The Swarm Magnetometry Package

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Abstract The Swarm mission under the ESA's *Living Planet Programme* is planned for launch in 2010 and consists of a constellation of three satellites at LEO. The prime objective of Swarm is to measure the geomagnetic field with unprecedented accuracy in space and time. The magnetometry package consists of an extremely accurate and stable vector magnetometer, which is co-mounted in an optical bench together with a start tracker system to ensure mechanical stability of the measurements.

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R. Sandau et al. (eds.), *Small Satellites for Earth Observation*,

1 Introduction

High precision measurements of the geomagnetic field have been and are essential to provide insight into the internal structure of the Earth and the solar interaction with the Earth's magnetic field. These measurements reveal the resulting magnetic field that stems from the superposition of three sources: the core field, the crustal field and the current driven field. The spatial and temporal structure of these sources are very different from each other, and therefore not only signal extraction methods and modelling but also measurement strategies have to be taken into account in order to successfully separate these signal contributors. Furthermore, this decomposition process requires that the global field is known at any given time with a relatively high accuracy, wherefore accurate magnetic field mapping is only viable using spaceborne observations.

The data obtained from one single spacecraft is extremely valuable. The first mission to ever map the Earth's magnetic field vector at LEO was the NASA MAGSAT (1978–9). Twenty years later, the Danish Ørsted micro satellite (1999–), the German CHAMP (2000–), the Argentine SAC-C (2000–5) have been designed specifically for mapping the LEO magnetic field. Common to these resent missions is the magnetometry package, which utilizes a vector field magnetometer co-mounted with a star tracker (2 in the case of CHAMP) on an optical bench.

As the accuracy of the instrument package has constantly increased, as well as the modelling methods have been improved towards optimized signal decomposition, it has been realized that simultaneous data from several points in space is needed, if the ultimate modelling barrier, the spatial-temporal ambiguity, has to be broken.

The ESA Swarm mission under the Living Planet Programme consists of three identical spacecraft orbiting in near polar orbits with altitudes varying between 400 km and 550 km. This constellation is to map the magnetic field of the Earth with unprecedented spatial and temporal accuracy. For this purpose, each spacecraft will be equipped with a vector field magnetometer and three star trackers co-mounted in an optical bench, which will ensure 100% data coverage over the orbit with arcsecond accuracy. This accuracy of the magnetometry package is essential for fulfilling the mission objectives.

This paper describes the basic design characteristics and the performance potentials of the Swarm Magnetometry Package. The key performance parameter is an absolute attitude recovery accuracy in the arcsecond range over time, temperature and aging. The methods used to achieve and validate this accuracy are discussed, as well as the potential for using this methodology on other future missions with extreme stability and accuracy demands.

2 The Swarm Mission

The Swarm mission [1] 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

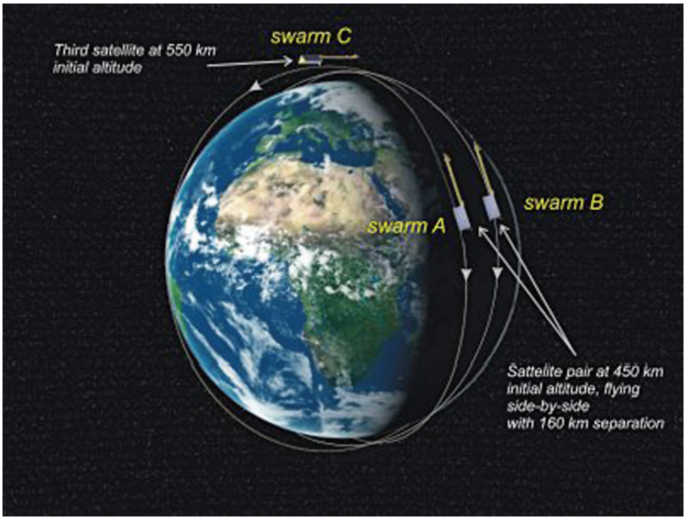

Fig. 1 Swarm constellation of three satellites

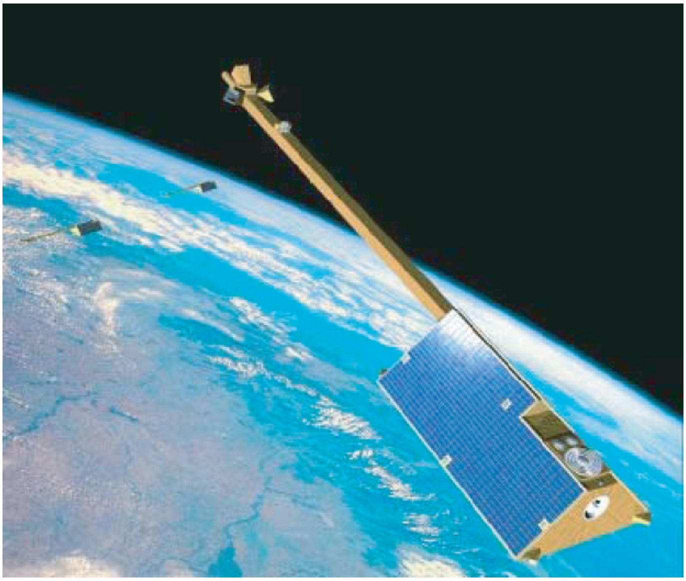

Fig. 2 Swarm satellite will be about 8 m long and have a weight of 300–400 kg

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.

The research objectives of Swarm mission [2] are:

- Related to the Earth's Interior:
  - Map the core flow
  - Determine core dynamics
  - Investigate jerks: their time-space structure and recurrence
  - Understand core-mantle coupling and its implication for Earth rotation
  - Perform 3D imaging of mantle conductivity
  - Determine remanent and induced magnetisation of the lithosphere
- Related to the Earth's environment:
  - Determine the position and development of the radiation belts and their near-Earth effects
  - Investigate the time-space structure of the magnetospheric and ionospheric current systems on all time scales
  - Monitor the solar wind energy input into the upper atmosphere and sense its effect on the thermospheric density
  - Sound the electron density of the ionosphere/plasmasphereand relate it to magnetic activity

The scientific payload consists of the following instruments:

- Vector Field Magnetometer (VFM), which is co-mounted together with a stellar compass for determining the components of the magnetic field very accuratey
- Absolute Scalar Magnetometer (ASM), which is used primarily for calibrating absolutely the vector field magnetometer.
- Electrical Field Instrument (EFI)
- Accelerometer (ACC)

3 The Magnetometry Package on Swarm

The high accurate magnetic field measurements are achieved by is co-mounting the magnetometer in a very stable optical bench together with three μASC star trackers, which ensures full (and continuous) data coverage regardless of the orientation of the satellite. I.e. in case of blinding of one of the star trackers due to the Sun or Earth being on the field of view, two star trackers can deliver full accurate attitude. The blinding of two camera heads (by both Sun and Earth) at the same time is also possible but extremely rare. The optical bench temperature gradients as well as the time thermal variation are designed to be as low as possible to minimize the potential effects that can be difficult to model to the level of accuracy required, i.e. few arc seconds.

3.1 Vector Field Magnetometer (VFM)

The Vector Field Magnetometer (VFM) from DTU is the prime instrument of the Swarm mission. It will provide ultra linear and low-noise measurements of the Earth's magnetic field vector components. The VFM full-scale range is $+/- 65\ \mu$T and it has been allocated a measurement random error of less than 1 nT integrated over frequencies up to 4Hz.

The proposed VFM (fluxgate type) consists of a Compact Spherical Coil (CSC) sensor, non redundant, mounted on the deployable boom, an internally redundant data processing unit (DPU) and the connecting harness.

The fluxgate magnetometer, which is based on the CSC (Compact Spherical Coil) sensor that exhibits extremely high directional linearity as well as thermal stability (30 ppm/C for the scale factors and very low for the non-orthogonal angles and offsets). The range of the magnetometer is $+/-65536$ nT with digitalization error of 21 bits, with a noise of less than 100 $\mathrm{pT_{RMS}}$ in the band 0.1–10Hz (for the sensor this

VFM Specifications	
Mass	1000 g
Power consumption	1 W
Dimension Sensor Head	82 mm Ø
Dimension DPU	100 × 100 × 50mm
Data Rate	
Dynamic Range	±65536.0 nT to 0.0625nT (21 bits)
Omnidirectional Linearity	±0.0001% of FS (±0.1nT in ±65536nT)
Intrinsic sensor noise	$15\mathrm{pT_{RMS}}$ in the band 0.01–10Hz ($6.6\mathrm{pT_{RMS}}/\sqrt{\mathrm{Hz}}$ at 1Hz)
Intrinsic electronics noise	$50\mathrm{pT_{RMS}}$ in the band 0.01–10Hz ($15\mathrm{pT_{RMS}}/\sqrt{\mathrm{Hz}}$ at 1Hz)
Sampling Rate	50Hz, linear phase filter, −3dB frequency 13.1Hz
Temperature range	−20°C to +40°C (Operating performance) −40°C to +50°C (Survival performance)
Thermal behavior	
•Offset	~0nT/°C (csc), ~0.1nT/°C (electronics)
•Scale Factors	~10ppm/°C (csc), ~2ppm/°C (electronics)
•Non-orthogonality angles	~0”/°C (0.06, 0.07, 0.04)

Zero stability (thermal & long term)	$< \pm$**0.5 nT**
Absolute accuracy of Ørsted magnetometer parameters (relative to ASM & STR):	
•Offset	<0.2nT (∼120dB)
•Scale Factors	<0.0005%
•Axes orthogonality	<0.0006 deg (∼2”)
•Axes alignment	<0.0002 deg (∼7”)
Ørsted magnetometer with 3 offsets, 3 scale factors & 3 angles for 6.5year:	
Accuracy	<0.5nT

figure is (15 pT_{RMS}). The sampling rate is 50Hz. The mass of the VFM is about 1 kg excluding harness and the power consumption is less than 1 W. The absolute accuracy as measured by the Ørsted mission in flight over 6.5 years is better than 0.5 nT.

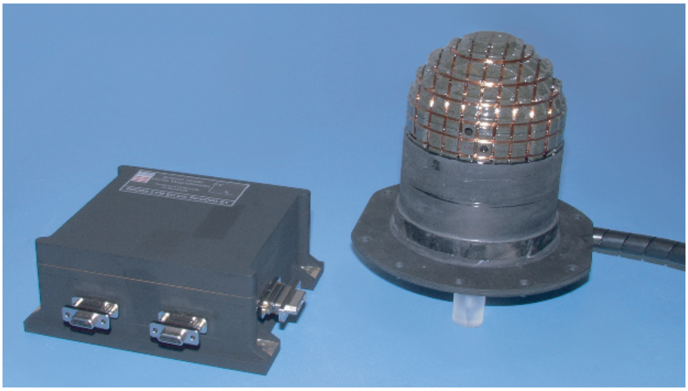

Fig. 3 The VFM magnetometer configuration for the Swarm mission. *Left*: redundant electronics box with *Right*: CSC sensor (shown with a CHAMP holder)

3.2 The Absolute Scalar Magnetometer (ASM)

The objective of the Absolute Scalar Magnetometer (ASM) from LETI is to calibrate the vector field magnetometer (VFM) to maintain the absolute accuracy in the multi-year geomagnetic field mission. The required main performance characteristics of the ASM are: absolute accuracy of < 0.3 nT (2σ), resolution <0.1 nT within its full-scale range of 15000–65000 nT. The ASM magnetometer is based on the Electron Spin Resonance (ESR) principle and makes use of the Zeeman effect which splits the emission and absorption lines of atoms in an ambient magnetic field. The pattern and amount of splitting is a signature of the magnetic field strength. The optically pumped helium magnetometer uses a High Frequency (HF) discharge within a gas cell to excite ^{4}He atoms from the ground state to the metastable state. This metastable level is split by the Earth magnetic field into 3 Zeeman sublevels. The separation of those sublevels is directly proportional to the ambient field strength and equals half the gyro frequency (eB/2m with m – electron mass).

ASM Specifications	
Mass	3000 g
Power consumption	5.3 W
Dimension Sensor Head	40 × 60mm
Dimension DPU	200 × 150 × 100mm
Data Rate	0.35 Mbyte/ day
Dynamic Range	15000 – 65000 nT full scale
Absolute Accuracy	<0.3 nT (2σ)
Omni-directional response	< 0.1 nT angular dependence

3.3 The Star Tracker (STR)

The STR provides the attitude of the VFM and both are co-mounted in a common optical bench. The μASC (Advanced Stellar Compass from DTU) star tracker is a well proven instrument with an extensive space heritage. It features two fully cold/hot redundant DPU's. Full cross-strapping, each DPU can control one to four CHU's. Mission specific baffles can be designed for optimum performance. It can provide 22 true solutions per sec. The absolute accuracy is <1". The mass is $<$ 1400g (3 × CHU, BFL's & DPU). The power is $<$ 5.7 W (3 × CHU+DPU). It can support asteroid science - Near Earth Object (NEO) detection and planets triangulation.

Fig. 4 The STR μASC for the Swarm mission. Central: redundant electronics box. Each side can operate up to four camera heads

3.4 The Optical Becnch (OB)

The purpose of the Optical Bench is the transference of the attitude from the extremely precise star trackers to the magnetometer field components. The OB ensures a highly mechanical stable platform for the magnetometer and the star trackers.

A exhaustive thermo mechanical design and analysis is carried out to determine and minimize any thermal gradient that could cause a shift in the relative attitude between the two systems.

The STR are very magnetically clean, however the separation between the two (STR and VFM) is about 40 cm to reduce magnetic perturbation from the STR's. Exploitation of symmetric system has been resulted in a cylindrical tube holding the VFM sensor, minimizing transversal thermal gradients. Emphasis has been on the matching of material parameter, use of iso-static support interfaces and detailed analysis of loads.

The instruments are calibrated as stand alone and once integrated in the OB, a inter-calibration and system verification is carried out in order to determine the relative orientation between the VFM and STR and to verify that the stability is as required.

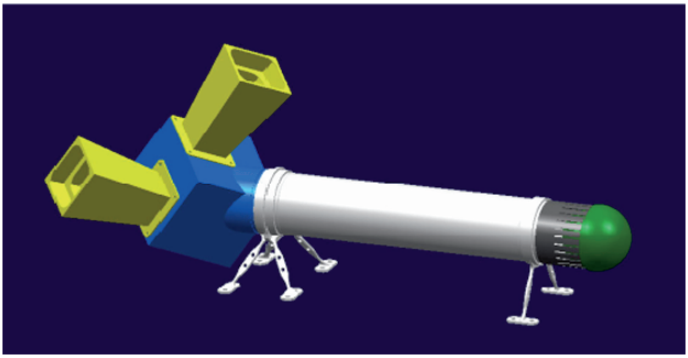

Fig. 5 The Optical Bench with three star tracker cameras (yellow, only two of them are shown) and the magnetometer sensor (green)

4 Discussion

The Ørsted, SAC-C and CHAMP satellites have had some overlaping during 1999–2007, whereas MAGSAT has produced a reference measurement point at 1980. These missions have produced a large amount of high quality magnetic field data and therefore contributed enormously for the understanding of the Earth's magnetic field. This has yielded models that can represent the many field contributions (Earth's core, Earth's crust, large scale ionospheric and magnetospheric currents, interactions with the Sun, galaxy, ocean currents, tidal currents, earthquakes, etc . . .).

In some occasions there has been conjuctions of the orbits of these satellites (Ørsted/CHAMP/SAC-C). However, the orbits are not optimized for certain field structures analysis. In addition, the instrumentation and platform in these satellites are not uniform. The field measure in space is the result of many sources, which can be spatial dependent but also time dependent. The volume out there in space is enormous, and therefore the space-time ambiguity can not be resolved with single point measurements. Since it is not possible to have a fixed measuring point in space, constellations have been devised in order to separate these sources in the models. Other constellations have been launched (Cluster, Stereo, Themis, ...) for the investigation of structures in specific regions of the Earth environment.

The rationale behind Swarm is that the signal extraction of space-temporal signatures can be optimized by designing the orbits of a constellation of three satellites. This is of quite importance for further understanding the Earth and its evolution, and therefore its history.

5 Conclusion

The instruments planed for Swarm are the evolved counterparts of those flown on Ørsted, with slightly better performance as well as mounted in a more mechanically stable optical bench. Therefore one could expect a factor of 5 better in overall performance. The instruments are 10 times as stable and since there are three star cameras, a much better attitude can be determined in all directions.

The Ørsted orbit was 600–800 km whereas Swarm is planned for abot 350 km. Ørsted is a low mass (60 kg) and gradient stabilized satellite, which need to be at high altitudes otherwise the air drag will unstabilize it and cause a fast orbital decay. On the other Swarm has higher mass (~300kg), which allows it to fly in a more aerodynamical regime, and at a lower orbits. In addition it also carries fuel and the altitude can be controlled as opposed to the case of Ørsted. By using the cubic attenuation law (i.e. $850/350)^3 \sim 10$), this could give up to a factor 10 on the measurement of the field. Therefore, in principle one of the Swarm satellites could provide a precision up to 50 times better that Ørsted.

Finally, the instruments can be tested, calibrated and verified to probe the high performance as stand alone. However, the VFM, which has to be calibrated with the ASM, has to be related to a geographical coordinate system via the STR. Therefore, one has to ensure that the measurement performance and thermal stability is not degraded from the instrument level towards the satellite level. In addition, the long term stability and timing between the three satellites has to also be ensured for the constellation level.

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