

From Ørsted to Swarm

– Challenges for exploring the Earth's magnetic field from Space

The *Swarm* satellite mission is designed to provide the best ever survey of the geomagnetic field and its temporal evolution. The mission, proposed by a European consortium led by the Danish National Space Center, is scheduled for launch in 2010.

Swarm comprises 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, acceleration and electric field measurements, provide information on

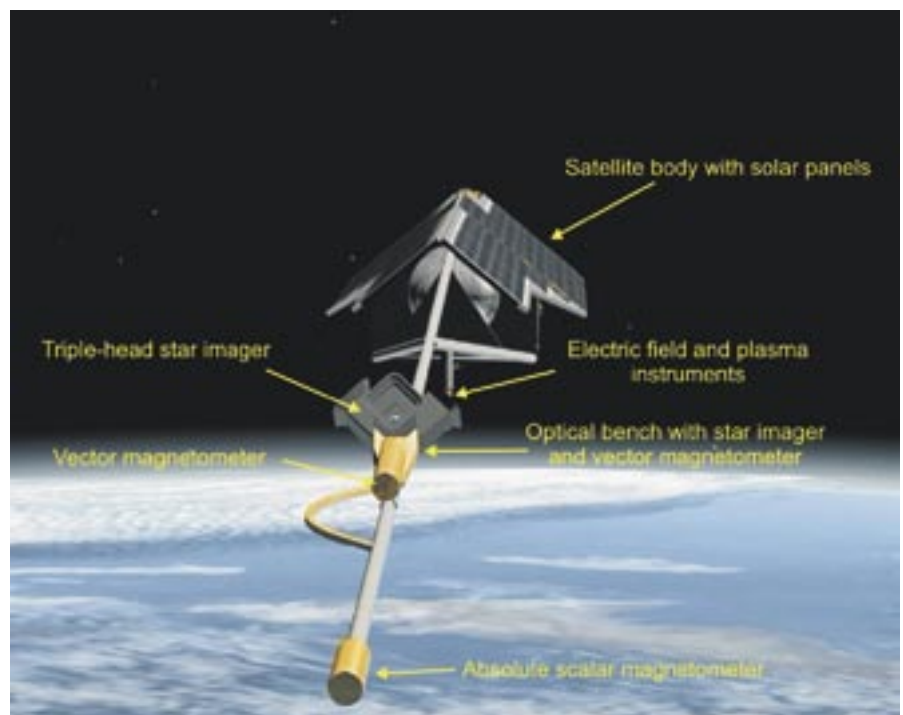


Fig. 1: One of the three *Swarm* satellites.

the various sources of the geomagnetic field, in the Earth's core, mantle, crust, ionosphere, and magnetosphere.

From Ørsted to Swarm

A new era of geomagnetic research started in 1999 with the launch of the Danish Ørsted satellite. Two other satellites, CHAMP and SAC-C, carrying similar instrumentation as Ørsted, have been launched a couple of months later. Analysis of magnetic data taken by these

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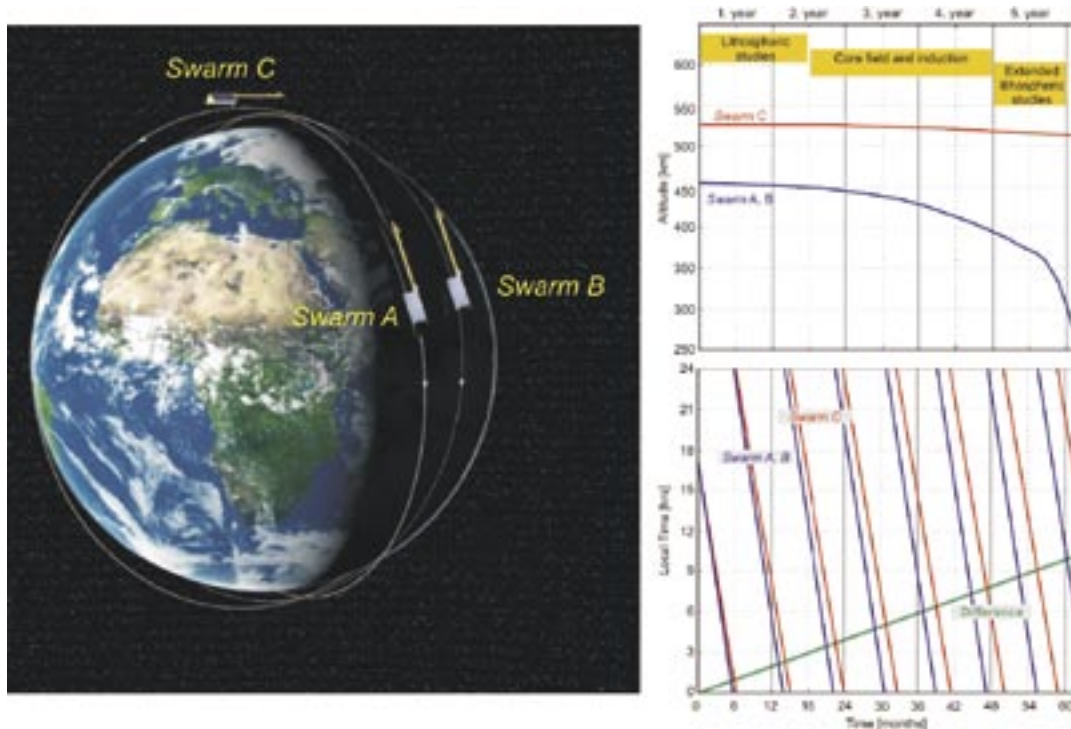


Fig. 2: Impression of the proposed three satellite constellation (left) and mission scenario (right). Local time evolution for the satellites in the two orbital planes (right bottom); change in altitude versus time (right top).

the Earth by time-varying external fields. The scientific challenge is the separation of these various sources, each having specific spatial and temporal characteristics. *Swarm* has 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. *Swarm* will therefore make it possible to derive the first global

representation of the geomagnetic field variations on time scales from hours to years.

The primary science objectives of *Swarm* concerns investigation of the Earth's interior: The core magnetic field is among the very few means available for probing the liquid core. Temporal variations of the magnetic field directly reflect the fluid flows in the outermost core and provides a unique experimental constraint on geodynamo theory. Our knowledge of the magnetisation of the crust has been greatly enhanced by analysing data from the recent satellites Ørsted and CHAMP. However, fundamental unresolved questions remain about the crustal 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, which *Swarm* will be able to provide.

In addition to these primary research objectives related to sources interior to the Earth, *Swarm* data will also be used to identify ocean circulation (moving sea-water produces a magnetic field which can be measured at satellite altitude) and to quantify magnetic forcing of the upper atmosphere (which is related to the direct control of the magnetic field on the dynamics of particles in the upper atmosphere).

satellites has led to an enormous amount of new scientific results, especially concerning variations of Earth's main field (which is generated at depths greater than 2900 km in the fluid outer core) and the magnetisation of rocks in the uppermost 10-20 km of the Earth's crust.

However, already before the launch of the Ørsted satellite it was recognized that single satellite missions will not be able to fully take advantage of the improvement in measurement accuracy that has been obtained during the last years. Studying the various contributions to the geomagnetic field requires their separation by means of geomagnetic field models, and the limiting factor in the accuracy of such models are electric currents in the ionosphere and magnetosphere. They hamper the precise determination of the core and crustal fields contributions. Single satellite missions like Ørsted are not able to describe these currents in a satisfactory way. Only multi-satellite missions measuring simultaneously over different regions of the Earth can do this and thereby are able to take full advantage of the accuracy of the new generation of instruments.

Recognizing this, Danish scientists proposed in 1997 a predecessor of *Swarm*,

called *Multiprobe*, to the Danish national Small Satellite Program. The mission comprises much of the key parameters of *Swarm*, as for instance multiple identical satellites in two drifting orbit planes, measuring the magnetic field at different local times.

Based on *Multiprobe* (which was regarded as too ambitious for the Danish national satellite programme), a slightly modified mission was proposed to the ESA Earth Observation Programme in 1998. Further modification of the concept resulted in a revised proposal sent to ESA in 2002. Among 25 submitted proposals *Swarm* was selected as one of the three candidates for feasibility studies, and in May 2004 the mission was selected as the fifth Earth Explorer Mission in ESA's Living Planet Programme for launch in 2010.

Scientific objectives

The main part of Earth's magnetic field originates in the fluid outer core. But satellites measure a superposition of the core field and fields caused by magnetised rocks in the crust, by electric currents flowing in the ionosphere, magnetosphere and oceans, and by currents induced in

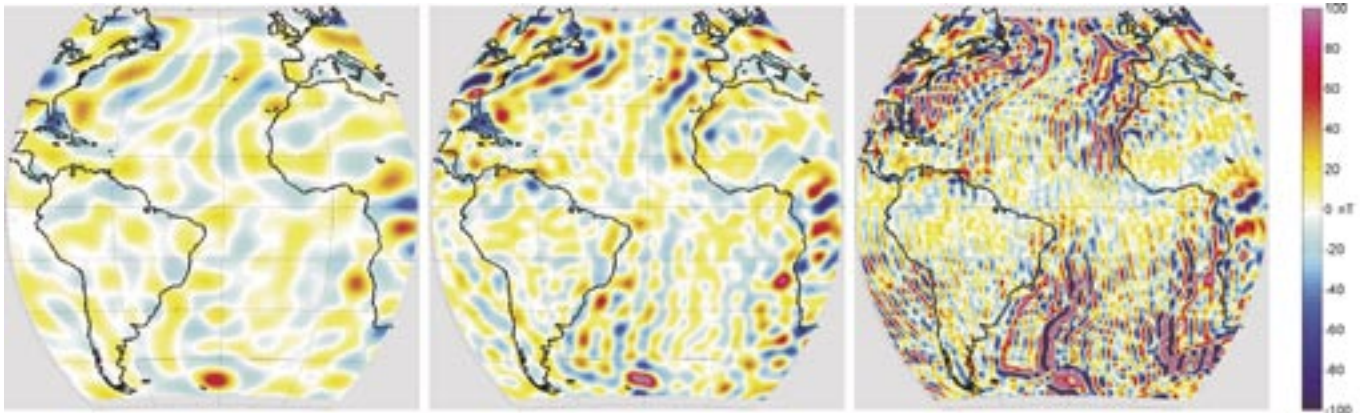


Fig. 3: *Swarm will lead to a significant increase in the resolution of crustal field maps. The left panel shows crustal field resolution as determined before Ørsted, the middle part indicates present resolution obtained from Ørsted and CHAMP, and the right part is the expected result from the Swarm mission. Shown is the magnetic radial component at 10 km altitude above surface based on a mission simulation.*

In summary, measuring the magnetic field provides a huge amount of information about our environment; no other single physical parameter may be used for such a variety of studies related to the Earth, its formation, its dynamic and its environment, stretching all the way from the Earth's core to the ultimate source of life on Earth, the Sun. The overall goal of *Swarm* is to study these phenomena and their interaction within the Earth system.

Spacecraft, instruments and mission constellation

Swarm is presently in Phase B, and the satellites are presently built by EADS Astrium (Friedrichshafen/Germany). Figure 1 shows one of the three satellites with the main instruments. The primary goal of *Swarm*, measuring the vector components of the magnetic field with high-precision, requires the combination of three instruments: a scalar magnetometer, a vector magnetometer, and a stellar compass to provide the attitude of the vector magnetometer. High-quality instruments for that purpose have been developed in the context of the Ørsted and CHAMP missions. However, *Swarm* is the most ambitious project so far regarding accurate measurements of the Earth's magnetic field, and the desired magnetic field accuracy is significantly higher than that of existing missions.

The vector magnetometers and star imagers are built by the Danish Spacecenter/DTU (Copenhagen/Denmark), while the scalar magnetometer is built by CNES/LETI (Toulouse/France). In order to study currents in the ionosphere, the payload also includes an instrument to measure the electric field, built by University of Calgary (Canada) and a

Langmuir probe from the Swedish Space Institute (Uppsala/Sweden). Precise orbit information is obtained from GNSS receivers.

Density variations in the neutral upper atmosphere are caused by Joule heating in the ionosphere. Combining air drag with electric and magnetic field measurements will contribute to the elucidation of the physical mechanism causing these density variations. The air drag, needed for deriving the thermospheric density, will be obtained from observing the non-gravitational forces using tri-axial accelerometers built by the Czech Aeronautical Research and Test Institute VZLÚ (Prague/Czech Republic).

Design of the constellation formation is an important issue, and the selected constellation reflects an attempt to optimise the various research objectives. It consists of three satellites with the following constellation parameters (see Figure 2):

One pair of satellites (*Swarm* A+B) will fly 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 about 1.4° in longitude (corresponding to 155 km at the Equator). Atmospheric re-entry at the end of the four year mission lifetime will allow to measure the magnetic field from rather low altitudes (below 300 km), which is beneficial for an improved crustal field determination.

The third, higher, satellite (*Swarm* C) is 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 that of the two other satellites, thus building up a difference of 6 hours in local time after 3 years (right panel of Fig. 2).

Combination of data from the two lower satellites yields the East-West gradient of the magnetic field, which is a key parameter for better resolving the crustal field. Combination of data from the lower with the higher satellites allow for an enhanced description of the space-time structure of magnetospheric currents, which is a key parameter for studying mantle conductivity and for accurate separation of internal and external fields.

What will Swarm bring?

The expected impact of *Swarm* has been investigated in an "End-to-End" mission simulation study, which also has been used to define the optimal mission constellation. Scientific results in a wide range of geomagnetic disciplines are expected, and in following we will concentrate on only two aspects: magnetisation in the crust and the time change of the core field.

Huge improvement is expected in spatial resolution of the crustal field, as indicated in Figure 3. Prior to Ørsted, only crustal field structures larger than 1000 km

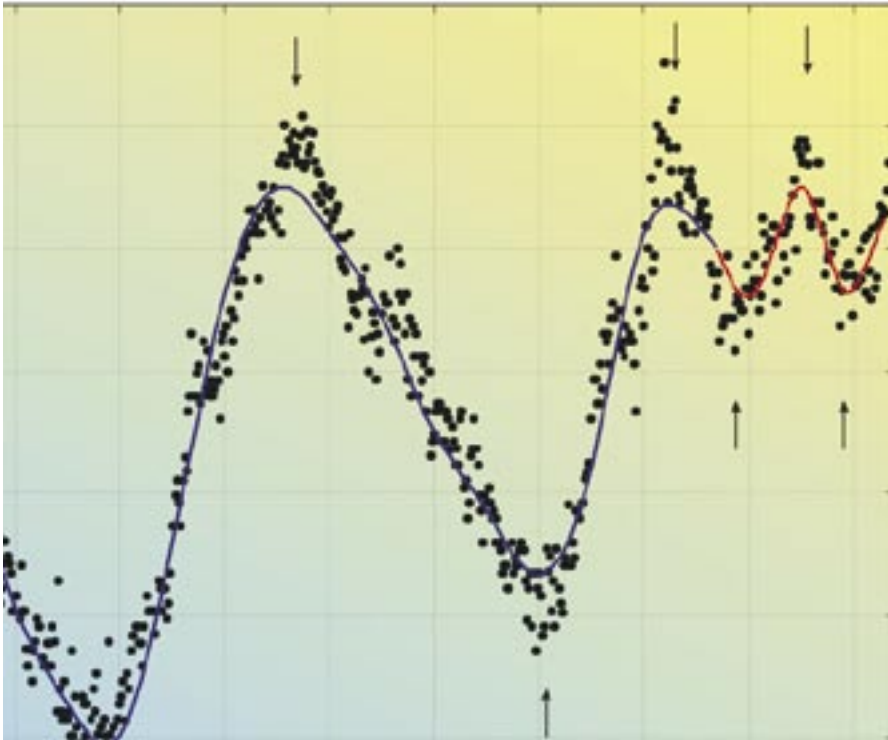


Fig. 4: *The origin of geomagnetic jerks – sharp changes in the magnetic field – is not yet fully understood, but it is believed that they are connected to sudden changes in flow of material in the molten outer core. The figure shows the first time derivative of the East-West component at the observatory Niemegk/Germany. Several jerks (indicated by arrows) occurred during the last years, and Swarm will help to identify their global extension.*

could be resolved (left panel); the present resolution obtained with Ørsted and CHAMP is about 600 km (middle panel), while with *Swarm* it is expected that structures down to 270 km scale size can be resolved (right panel). This allows for a determination of crustal field structures, for instance features caused by seafloor spreading, with unprecedented accuracy.

But also the resolution of core field models is expected to improve considerably, especially concerning its time changes. Several geomagnetic jerks – sudden abrupt changes in slope of the first time derivative, i.e. jumps in the second time derivative of the magnetic field – occurred during the last years (cf. Fig. 4). Neither their origin nor a mechanism to explain them has yet been found, but *Swarm* data will be crucial to explore their spatial distribution.



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