: Science and Mission Requirements Document, revision A, JPLD –15928, NASA's Earth System Science Pathfinder Program.

Hamilton W., 1979: Tectonics of the Indonesian region: *U.S. Geological Survey Prof. Paper 1078*.

Heirtzler J.R., J.H. Allen, and D.C. Wilkinson, 2002: Ever-present South Atlantic Anomaly damages spacecraft, *EOS, Trans. AGU*, 83, 165.

Holme, R., 2000: Electromagnetic core-mantle coupling - III. Laterally varying mantle conductance, *Phys. Earth Planet. Inter.*, 117, 329-344.

Hulot G., C. Eymin, B. Langlais, M. Mandea, and N. Olsen, 2002: Small-scale structure of the Geodynamo inferred from Oersted and Magsat satellite data, *Nature*, 416, 620-623.

IAGA, 2004: Int. Assoc. Geomag. & Aeronomy (IAGA) Working group on Earth and Planetary Magnetic Survey satellites. Web page at geodynamics.gsfc.nasa.gov/research/mag_field/purucker/mag_missions.html

ILWS, 2004: International Living with a Star (ILWS). Web page at ilws.gsfc.nasa.gov

IJssel J. van den and P.N.A.M. Visser, 2004: Swarm End-to-End Simulator: CCN 2-EOP-SM1000/Is.: 1-2, extension to ESTEC Contract No. 17263/03/NL/CB, Final Report.

Jackson A., 2003: Intense equatorial flux spots on the surface of the Earth's core, *Nature*, **424** (6950): 760-763.

Jackson A., J. Bloxham, and D. Gubbins, 1993: Time-dependent flow at the core surface and conservation of angular momentum in the coupled core-mantle system, *Dynamics of Earth's Deep Interior and Earth Rotation, IUGG Vol. 12. AGU Geophysical Monograph*, (Eds. Le Mouél J.-L., Smylie D.E., Herring T.), **72**, 97-107.

Jackson A., A. Jonkers, and M. Walker, 2000: Four Centuries of Geomagnetic Secular Variation from Historical Records, *Phil. Trans. R. Soc. Lond.*, **358** 957-990.

Jault D. 2003: Electromagnetic and Topographic Coupling, and LOD variations, in Earth's core and lower mantle (Eds. Jones C.A., A.M. Soward, K. Zhang), *The Fluid Mechanics of Astrophysics and Geophysics*, (Series Editors A. Soward and M. Ghil), 56-76, Taylor & Francis, London.

Jault D., G. Hulot, and J.-L. Le Mouél, 1996: Mechanical core-mantle coupling and dynamo modelling, *Phys. Earth Planet. Inter.*, **98**, 187-192.

Kono M. and P. H. Roberts, 2002: Recent geodynamo simulations and observations of the geomagnetic field, *Rev. Geophys.*, **40**, 1-53.

Kuang W. and B.F. Chao, 2003: Geodynamo modeling and core-mantle interactions, in *Earth's Core: Dynamics, Structure, Rotation*, (Eds. Dehant V., K.C. Creager, S. Karato, S. Zatman), AGU Geodynamics, Series 31, 193-212.

Kuang W., A. Tangborn, T. Sabaka, 2004: On the possibilities of predicting geomagnetic secular variation with geodynamo modelling, *Geophys. Res. Lett.*, submitted.

Langel R. A., 1987: The Main Field, in *Geomagnetism*, (Ed. J. A. Jacobs), Academic Press, San Diego, Calif., 249.

Langel R. A. and W. J. Hinze, 1998: *The magnetic field of the Earth's Lithosphere: the satellite perspective*, Cambridge, U.K.; New York, N.Y., Cambridge University Press.

Langlais B., M. Manda and P. Ultré-Guérard, 2003: High-resolution magnetic field modelling: application to MAGSAT and Ørsted data, *Phys. Earth Planet. Int.*, **135**, 77-92.

-
- Langlais B., M. Purucker, and M. Manda, 2004: Crustal magnetic field of Mars, *J. Geophys. Res.- Planets*, 109(E2), E02008, doi:10.1029/2003JE002048.
- Lühr H., M. Rother, S. Maus, W. Mai, and D. Cooke, 2003: The diamagnetic effect of the equatorial Appleton anomaly: Its characteristics and impact on geomagnetic field modelling. *Geophys. Res. Lett.*, **30**, 17, 1906, doi: 10.1029/2003GL017407.
- Lühr H., M. Rother, W. Köhler, P. Ritter, and L. Grunwaldt, 2004: Thermospheric upwelling in the cusp region, evidence from CHAMP observations, *Geophys. Res. Lett.*, in print.
- Macmillan S., S. Maus, T. Bondar, A. Chambodut, V. Golovkov, R. Holme, B. Langlais, V. Lesur, F. Lowes, H. Lühr, W. Mai, M. Manda, N. Olsen, M. Rother, T. Sabaka, A. Thomson, and I. Wardinski, 2003: The 9th –Generation International Geomagnetic Reference field. *Geophys. J. Int.*, **155**, 1051-1056.
- Manda Alexandrescu M., D. Gibert, J.-L. Le Mouél, G. Hulot, and G. Saracco, 1999: An estimate of average lower mantle conductivity by wavelet analysis of geomagnetic jerks, *J. Geophys. Res.*, **104**, 17735-17745.
- Marsh N., and H. Svensmark, 2000: Low cloud properties influenced by cosmic rays. *Phys. Rev. Lett.*, **85**, 5004–5007.
- Maus S., M. Rother, R. Holme, H. Lühr, N. Olsen, and V. Haak, 2002: First scalar magnetic anomaly map from CHAMP satellite data indicates weak lithospheric field, *Geophys. Res. Lett.*, **29**, 14, 10.1029/2001GL013685.
- Maus S., M. Rother, H. Lühr, G. Balasis, N. Olsen, and A. Kuvshinov, 2004: The CHAMP MF-3 model, <http://www.gfz-potsdam.de/pb2/pb23/SatMag/litmod3.html>.
- Mound, J.E. and Buffett, B.A., 2003: Interannual oscillations in length of day: Implications for the structure of the mantle and core. *J. Geophys. Res.*, **108**, doi:10.1029/2002JB002054.
- Nataf H.-C., and Y. Ricard, 1996: 3SMAC: an *a priori* tomographic model of the upper mantle based on geophysical modeling, *Phys. Earth Planet. Int.*, **95**, 101-122.
- Neubert T., and F. Christensen, 2003: Small-scale, field-aligned currents at the top-side ionosphere, *Geophys. Res. Lett.*, 30(19), 2010, doi: 10.1029/2003GL017808.
- Olsen N., 1999: Induction Studies with Satellite Data, *Surveys in Geophysics*, **20**, 309-340.

Olsen N., E. Friis-Christensen, and T. Moretto, 2002: New approaches to explore the Earth's magnetic field, *J. Geodynamics*, **33**, 29-41.

Olsen N., L. Tøffner-Clausen, T. J. Sabaka, P. Brauer, J. M. G. Merayo, J. L. Jørgensen, J.-M. Léger, O. V. Nielsen, F. Primdahl, and T. Risbo, 2003: Calibration of the Ørsted Vector Magnetometer, *Earth, Planets and Space*, **55**, 11-18.

Olsen N., E. Friis-Christensen, G. Hulot, M. Korte, A. Kuvshinov, V. Lesur, H. Lühr, S. Macmillan, M. Manda, S. Maus, M., Purucker, C. Reigber, P. Ritter, M. Rother, T. Sabaka, P. Tarits, and A. Thomson, 2004: Swarm – End-to-End mission performance simulator study, February 2004, ESA Contract No. 17263/03/NL/CB, DSRI Report 1/2004.

Paschmann G., and P. Daly (Eds.), 1998: Analysis Methods for Multi-Spacecraft Data, *ISSI Science Report*, SR-001.

Ponsar S., V. Dehant, R. Holme, D. Jault, A. Pais., and T. Van Hoolst, 2003: The core and fluctuations in the Earth's rotation, , in *Earth's Core: Dynamics, Structure, Rotation* (Eds. Dehant V., K.C. Creager, S. Karato, S. Zatman), AGU Geodynamics, Series 31, 193-212.

Purucker M., B. Langlais, N. Olsen, G. Hulot, and M. Manda, 2002a: The southern edge of cratonic North America: Evidence from new satellite magnetometer observations, *Geophys. Res. Lett.*, **29(15)**, 8000, doi:10.1029/2001GL013645.

Purucker M., H. McCreadie, S. Vennerstrøm, G. Hulot, N. Olsen, H. Luehr, and E. Garnero, 2002b: Highlights from AGU's Virtual Session on New Magnetic Field Satellites, *EOS, Trans. AGU*, **83**, no. 34, 368, (with associated CD-ROM).

Purucker, M. and Olsen, N., 2003: Modeling of the Earth's magnetic field and its variation with Ørsted, CHAMP, and Ørsted-2/SAC-C, OIST-4 Proceedings, 319-327.

Ravat D., W.J. Hinze, and P.T. Taylor, 1993: European tectonic features observed by Magsat. *Tectonophysics*. **220**, 157-173.

Ravat D, M. Ghidella, J. Korhonen, S. Maus, S. McLean, and C. Reeves, 2003: Toward the World Digital Magnetic Anomaly Map, *Eos Trans. AGU*, **84** (46), Fall meet. Suppl., Abstract GP21D-01.

Reigber C., H. Lühr, P. Schwintzer, (Eds.), 2003: First CHAMP Mission Results for Gravity, Magnetic and Atmospheric Studies, *Springer-Verlag*, Berlin, ISBN 3-540-00206-5, 556pp.

-
- Russell J.P., G. Shiells, and D.J. Kerridge,. 1995: Reduction of well-bore positional uncertainty through application of a new geomagnetic in-field referencing technique. Paper SPE 30452, presented at the 1995 SPE Annual Technical Conference and Exhibition, Dallas, October 22-25,.
- Sabaka T.J., N. Olsen, and R.A. Langel, 2002: A comprehensive model of the quiet-time, near-Earth magnetic field: phase 3, *Geophys. J. Int.*, **151**, 32-68.
- Sabaka T.J., N. Olsen, and M. Purucker, 2004: Extending Comprehensive Models of the Earth's Magnetic Field with Ørsted and CHAMP, *Geophys. J. Int.*, accepted.
- Schmucker U., 1985: Magnetic and electric fields due to electromagnetic induction by external sources, *Landolt-Börnstein, New-Series, 5/2b*, Springer-Verlag, Berlin-Heidelberg, 100-125.
- SESWG, 2003: Solid Earth Science Working Group report. Web page at solidearth.jpl.nasa.gov
- Stacey F. D., 1992: Physics of the Earth, 3rd edn., Brisbane, Qld., Brookfield Press.
- Stammer D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C.N. Hill, and J. Marshall, 2003: Volume, heat and freshwater transports of the global ocean circulation 1993 --2000, estimated from a general circulation model constrained by World Ocean Circulation Experiment (WOCE) data , *J. Geophys. Res.*, **108**, C13007, doi:10.1029/2001JC001115.
- Stauning P., H. Lühr, P. Ulte-Guerard, J. LaBrecque, M. Purucker, F. Primdahl, J.L. Jørgensen, F. Christiansen, P. Hoeg, and K.B. Lauritsen (Eds.), 2003: OIST-4 Proceedings, 4th Ørsted International Science Team Conference, DMI Scientific Report 03-09, Copenhagen, 370 pp, 2003.
- Trampert, J, F. Deschamps, J. Resovsky, and D. Yuen, 2004: Probabilistic tomography maps chemical heterogeneities in the lower mantle, submitted to *Science*.
- Tyler R., S. Maus, and H. Lühr, 2003: Satellite observations of magnetic fields due to ocean flow. *Science*, 299, 239-241.
- Vennerstrøm S., E. Friis-Christensen, H. Lühr, T. Moretto, N. Olsen, C. Manoj, P. Ritter, L. Rastätter, A. Kuvshinov, and S. Maus, 2004: The Impact of Combined Magnetic and Electric Field Analysis and of Ocean Circulation Effects on Swarm Mission Performance, ESA CONTRACT No 3-10901/03/NL/CB, DSRI Report 2/2004, 2004.

Visser P.N.A.M. and J. van den IJssel, 2003: Verification of CHAMP accelerometer observations, *Adv. Space Res.*, **31/8**, 1905-1910.

Webb D (with Joseph H. Allen of SCOSTEP), 2003: Anomalies related to recent solar activity, <http://beauty.nascom.nasa.gov/~ptg/anomalies.pdf>.

Yu F. and R.P. Turco, 2001: From molecular clusters to nanoparticles: Role of ambient ionisation in tropospheric aerosol formation, *J. Geophys. Res.*, **106**, 4797-4814.

Zhang K., 1993: On equatorially trapped boundary inertial waves. *J. Fluid Mech.* **248**, 203-217.



European Space Agency
Agence spatiale européenne

Contact: ESA Publications Division
c/o ESTEC, PO Box 299, 2200 AG Noordwijk, The Netherlands
Tel. (31) 71 565 3400 - Fax (31) 71 565 5433