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Swarm: A constellation to study the Earth's magnetic field

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The *Swarm* mission was selected as the 5th mission in ESA's Earth Explorer Programme in 2004. The mission will provide the best ever survey of the geomagnetic field and its temporal evolution that will lead to new insights into the Earth system by improving our understanding of the Earth's interior and its effect on Geospace, the vast region around the Earth where electrodynamic processes are influenced by the Earth's magnetic field. Scheduled for launch in 2010, the mission will comprise a constellation of three satellites, with two spacecraft flying side-by-side at lower altitude (450 km initial altitude), thereby measuring the East-West gradient of the magnetic field, and the third one flying at higher altitude (530 km). High-precision and high-resolution measurements of the strength, direction and variation of the magnetic field, complemented by precise navigation, accelerometer and electric field measurements, will provide the necessary observations that are required to separate and model the various sources of the geomagnetic field. This results in a unique "view" inside the Earth from space to study the composition and processes of its interior. It also allows analysing the Sun's influence within the Earth system. In addition practical applications in many different areas, such as space weather, radiation hazards, navigation and resource management, will benefit from the *Swarm* concept.

Key words: Geomagnetism, magnetic field mission, Swarm satellites.

1. Introduction

The major part of the Earth's magnetic field has its origin deep inside our planet, in the outer fluid core. It is created by a self-sustaining dynamo process involving turbulent motions of molten iron. The magnetic dipole component, which is the dominant part of the field outside the core, is, however, currently decreasing at a rate presumably ten times faster than its natural decay, were the dynamo to be switched off. The dipole moment has decreased by nearly 8% over the last 150 years (Jackson *et al.*, 2000). This trend is still ongoing, at a rate comparable to that seen at times of magnetic reversals (Hulot *et al.*, 2002). Combined with non-dipole changes, this decline has led to even larger regional changes, by as much as 10% during the last 20 years in the South Atlantic Anomaly, where the field is already the weakest (see Fig. 1)

These results were achieved during a new era of satellite measurements of the geomagnetic field that started in 1999 with the launch of the Ørsted satellite (Neubert *et al.*, 2001) and which initiated a new effort of intensely focussed geomagnetic research, paralleled only by the activity generated by the Magsat mission some twenty years earlier (Langel *et al.*, 1982). This activity has evolved to the present day due to the launch in 2000 of two additional magnetic mapping satellites CHAMP (Reigber *et al.*, 2002) and SAC-C, which all have delivered high-precision geomagnetic data during the first years of this decade.

However, all these three missions have been conceived as single-satellite missions. Although they share similar magnetic instruments, they have different science payloads, spacecraft designs and orbits. As a result they produce data with fairly different characteristics. This limits the scientific advantage of comparing data simultaneously acquired at different locations by different satellites. In particular, the irregularly varying fields produced by the external currents are then difficult to adequately model. This happens to be the main limiting factor in the accuracy of present geomagnetic field models. Single-satellite missions simply cannot take full advantage of the impressive instrument improvement achieved during the past decade. A dedicated multi-satellite mission making simultaneous measurements over different regions of the Earth is clearly needed. Results from combined analysis of Ørsted, CHAMP and SAC-C data, whenever this was technically feasible, confirmed this (e.g., Purucker *et al.*, 2002b; Sabaka *et al.*, 2004; Olsen *et al.*, 2006b). *Swarm* has been designed to be one such dedicated mission.

The recent high-precision measurements have also revealed that measurements during a full solar cycle will be needed to properly distinguish between solar cycle (external) and short-term secular variation (internal) effects.

Scientists in the various geomagnetic research disciplines are exploring the available data with increasingly sophisticated methods. But continued scientific progress calls for an interdisciplinary approach based on the development of new tools to deal with all the various contributions, from the outer magnetosphere to the deep core (see Fig. 2), in a comprehensive way. Only by such an approach we can hope to

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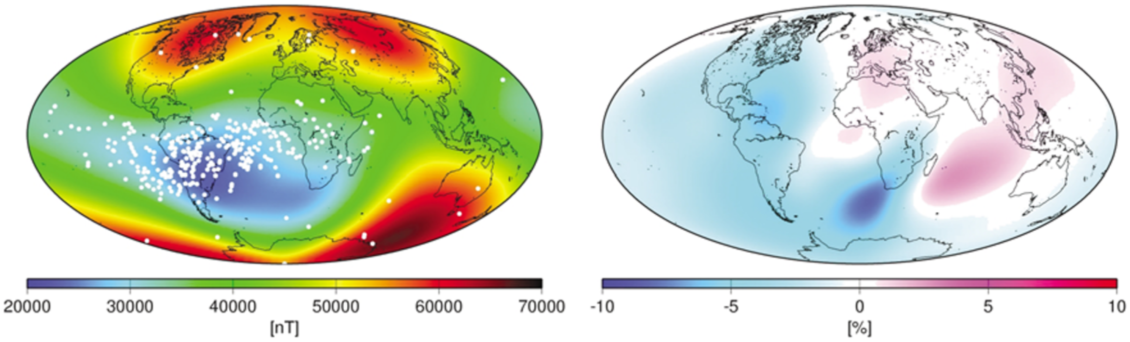

Fig. 1. The geomagnetic field intensity at the Earth's surface with the South Atlantic Anomaly defined by the low values of the field. The white dots indicate positions where the TOPEX/Poseidon satellite experienced single event upsets (left). The change in field intensity over 20 years (from MAGSAT to Ørsted) is shown in percentage (right).

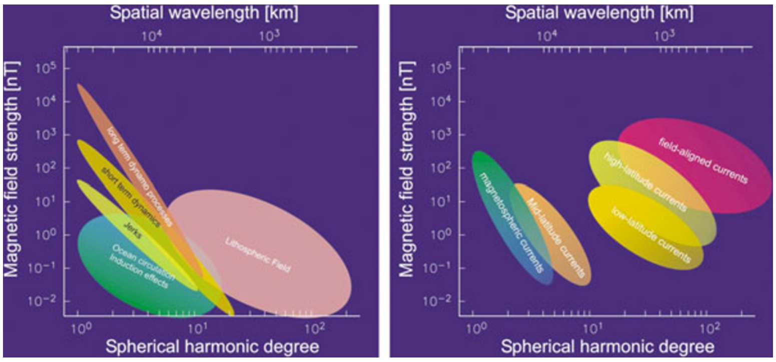

Fig. 2. Signal amplitude at orbit altitude of the contributions from processes contributing to the magnetic field as a function of spatial scale. Source terms from within the solid Earth and the oceans (left), and contributions from external sources (right).

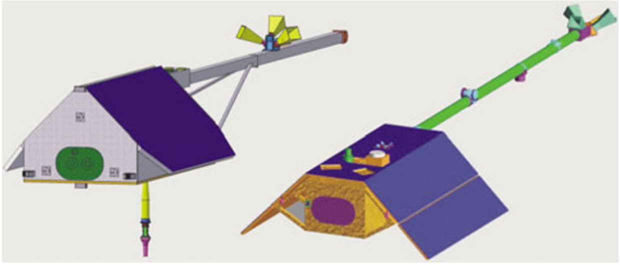

Fig. 3. Spacecraft designs proposed by the industrial consortia in Phase A.

synthesise a multitude of scientific issues into a consistent model of the coupled Sun-Earth system.

The *Swarm* mission is based on a mission proposal (Friis-Christensen *et al.*, 2002) submitted in response to the ESA Earth Observation Programme call for Opportunity Mission proposals. Among 25 submitted proposals *Swarm* was one of the three candidates selected for feasibility studies. The Phase-A studies were finalised during 2004 and the results were included in an evaluation report (ESA SP-1279(6) and Technical and Programmatic Annex, 2004) presented for the final mission selection. Figure 3 shows the spacecraft designs proposed by the industrial consortia in Phase A. In May 2004 the *Swarm* mission was selected as the fifth Earth Explorer Mission in ESA's Living Planet Programme aiming at a launch in 2010.

The purpose of this paper is to present and briefly review the scientific objectives of the *Swarm* mission. Particular emphasis has been put on the advancement of science, which will result from the specific choice of a constellation of three satellites. Most of these assessments are based on scientific studies performed during the Phase A, the results of which are described in accompanying papers of this special issue. The interested reader is referred to these articles for more detailed information.

2. Science Objectives

The objective of the *Swarm* mission is to provide the best ever survey of the geomagnetic field and its temporal evolution, in order to gain new insights into the Earth system by improving our understanding of the Earth's interior and the Geospace environment including the Sun-Earth connection processes.

More precisely, the *Swarm* mission will make it possible to derive the first global representation of the geomagnetic field variations on time scales from an hour to several years and directly address the challenging issue of separating the contributions from the various field sources. *Swarm* has indeed been specifically designed to simultaneously obtain a space-time characterisation of both the internal field sources in the Earth's core, mantle, and crust, and the external current systems in the ionosphere and magnetosphere.

The primary research objectives of the mission are:

- Core dynamics, geodynamo processes, and core-mantle interaction,

- Lithospheric magnetisation and its geological interpretation,
- 3-D electrical conductivity of the mantle,
- Currents flowing in the magnetosphere and ionosphere.

In addition, two secondary research objectives have been defined:

- Identification of ocean circulation by its magnetic signature,
- Quantification of magnetic forcing of the upper atmosphere.

2.1 Core dynamics and geodynamo processes

Ørsted, CHAMP, and SAC-C have recently demonstrated the capability of satellite missions to increase the spatial resolution of secular-variation models (Maus *et al.*, 2005; Sabaka *et al.*, 2004; Olsen *et al.*, 2006b). *Swarm* will further improve models of the core field dynamics by ensuring long-term space observations with an even better spatial and temporal resolution as discussed in the accompanying papers of this issue by Olsen *et al.* (2006a), Sabaka and Olsen (2006), and Lesur *et al.* (2006). New science opportunities will include challenging the validity of fundamental assumptions, such as the classical frozen-flux and tangentially geostrophic assumptions used to interpret the short-term evolution of the main field (Hulot and Chulliat, 2003; Pais *et al.*, 2004) or the alternative more recent "helical flow" assumption proposed by Amit and Olson (2004). It will also include detailed core surface flow models computed with better temporal resolution, improving on the current situation where temporal changes within core surface flows remain poorly resolved (e.g. Jackson, 1997; Pais and Hulot, 2000) and only average flows over the past 20 years can be computed in some detail (Hulot *et al.*, 2002). Such detailed core surface flow models will make it possible to further investigate torsional oscillations (Zatman and Bloxham, 1997; Pais and Hulot, 2000), core-mantle interactions (Holme, 2000; Jault, 2003), as well as geomagnetic jerks (Mandea *et al.*, 2000). Given the known occurrence of such jerks in the past decades (Alexandrescu *et al.*, 1996), it is indeed very likely that *Swarm* would witness such an event. Some proposed connections between geomagnetic jerks, core surface flows, torsionnal oscillations and core-mantle interactions could then also be investigated in much greater detail than has been done so far (Le Huy *et al.*, 2000; Bloxham *et al.*, 2002; Holme and de Viron, 2005).

Combining existing Ørsted, CHAMP and future *Swarm* observations will also more generally allow the investigation of all magnetohydrodynamic phenomena potentially affecting the core on sub-annual to decadal scales, down to wavelengths of about 2000 km. Of particular interest are those phenomena responsible for field changes that cannot be accounted for by core surface flow models (Eymin and Hulot, 2005). The role of magnetic diffusion in the core will be further investigated. This diffusion is believed to mainly act at small length scales and to play a significant role in the creation of the reverse patch currently seen below the South Atlantic Ocean (Bloxham and Jackson, 1992). Also, wave motion that 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, could possibly be identified (Finlay and Jackson, 2003; Dormy and Mandea, 2005). Such identification could provide a strong and crucial constraint on the strength of the toroidal magnetic field at the top of the core. Finally, by making it possible to access the detailed evolution of the field at the core surface over a significant time period, new data assimilation approaches could be used to predict the future behaviour of the Earth's magnetic field, and of the South Atlantic Anomaly in particular.

2.2 Lithospheric magnetisation

The field from the Earth's core masks the lithospheric field at degrees less than 14. Hence the lithospheric field we can hope to recover will only contain wavelengths less than 2850 km. The present satellite missions have provided impressive results regarding the global and regional magnetisation of the crust and uppermost mantle and their geodynamic implications (Purucker *et al.*, 2002a; Maus *et al.*, 2006a), features up to spherical harmonic degree 60 are now believed to be resolvable. The magnetic field originating from the lithosphere appears globally weaker in the oceanic domain than above continental areas, reflecting a difference of a factor of five in magnetic thickness between continental and oceanic crust. The resolution of present day satellite data is not sufficient to image the entire crust. Spherical harmonic degrees above 150, corresponding mainly to sources in the upper crust, can be derived from high-quality airborne surveys but there remains a spectral "hole" between degrees 60 and 150, corresponding to the middle crust. The higher resolution provided by the *Swarm* satellites will allow, in combination with aeromagnetic surveys, to close this spectral gap and provide global compilations of lithospheric fields at scales from 5–3000 km as demonstrated in the accompanying papers by Maus *et al.* (2006b) and Sabaka and Olsen (2006). The increased resolution of the *Swarm* satellites will allow, for the first time, the identification from satellite altitude of the oceanic magnetic stripes corresponding to periods of reversing magnetic polarity. Such a global mapping is important because the sparse data coverage in the southern oceans has been a severe limitation regarding our understanding of plate tectonics in the oceanic lithosphere. In addition, the north-south trending magnetic anomaly stripes are examples for along-track features, which are difficult to extract from a single polar-orbiting satellite. The unique *Swarm* constellation with a small East-West separation of the two lower satellites will contribute significantly to overcome this difficulty (Maus *et al.*, 2006b, this issue). Another important implication of improved resolution of the lithospheric magnetic field is the possibility to derive global maps of heat flux. Areas of high heat flux are associated with weak magnetic field strength caused by material having a temperature higher than the Curie temperature. Fox Maule *et al.* (2005) identified such areas underneath the ice sheets of Antarctica using lithospheric field models based on measurements of the CHAMP and Ørsted satellites.

2.3 3-D electrical conductivity of the mantle

Our knowledge of the physical and chemical properties of the mantle can be significantly improved if we know its electrical conductivity. The deep mantle can be probed using signals originating in the core and observed at the surface (Mandea Alexandrescu *et al.*, 1999). This method is based on a precise determination of the field during rapid and isolated events such as geomagnetic jerks and requires some a priori assumptions about the kinematics of the fluid motion at the top of the core. Conductivity of the upper mantle can be inferred by analysing the geomagnetic effect of magnetic field variations of external origin (Olsen, 1999).

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 reflect the connectivity of constituents as graphite, fluids, partial melt, and volatiles, all of which may have profound effects on rheology and, eventually, on mantle convection and tectonic activity.

Due to the sparse and inhomogeneous distribution of geomagnetic observatories, with only few in oceanic regions, a true global picture of mantle conductivity can only be obtained from space (Olsen, 1999; Constable and Constable, 2004). Accurate mapping of the 3-D electrical conductivity structure of the deep Earth requires better spatial data coverage and improved estimates of the electrical response of the mantle at periods between hours and days. This is not possible with single satellite data. Magnetic data from satellites in a constellation as proposed in the *Swarm* mission will provide the necessary simultaneous observations over different regions (Kuvshinov *et al.*, 2006, this issue).

2.4 Magnetospheric and ionospheric current systems

Studies of the Earth's interior are limited by the effect on the magnetic field models of the contribution from currents in the ionosphere and magnetosphere. Even during magnetically quiet conditions, there is a systematic effect due to these sources. Recently, much progress has been achieved in 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.*, 2004), and utilizing a priori information about the sources to be modelled (Maus and Lühr, 2005; Olsen *et al.*, 2005). Simultaneous measurements at different altitudes and local times, as foreseen with the *Swarm* mission, will allow better separation of internal and external sources, thereby improving geomagnetic field models cf. the accompanying paper by Olsen *et al.* (2006a).

In addition to the benefit of internal field research, a better description of the external magnetic field contributions is of direct interest to the science community, in particular for Space Weather research and applications. The local time distribution of simultaneous data will foster the development of new methods of co-estimating the internal and external contributions. 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.

The specific instrumentation with combined electric and magnetic field measurements as well as *in-situ* plasma density measurements, and the specifically designed constellation of the *Swarm* mission will enable us to estimate also other current components (like near-Earth field aligned currents) and thus significantly increase our understanding of the upper atmosphere dynamics, as demonstrated in the accompanying papers by Ritter and Lühr (2006), Moretto *et al.* (2006), and Vennerström *et al.* (2006).

2.5 Ocean circulation and its magnetic signature

Moving sea-water produces a magnetic field, the signature of which contributes to the magnetic field at satellite altitude. This encourages—as a secondary research objective—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 e.g. for ocean-climate modelling. Furthermore, the magnetic signal due to ocean circulation can also be sensed in regions covered by ice. Based on state-of-the-art ocean circulation and conductivity models it has been demonstrated that the expected field amplitudes are well within the resolution of the *Swarm* satellites cf. the accompanying paper by Manoj *et al.* (2006). Correcting magnetic data for ocean tidal signals will increase the accuracy of lithospheric field models. With the improved separation capabilities of *Swarm*, and using statistical methods, large-scale ocean flow patterns might be recoverable as well.

2.6 Magnetic forcing of the upper atmosphere

The geomagnetic field exerts a direct control of on the dynamics of the ionised and neutral particles in the upper atmosphere, which may even have some influence on the lower atmosphere. With the dedicated set of instruments, each of the *Swarm* satellites will be able to acquire high-resolution and simultaneous *in-situ* measurements of the interacting fields and particles, which are the key to understanding the system.

This secondary research objective involves a detailed mapping of the structure of the ionospheric phenomena using the plasma density measurements. Density variations in the neutral upper atmosphere are believed to occur in response to Joule heating in the ionosphere (Lühr *et al.*, 2004; Liu and Lühr, 2005). By combining air drag observations with precise electric and magnetic field measurements, the physical mechanism causing the neutral density variation can be elucidated.

3. Mission Concept

Single-satellite magnetic missions do not allow taking full scientific advantage of currently obtainable instrument precision because the sequential data sampling results in an inadequate capability of separating the contributions from various sources. In principle, the field modelling algorithms

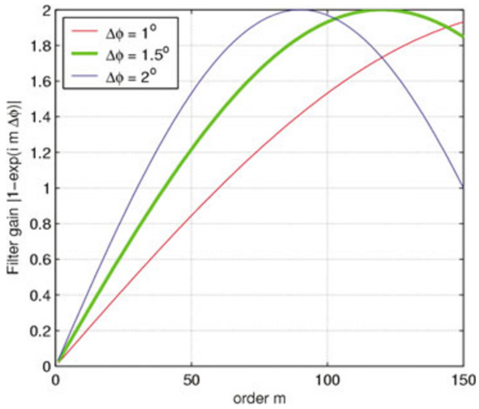

Fig. 4. Relative sensitivity of the "gradient" method versus spatial scales. Three examples with different spacecraft separations in longitude are shown.

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 primarily Earth-fixed, while external contributions are ordered primarily in a Sun-fixed (i.e. local time) frame. A single polar orbiting satellite can obtain a reasonably dense sampling of the internal field components within a few days, but fails to provide an adequate spatial coverage of the external contributions, because of the slow orbital precession through local time. To separate the internal and the external contributions a mission with several spacecraft simultaneously orbiting the Earth at different local times is necessary.

The scientific return for each of the research objectives can be considerably enhanced when optimised spacecraft constellations are obtainable. An important task is to define an orbit configuration, which is a viable compromise for all science objectives. The selected constellation reflects an attempt to optimise the primary research objectives related to the interior field: 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 reduced (by data selection), subtracted (using a-priori models of external fields), or modelled (co-estimated). From the research objectives it follows that the orbit inclination shall be near-polar, primarily to obtain a good global coverage. The research objectives demand that the unsampled areas around the poles should be kept small, to obtain complete maps of the magnetic field contributions. 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 seasonal and local time effects.

Accurate determination and separation of the large scale magnetospheric field, which is essential for better separation of core and lithospheric fields, and for induction studies, requires that the orbital planes of the spacecraft are separated by 3 to 9 hours in local time. (Olsen *et al.*, 2006a).

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 in the inversion algorithm, differences between readings of two satellites orbiting side by side in addition to the full magnetic field readings. Optimal spacecraft separations for taking best advantage of such differences 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. A spacecraft separation in longitude between 1 and 2° appears to be optimal for such a "gradient" method, as demonstrated in Fig. 4. A further advantage is that signals from large-scale external contributions that predominantly change in North-South direction are suppressed by making use of such differences in East-West direction.

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 (Ritter and Lühr, 2006, this issue). 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 5 seconds at the four corners of a symmetric quad to calculate

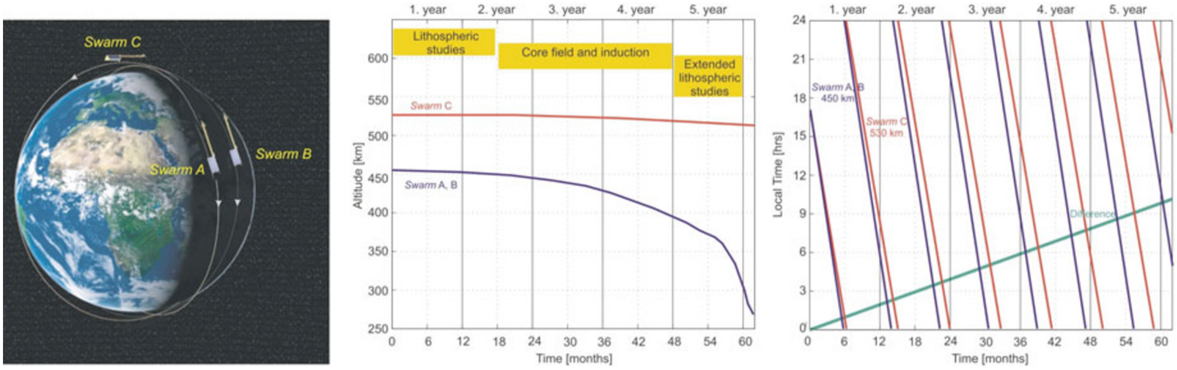

Fig. 5. Impression of the studied three satellite constellation (left) and mission scenario. Local time evolution for the satellites in the two orbital planes (centre); change in altitude versus time (right).

the 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 with increased accuracy. The multi-point measurements also taken at different altitudes allow the determination of the interaction of thermospheric density structures with ionospheric plasma enhancements (Liu *et al.*, 2005). In addition, the propagation direction and velocity of such features can be obtained. The multi-point measurements also allow studying the characteristics of atmospheric waves, which are known to play an important role in the energy transfer. All these items are necessary pieces for a systematic understanding of the atmosphere.

An example of a studied three-satellite orbit constellation that can be achieved through a single launch comprises the following parameters (see Fig. 5):

- 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 shall be between 1–1.5° in longitude, and the maximal differential delay in orbit shall be approximately 10 seconds.
- One higher satellite (*Swarm* C) in a circular orbit with 88° inclination at an initial altitude of 530 km. The right ascension of the ascending node is drifting somewhat slower than the two other satellites, thus building up a difference of 9 hours in local time after 4 years.

4. Instrumentation

The payload complement of the *Swarm* satellites consists of core instruments, which are required for a precise determination of the ambient magnetic field and of auxiliary-type instruments, which are needed for a better separation of the various field sources and for the detection of effects related to geomagnetic activity.

Measuring the vector components of the magnetic field with an absolute accuracy requires the combination of readings from three instruments: A scalar magnetometer, a vector magnetometer, and a stellar compass to provide the attitude of the vector magnetometer. Only if the performances of all three instruments are matched an optimal result is achieved. These are therefore treated as a single package.

High-quality instruments for such packages have been developed in the context of the Ørsted and CHAMP missions. However, the desired accuracy of the magnetic field products is significantly higher than that of existing missions. This demands a 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.

In order to improve the determination of the contribution to the magnetic field from currents in the ionosphere, the payload includes an instrument to measure the electric field. Plasma density measurements are also included since 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 modelling (Lühr *et al.*, 2003). Besides the local sampling by means of a Langmuir probe the surrounding plasma density will be determined from GNSS receiver-derived TEC measurements.

Density variations in the neutral upper atmosphere are believed to occur in response to Joule heating in the ionosphere (Lühr *et al.*, 2004). Combining air drag with electric and magnetic field measurements will contribute to the elucidation of the physical mechanism causing the density variation. The air drag, needed for deriving the thermospheric density, can be obtained from 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.

The overall 2σ (σ being the standard deviation) accuracies of the data products at level 1b for the various quantities for each single satellite are:

- Magnetic field magnitude: 0.3 nT accuracy for signals ranging from global to 20 km, and with stability in time accurate to 0.1 nT/3 months for the slow variations.
- Magnetic field vector components: 1 nT accuracy for signals ranging from global to 2 km, and with stability in time accurate to 1 nT/year for the slow variations.
- Electric field components: 5 mV/m accuracy for signals ranging from global to 10 km, and with stability in time accurate to 1 mV/m/month for the slow variations.
- Plasma density distribution of the ionosphere: $0.5{*}10^{10}\mathrm{m}^{-3}$ RMS accuracy for scales from global to 10 km.
- Air drag vector components: $5{*}10^{-8}\mathrm{ms}^{-2}$ accuracy for signals ranging from global to 200 km.
- Ion and electron temperature: 5% accuracy for temperatures above 1000 K for scales from global to 200 km and for periods up to 3 months.
- Ion drift velocity vector components: 100 m/s accuracy for all scales from global to 10 km and for periods up to 3 months.
- Satellite position: 10 cm RMS in all directions.
- Satellite attitude: 0.1 deg.

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, as listed above for a single satellite, also on *Swarm* system level.

5. Impact of *Swarm*

The unique data set from *Swarm* will be crucial for various international scientific programmes regarding a wide range of geophysical disciplines, addressing problems from the very deep Earth's interior to the Earth's environment. This effort is in line with previous international coordinated efforts aiming at better understanding the geomagnetic field and its variations. 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), the International Geophysical Year (1957–58) and the International Year of the Quiet Sun (1964–65). The International Association of Geomagnetism and Aeronomy, IAGA, has been instrumental in ensuring adequate data handling procedures for all these research campaigns. When measurements from space became available IAGA was the natural organisation to coordinate the implementation of this new data source into the various research programmes and applications.

Swarm is the most ambitious project so far regarding a dedicated effort to provide the most accurate measurements ever of the Earth's magnetic field. The mission is an important contribution to the International Decade of Geopotential Research, an initiative of the International Union of Geophysics and Geodesy, IUGG, with the primary goal to elucidate the time-variable nature of the terrestrial gravity and magnetic signals. A decade-long program is necessary to capture time variations at a wide variety of scales. Gravity and magnetic fields are the only two remotely sensed fields, which can provide constraints on the Earth's deep interior from space in a very different manner than from natural seismic analyses.

In addition to the wide range of research topics that can be addressed with geomagnetic data, the data are also indispensable for a variety of operational functions and applications. These applications fall into four main categories. The first category comprises applications that depend on accurate models of the static or slowly varying component of the geomagnetic field. The second category includes applications of near real-time models to characterize the rapid time-varying part of the field and particle environment. The third and fourth categories consist of models of core dynamics, and lithospheric properties, respectively.

The geomagnetic field is one of the primary factors controlling the impact of solar variations on the Earth's environment. Due to the specific emphasis on separating the internal and external sources and the completeness of the instrumentation to pursue this goal the *Swarm* mission therefore fits well into the research programme of the International Living with a Star (ILWS) program. Consequently, the ILWS programme steering committee including representatives from the Canadian, Russian, Japanese, European, and American space agencies have identified *Swarm* as an important element in the ILWS suite of missions.

Better understanding of the geographical distribution and the time variations of the geomagnetic field, due to internal dynamics as well as to the changes introduced by solar variability, may help 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. Furthermore, with satellites crossing the auroral electrojets in two orbital planes there is a large potential of deriving a satellite based index of planetary geomagnetic activity that is more representative for many applications than the existing ground based indices.

In recent 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 this hypothesis is 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.

6. Conclusion

There is a multitude of research topics across several scientific disciplines that are ready to take advantage of the increased knowledge about the Earth's magnetic field and its variations that the *Swarm* mission will bring. This means that several scientific communities with different scientific background will be using the data for various purposes.

Each of the various research objectives and applications focuses on certain aspects of the data related to specific sources. But to extract the relevant information expertise is needed related to all the sources. All this expertise is not available in any single organisation but is distributed in the scientific community that is supporting the mission. A major challenge for the community will be to make sure that this rich data set is communicated and distributed in a form that can really be exploited by the broad user and science community, in particular by those users that do not have the scientific knowledge and tools, which are necessary to derive and interpret the contribution from all the various and complex sources.

One way of achieving this goal would be to establish a coordinated modelling effort including the expertise and competence from a number of expert groups from each of the disciplines. The derived models should be accessible also by the inexperienced user to extract exactly the information from the combined data set, which is relevant for the science task or application in question. Dedicated resources have to be allocated to this task, which is not trivial because it relies on suitably developed algorithms that fully take into account the new constellation concept and the suite of instruments that are available for providing the necessary additional data for enhancing the quality of the models.

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