Development and Space Qualification of the Swarm Absolute Scalar Magnetometer

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Abstract— The Absolute Scalar Magnetometer will be flown on the three Swarm satellites to be launched by ESA in 2012. It will offer the best resolution and absolute accuracy ever attained in space. Since this instrument is essential to fulfill the project's scientific objectives, its reliability and availability have to be guaranteed over the lifetime of the four year mission. To achieve these ambitious goals, the instrument is at the cutting edge of technology. It implements an innovative fiber laser used for the optical pumping of a helium 4 gas cell located within a non magnetic rotating sensor. This led us to use specific parts, materials and processes which had to be previously space qualified. The success of the Proto-Flight Model qualification was a major achievement this year. The testing of the flight models is now in progress. This paper illustrates the long way to reach the required Technology Readiness Level starting from a concept which had already been validated on a prototype.

I. INTRODUCTION

This paper first introduces the main goals of the Swarm space mission and the role of the Absolute Scalar Magnetometer provided by CNES and CEA-LETI. The instrument's principle and architecture are then presented, followed by the development characteristics and constraints. The current development status is finally reported.

II. THE SWARM MISSION

The Earth has a large and complicated magnetic field, the major part of which is produced by a self-sustaining dynamo, operating in the fluid outer-core (Cf. Fig. 1). However, measurements taken at or near the surface of the Earth are the superposition of a magnetic field originating from the outer core as well as the fields caused by magnetized rocks in the Earth's crust, electric currents flowing in the ionosphere, magnetosphere and oceans, and by currents induced in the Earth by time-varying external fields. The challenge for scientists is to separate the contributions from these different sources, taking into account their different temporal variations. This is the purpose of the Swarm mission conducted by the European Space Agency (ESA). The objective of this space mission is to provide the best ever survey of the Earth's magnetic field and its temporal evolution.

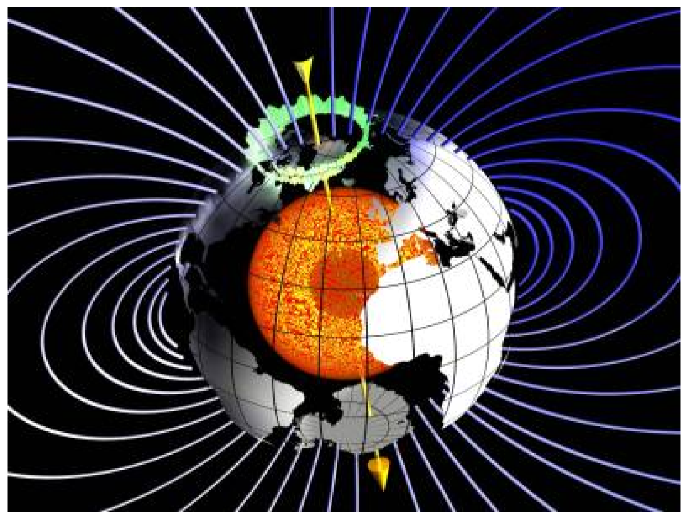

Figure 1. The Earth's magnetic field is mainly produced by a self-sustaining dynamo in the fluid outer-core. Credits: GeoForschungsZentrum Potsdam (GFZ)

This will be achieved by a constellation of three identical satellites in three different polar orbits. After release from a single launcher, a side-by-side flying lower pair of satellites at an initial altitude of 490 km and a single higher satellite at 530 km will form the Swarm constellation. Each satellite weighs around 460 kg (including propellant) and is 9 meters long, including a 4 meter boom which will be deployed in orbit (Cf. Fig. 2).

High-precision and high-resolution measurements of the strength and direction of the magnetic field will be acquired by each satellite, complemented by precise navigation, accelerometer and electric field measurements. Combined, they will provide the necessary observations that are required to separate and model various sources of the geomagnetic field.

The results will offer new insights into the Earth's system by improving our understanding of the composition and processes in the interior and of the Sun's influence within the Earth's system. In addition, it is foreseen that Swarm will also have practical applications in areas such as space weather and radiation hazards.

The launch will take place from the Plesetsk Cosmodrome in northern Russia using a Rockot launcher from Eurockot. The mission is scheduled for launch by mid 2012. The planned operational lifetime is 48 months, after a three month commissioning phase.

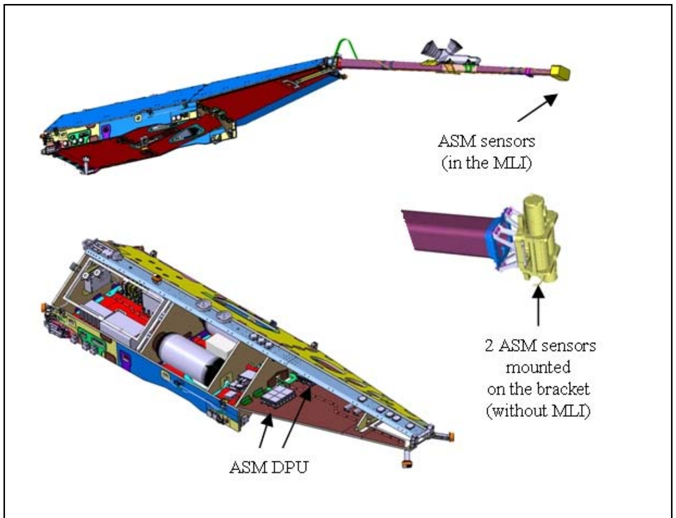

Figure 2. Top : General view of a Swarm satellite with boom deployed. Middle right : A zoom on the sensors' accommodation. Bottom left : An open view of the satellite's main body. Credits: EADS

III. The Absolute Scalar Magnetometer

A. The ASM contribution to the Swarm mission

The Swarm payload includes a fluxgate magnetometer, the Vector Field Magnetometer (VFM, from Denmark Technical University), which measures with high precision the Earth's magnetic field vector components. However, this measurement is not absolute. To maintain a high level of accuracy of the measurements in a multi-year geomagnetic field mission an absolute reference (with no drift nor offset) is then necessary to calibrate the VFM. The Absolute Scalar Magnetometer (ASM) proposed by CNES and CEA-LETI was therefore selected by ESA in 2005 as the Swarm reference magnetometer. With its absolute scalar measurements, the ASM will allow an in-flight calibration of the VFM.

B. The ASM vector mode experiment

In addition, on an experimental basis, the ASM will be able to operate as a vector field magnetometer thanks to an innovative concept offering the capacity to carry out absolute and vectorial measurements with the same instrument at the same point in space, at the same time. This has required two separate instruments so far. It is planned to operate the vector mode in a demonstration mode in order to validate, in space, this new instrumental concept which should open up interesting possibilities for future space missions measuring the Earth's or planetary magnetic fields.

C. The Technology Readiness Level at the outset

When the instrument was selected, the concept and the performance of the ASM were already demonstrated on a prototype tested at IPGP's Magnetic Observatory at "Chambon-la-Forêt". This proved that the ASM was suitable for terrestrial applications. Using the Technology Readiness Level (TRL) scale to assess the maturity of the technology, the prototype could be considered to be at TRL 4. The challenge was to raise the technology to TRL 8 before delivering the flight models to ESA. CNES and CEA-LETI have worked in close partnership since then, sharing their skills in order to adapt this design for space and bring it up to the high standards required by space applications. CEA-LETI's area of competence was centered on the design and the performance while the field of expertise at CNES was focused on the development methodology and the space experience feedback.

D. The ASM physical principle

The ASM is based on the atomic spectroscopy of the helium 4 in its metastable level 2^3S_1 [1]. In the presence of a magnetic field B_0, this level is split into three sub-levels whose energy levels are separated, via the Zeeman effect, by an energy ΔE that is directly proportional to the applied field (Cf. Fig. 3). The determination of this separation is a direct method of measurement of B_0. The ASM uses conventional magnetic resonance techniques to measure this energy, the signal being amplified thanks to optical pumping. The light source realizes two functions simultaneously for the magnetometer: on one hand it performs the optical pumping necessary to detect more easily the resonance, and on the other hand, it is used for the detection of the magnetic resonance.

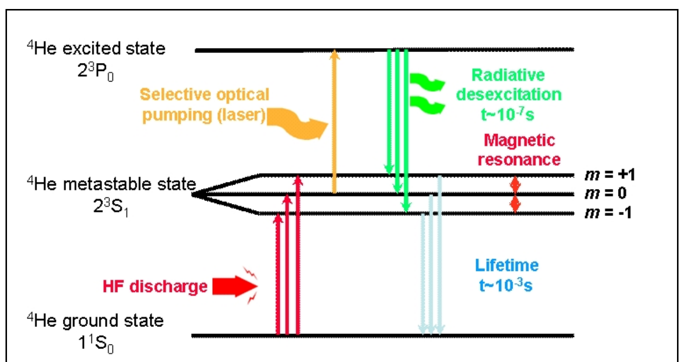

Figure 3. Helium magnetometer relevant energy levels

Once the magnetometer resonance frequency F is determined, the magnetic field modulus B_0 can be directly derived using the electron gyromagnetic ratio $\gamma 4_{He}$ in the helium 4 metastable 2^3S_1 state (1).

$$B_0 = F / \gamma 4_{He}, \text{ with } \gamma 4_{He} / 2\pi \approx 28 \text{ GHz / T} \quad (1)$$

The ASM helium 4 magnetometer can therefore be considered as a magnetic field to frequency converter.

For space applications, it was essential to define an isotropic probe architecture fully independent of the spatial position and orientation in order to avoid resonance signal extinction and dead zones. For a linearly polarized pumping beam, the amplitudes of the resonance signals reach an extremum when both the RF excitation field and the polarization direction are perpendicular to the ambient magnetic field. This is achieved with a specific design of the sensor using a piezoelectric motor, which allows a common rotation of a polarizer and RF excitation coils placed upstream of the helium 4 cell. This controls both directions of the RF excitation field and of the beam polarization.

The scalar and isotropic magnetometer can also provide a vector measurement of the magnetic field using the information provided by the superimposition of three low frequency orthogonal magnetic fields (< 50 Hz) by means of a set of three vector coils. This technique allows simultaneous scalar and offset-free vector measurements. Further details are provided in [2].

E. The ASM architecture

The instrument assembly consists of an electronic box, the Digital Process Unit (DPU), installed in the main body of the satellite and a sensor installed at the tip of the boom, in order to keep it as far away as possible from any magnetic disturbance generated by the satellite. It is connected to the DPU by a bundle of optical fibers and electrical cables which form the ASM harness (Cf. Fig. 2 and Fig. 4). The ASM laser is included in the DPU (Cf. Fig. 5). The DPU drives the sensor, manages all the magnetometer's functions and interfaces with the satellite's on board computer.

As the ASM is essential for the Swarm mission, a full cold redundancy was required by ESA. Therefore two complete instruments will be installed on each satellite and a specific sensors' bracket was designed to accommodate the two sensors on the satellite boom (Cf. Fig. 2 and Fig. 4).

Figure 4. The Absolute Scalar Magnetometer (ASM) : left, two sensors mounted on the bracket. Right, one DPU. Credits : CEA-LETI

IV. DEVELOPMENT CHARACTERISTICS AND CONSTRAINTS

The space mission, the instrument's principle and architecture imposed many development characteristics and constraints which are listed here.

The first challenge was to find non magnetic parts and materials capable of withstanding the space environment. To guarantee the magnetic cleanliness of the instrument, all the materials and parts had to be carefully selected and then individually magnetically tested. This led us to select materials that are not commonly used for space applications. For example the sensors and the sensors' bracket are mainly made of non reinforced PEEK (Polyetheretherketone). Due to the high sensitivity of the sensor, some screws in the vicinity of the helium 4 cell are also made of PEEK. The use of this polymer required in-depth analyses and tests to ensure the sensor's mechanical and thermal behavior. Several iterations with prototyping were necessary to obtain a good design. Despite rigorous material selection criteria, the magnetic signature of some parts was still too high, even after a proper cleaning, and it was then necessary to replace the parts by custom made parts. That was the case for some electrical connectors' caps and pins or for some parts within the piezoelectric motor.

The instrument had to be compliant with the space environment specifications (vibration and shocks, thermal vacuum with wide temperature ranges, space radiations, low power consumption and electromagnetic compatibility), with different specifications for the sensor, the harness and the DPU due to their different location within the satellite. The required four year lifetime with high reliability and availability requirements had also to be taken into account. To achieve this, each subsystem of the instrument's prototype was substantially modified. Starting from the ground prototype, materials had to be replaced with space compatible materials, high reliability parts took the place of standard parts, processes had to be completely reworked and improved to be able to sustain the space conditions as well as a period of ground storage. This led us to completely redesign the athermal fiber laser used for the optical pumping of the sensor's cell since the prototype did not operate in the vacuum nor in the specified temperature range. Furthermore, it was not compatible with the Swarm mechanical specifications. A full qualification program was carried out for all the laser parts and processes in order to verify their suitability over the mission lifetime. It will be, to our knowledge, the first fiber laser to be flown in space (Cf. Fig. 5). In a similar way, a non magnetic piezoelectric motor, used to rotate the sensor in order to guarantee the magnetometer's isotropy was qualified after significant modifications were made on a commercial product basis (Cf. Fig. 6). A life test was carried out first on the motor and then on the complete sensor's mechanism. An Application Specific Integrated Circuit (ASIC) had to be specifically developed for this application. The design was first validated on a Field Programmable Gate Array (FPGA).

The instrument had to be compliant with the satellite's interface specifications. The main difficulty was the mechanical accommodation of the sensors at the tip of the boom and their thermal control. The DPU DC/DC converter was redesigned. Finally, the onboard software had to be compliant with the satellite's interface requirements based on the ESA Packet Utilization Standard (PUS) which required an extensive software development and a demanding validation process.

In addition, it shall be noted that the number of models being built has led to a quite unusual “series” for a space scientific program : one proto-flight model was manufactured and was used for the space qualification of the instrument; six flight models were manufactured and are being tested in order to deliver two flight models per satellite to ensure the full redundancy of the ASM. In order to obtain similar capacities on all models, appropriate processes had to be established and replicated. This also required a good organization of the teams to allow the parallelization of the different tasks.

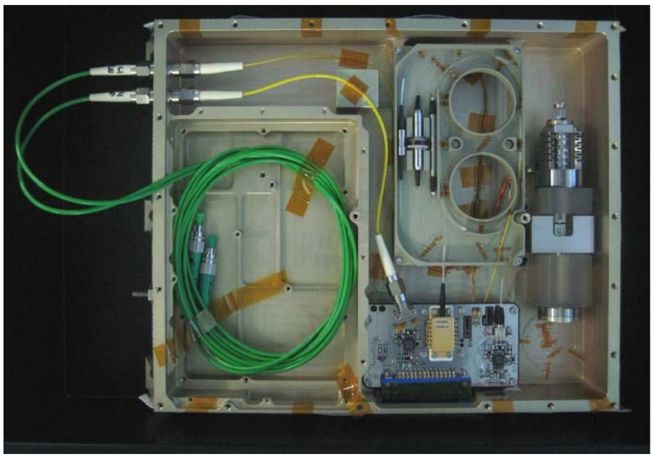

Figure 5. The ASM laser

Figure 6. The ASM non magnetic piezoelectric motor, based on a component commercialized by Shinsei

V. CURRENT DEVELOPMENT STATUS

The major technical difficulties encountered during the development and the qualification of this magnetometer have been overcome. All the materials, parts and processes qualifications including life tests were successfully completed. The Proto-Flight model of the Absolute Scalar Magnetometer was qualified with excellent performances [3]. The objective of TRL 8 was reached.

The success of the PFM qualification is the result of a good cooperation between CNES and CEA-LETI, and an efficient use of the complementary skills of the two companies.

The first flight models’ acceptance tests are now ongoing. They will be delivered to ESA by the end of the year.

VI. CONCLUSION

The ASM PFM passed the space qualification tests, but it was a challenging process to reach the required Technology Readiness Level, despite starting from a concept which had already been validated on the ground. Space missions are particular as they demand a lot of testing to demonstrate that the instrument can withstand the harsh space environment over its lifetime in orbit. Starting from the ground prototype, materials and parts had to be replaced with space compatible items, processes had to be modified to sustain the space conditions. The instrument’s interfaces had to be adapted to the satellite’s requirements. All these changes led to significant design modifications and required a lot of prototyping and testing. The feasibility of the laser in space conditions had been challenged. So, whatever the starting point is, the effort to reach a high TRL should not be underestimated, especially in the case of innovative instruments implementing new features at the cutting edge of technology.

ABBREVIATIONS AND ACRONYMS

- ASM : Absolute Scalar Magnetometer
- CEA : Commissariat à l’Energie Atomique et aux Energies Alternatives, the French atomic and alternative energies agency, a French government-funded technological research organization. LETI : The CEA Laboratory of Electronics and Information Technologies (LETI) is one of the largest European centers in applied electronics research.
- CNES : Centre National d’Etudes Spatiales, the French Space Agency
- DPU : Digital Process Unit
- ESA : European Space Agency
- IPGP : Institut de Physique du Globe de Paris, Institute of Earth Physics of Paris
- TRL : definition from Wikipedia, the free encyclopedia : Technology Readiness Level (TRL) is a measure used by some United States government agencies and many of the world's major companies (and agencies) to assess the maturity of evolving (materials, components, devices, etc.) prior to incorporating that technology into a system or subsystem.

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