SCIENTIFIC GOALS OF *SWARM*

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ABSTRACT

The *Swarm* mission has been selected as the 5th mission in ESA's Earth Explorer Programme. The mission will provide the best ever survey of the geomagnetic field and its temporal evolution and will improve our understanding of the Earth's interior and 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 a third spacecraft 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.

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 [1]. This trend is still ongoing, at a rate comparable to that seen at times of magnetic reversals [2]. 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. 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 [3] 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 [4]. This activity has evolved to the present day due to the launch in 2000 of two additional magnetic mapping satellites CHAMP [5] 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 satellite data simultaneously acquired at different locations. The irregularly varying fields produced by the external currents are the main limiting factor in the accuracy of present geomagnetic field models. Single-satellite missions 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 the next natural step forward as demonstrated by results from combined analysis of Ørsted, CHAMP and SAC-C data [6], [7], [8]. Based on an interdisciplinary approach and the development of new tools to deal with all the various contributions, from the outer magnetosphere to the deep core, in a comprehensive way (see Fig. 1), the goal is to 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 [9] 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 a Phase-A study that was finalised during 2004.

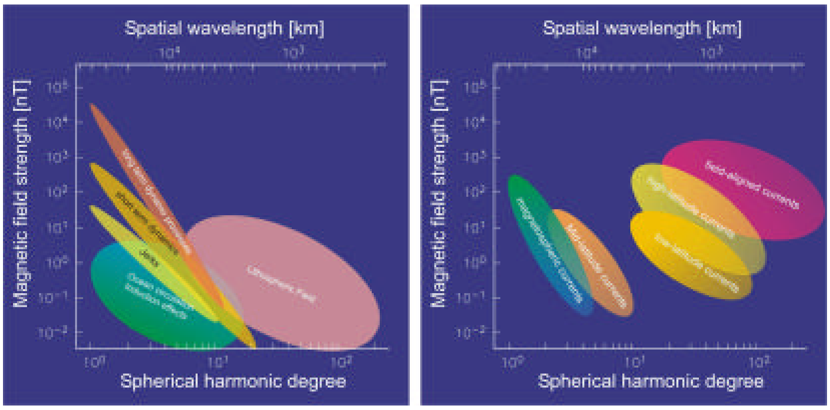

Figure 1. Signal amplitude at orbit altitude of the contributions from processes contributing to the magnetic field as a function of spatial scale. Source terms from within the solid Earth and the oceans (left, and contributions from external sources (right).

The results of the Phase-A study were included in the evaluation report [10] presented for the final mission selection. 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.

2. SCIENCE OBJECTIVES

The objective of the *Swarm* mission is to provide the best ever survey of the geomagnetic field and its temporal evolution with the aim of improving our understanding of the Earth's interior and the Geospace environment including the Sun-Earth connection processes.

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 will directly address the challenging issue of separating the contributions from the various field sources.
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 [11], [7], [8], [12]. *Swarm* will further improve models of the core field dynamics by ensuring long-term space observations with an even better spatial and temporal resolution. 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 [13], [14] or the alternative more recent "helical flow" assumption [15]. It will also include detailed core surface flow models, which will make it possible to further investigate torsional oscillations, core-mantle interactions as well as geomagnetic jerks.

Swarm observations will 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. The role of magnetic diffusion in the core will be further investigated. This diffusion is believed to play a significant role in the creation of the reverse patch currently seen below the South Atlantic Ocean [16]. 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. Such identification could provide a strong and crucial constraint on the strength of the toroidal magnetic field at the top of the core.

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 [17], [18]. Features up to spherical harmonic degree 60 are now believed to be resolvable. 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. 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. An 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. Such areas underneath the ice sheets of Antarctica have been identified using lithospheric field models based on measurements of the CHAMP and Ørsted satellites [19].

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 [20]. This method is based on a precise determination of the field during rapid and isolated events such as geomagnetic jerks. Conductivity of the upper mantle can be inferred by analysing the geomagnetic effect of magnetic field variations of external origin [21].

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 provide insight into geodynamic processes such as mantle convection, the fate of subducting slabs, and the origin of continents.

Accurate mapping of the 3-D electrical conductivity structure of the deep Earth requires data obtained simultaneously over different regions such as proposed in the *Swarm* constellation mission [22].

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 [7], and utilizing a priori information about the sources to be modelled [23], [24]. 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.

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. 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 [25], [26], [27].

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 [28]. 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. Correcting magnetic data for ocean tidal signals will increase the accuracy of lithospheric field models.

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 [29], [30]. 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. 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 can be obtained. 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.

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.

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. 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. 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.

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 [25]. 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

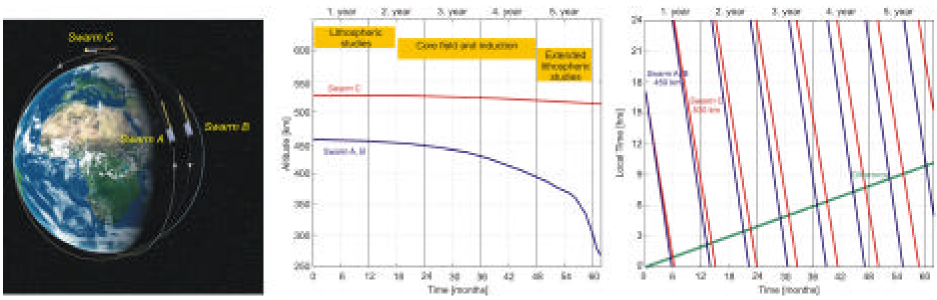

Figure 2. Impression of the studied three satellite constellation (left) and mission scenario. Local time evolution for the satellites in the two orbital planes (centre); change in altitude versus time (right).

determination of the interaction of thermospheric density structures with ionospheric plasma enhancements [31]. 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 comprises the following parameters (see Fig. 2):

- 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. 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 instruments to measure the electric field and the plasma density. 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. Besides the local sampling by means of a Langmuir probe the surrounding plasma density will be determined from GNSS receiver-derived TEC measurements. The air drag, needed for deriving the thermospheric density, will be obtained from observing the non-gravitational forces measured by an accelerometer.

5. SUMMARY

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. *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.

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.

Each of the various research objectives and applications focuses on certain aspects of the data related to specific sources. A major challenge for the community will be to make sure that the rich data set is communicated and distributed in a form that can really be exploited by the broad user and science community. One way of achieving this goal is 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 non-specialised user to extract exactly the information from the combined data set, which is relevant for the science task or application in question.

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