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SPACEBORN SCALAR MAGNETOMETERS FOR EARTH'S FIELD STUDIES

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Although the evolution of the Earth's magnetic field has been recorded for decades or even centuries in ground-based observatories, these measurements are very sparsely and unevenly distributed on the globe's surface. As a consequence, these data sets are not sufficient to establish accurate global field models. To mitigate that problem, they have been completed by numerous additional snapshot surveys accumulated over the years, carried out either on aircrafts or ships. The situation has however radically evolved with the emergence in the late 1950's of satellites, which offer the possibility to obtain a global coverage in a relatively short period. While the first magnetometer was flown on Sputnik 3 in 1958, high resolution vector measurements were obtained only with Magsat in 1980. Since then, the standard payload of Earth magnetic mapping satellites combines both scalar and vector magnetometers: the scalar sensor provides the absolute reference to calibrate the vector instrument in flight, which is then basically operated as a variometer. In this paper we present two generations of scalar magnetometers developed by Leti in collaboration with CNES for Earth observation space missions: first the Overhauser magnetometers based on Nuclear Magnetic Resonance, flown with success respectively on the Oersted (operating since 1999) and Champ (2000-2010) satellites, and second the helium magnetometer integrated on the three Swarm ESA satellites to be launched in 2012. Their respective design constraints and main characteristics are analyzed in view of the scalar performances requirements, which directly derive from the missions scientific objectives. A focus is made on their heading errors since the spatial anisotropy directly affects the instruments' accuracy, and the issues related to the long term stability, which is mandatory for the magnetic field's secular variation studies, are also reviewed in detail.
Apart from enhanced metrological performances, the helium magnetometer also implements a dedicated architecture thanks to which continuous vector measurements are derived. This intrinsically scalar instrument hence delivers simultaneously absolute measurements of both the intensity and the direction of the ambient magnetic field. The operation principles are presented and results of its calibration process and the subsequent performances in terms of vector precision and accuracy are analyzed. Finally, mid term outlooks are described: they essentially consist in the miniaturization of the helium magnetometer and evolutions of the sensor mode of operation to allow its exploitation at very low fields, making it suitable for future planetary exploration missions.

INTRODUCTION

Since the magnetic field is intrinsically a vector quantity, meaning that not only its amplitude but also its direction are needed to fully characterize it, the ultimate need in high precision surveys is for instruments able to deliver accurate measurements of its components along three mutually orthogonal axes. Now vector magnetometers usually exhibit low frequency excess noise and offsets and therefore require to be periodically calibrated with an absolute magnetic reference. This is the role devoted to the scalar magnetometers, sensitive to the field strength only, that have been flown in conjunction with the on-board vector fluxgate sensors for every Earth magnetic field mapping space mission launched since Magsat in 1980. Given that, it follows that the most important feature of the scalar instruments of such spaceborn magnetic payloads is the accuracy of its measurements, hence the paramount importance of the magnetic cleanliness in the vicinity of the scalar magnetometer environment for the success of a magnetic mapping satellite mission.

In this paper, after a very brief summary of the physical principles at work in all scalar devices, we will describe the Overhauser Nuclear Magnetic Resonance sensor developed for the Oersted and Champ satellites as well as the optically pumped helium device that will be the magnetic reference for the 3 satellites of the

Swarm mission. Their main features in terms of metrological performances will be listed with a specific emphasis on the new possibilities offered by the helium magnetometer, both in terms of extended bandwidth for scalar measurements and of a specific architecture making it possible to derive simultaneously absolute scalar and vector measurements.

SCALAR MAGNETOMETERS OPERATING PRINCIPLES

Scalar devices all rely on the Zeeman effect: when submitted to a static magnetic field, atomic levels with non-zero magnetic moment split into sublevels whose energy difference is proportional to the field amplitude. Measuring this energy gap provides thus a direct means to determine the magnetic field intensity, and scalar magnetometers can therefore be viewed as field to frequency converters based on atomic spectroscopy. The most widespread way to carry out this measurement is the magnetic resonance technique: an RF-field applied to the sample strongly interacts with the atoms only when its frequency is close to the Larmor frequency corresponding to the energy separation between the magnetic sublevels. Once this condition is met, the RF-field causes transitions between the magnetic sublevels and tends to equalize their respective populations. Now at thermal equilibrium under nominal operation conditions (ambient temperature ranging between -30 °C and + 50 °C and magnetic field intensity < 100 µT), the initial population imbalance between different Zeeman sublevels is extremely small and the magnetic resonance cannot be detected. Hence all scalar magnetometers require a preliminary amplification of the initial polarization of the sample to operate at a sufficient signal to noise ratio. The choice of the method to achieve this amplification determines largely the characteristics of the resonance that will be used to monitor the magnetic field variations, and hence directly affects the performances of the instrument. In particular, it turns out that the amplification processes usually depend strongly on the relative orientation of the device with respect to the magnetic field direction, thus resulting in attitude induced effects on both the magnetometer's resolution (signal amplitude dependence, leading in the worst case to dead zones, i.e sensor attitudes in which no measurement can be carried out) and accuracy (so called heading errors). This point has to be considered very carefully as soon as the instrument needs to be operated on mobile platforms, so that the choice of the polarization amplification method on the one hand and the isotropy considerations on the other hand turn out to be the main design drivers for a scalar device. This will be illustrated in the following paragraphs for the two generations of scalar magnetometers developed by Leti for Earth magnetic field mapping satellite missions.

THE OERSTED / CHAMP OVERHAUSER MAGNETOMETER (OVM)

The OVM was selected as the magnetic absolute reference for the Oersted and Champ missions in the 90's. It directly derives from instruments previously developed at Leti [1, 2], but also exhibits several specific features to meet the missions' requirements in terms of both physical parameters (essentially weight and power consumption) and metrological performances (mostly its accuracy) [3, 4].

As stated above, the first point to consider for any given scalar magnetometer is the choice of the method for the initial signal amplification. Here the nuclear magnetic resonance signal is amplified thanks to a dynamic nuclear polarization process: the sample consists of a solvent whose nuclear spins are coupled to the electronic spins of a free radical in solution. A saturation of the electronic transitions first leads to an increased electronic polarization, which in turn results in a nuclear polarization amplified by a factor of about 3000. By properly choosing the RF frequency for a given solvent/radical pair, one can obtain either positive or negative polarization of the solvent's nuclear spins. This feature is exploited to build a CW oscillator around two flasks with opposite polarities, as illustrated on Fig. 1, so that the resonance signal generated in each flask and picked-up by the detection coils is amplified, while the common mode signal resulting from the injection is rejected by the differential amplifier.

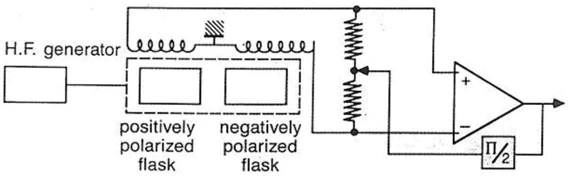

Fig. 1: Overhauser nuclear magnetic resonance auto-oscillator architecture.

The sensor's omnidirectionality on the other hand is ensured by the coils design: they create highly inhomogeneous RF injection signals in such a way that, regardless of the direction of the static magnetic field, a constant fraction of the cells volume is submitted to the proper excitation and detection conditions. (see Fig. 2).

Such magnetometers have been operated for many years in various environments, in particular for aeromagnetic surveys for which the operational constraints are similar in many ways to the ones met in satellite applications. However, as mentioned previously, several design evolutions were nevertheless

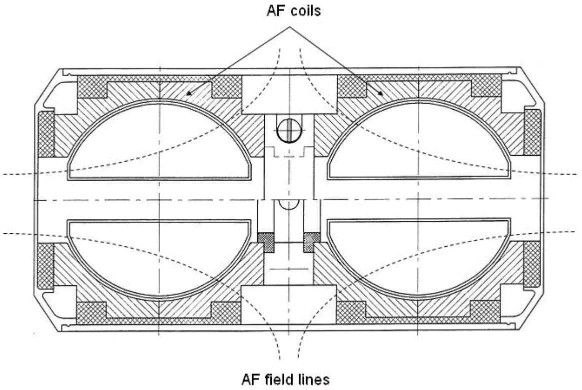

Fig. 2: Schematic view of the NMR sensor head.

necessary to comply with the mass and power budgets allocated to the OVM.

First of all, the mass budget put strong limitations on the sensing head dimensions, inducing a very challenging issue for the operation at low fields. Given the polarization process on the one hand and the resonance detection method on the other hand, the signal amplitude varies indeed with the square of the magnetic field modulus. Once the various constraints taken into account, the sensor design resulted in a resonance signal at 16 µT of the order of about 0,2 µV only. This rather low value combined with the cable length connecting the sensor head to its electronics located several meters away within the satellite body motivated the implementation of the differential preamplifier directly next to the sensor. Special attention was devoted to the selection of the preamplifier components and a systematic magnetic screening plan was implemented to reduce as much as possible the induced magnetic signature. Thanks to these precautions, the magnetometer frequency anisotropy, which represents the main contribution to the instrument's accuracy error budget, was kept below 400 pT_{pp} after a 3mT magnetization, corresponding to a magnetic moment of less than 100µA.m^2.

Concerning the power budget, the main contributor for Overhauser NMR magnetometers is due to the generation of the HF signals required to saturate the electronic transitions in the two sensor flaks. To reduce it significantly, the two solvent/radical couples have been chosen so that one single HF excitation creates optimal polarizations of opposite polarities in each flask (Fig. 3).

This was achieved thanks to an extensive characterization of the evolution of the dynamic nuclear polarization efficiency as a function of the HF frequency for a number of solvent/radical couples. Moreover, as the polarization frequency also depends on the static magnetic field, it was chosen so as to optimize the magnetometer's operation at low field where the metrological performances are otherwise significantly degraded. Finally, the variation of the signal resolution as a function of the magnetic field was reduced by a factor of 2, as illustrated in Table 1 below.

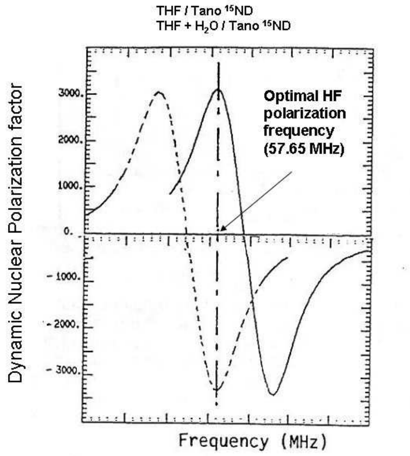

Fig. 3: Differential polarization scheme (respectively positive/negative for THF/THF+H_2Osolvents).

Magnetic field (µT)	15	20	30	45	60
OVM resolution (pT/√Hz)	35	13	6.5	5	4

Table 1: Evolution of the OVM resolution as a function of the magnetic field amplitude

It should be noted that part of the excess noise at low field is due to the spatial magnetic gradients created by the coils used to change the magnetic field modulus, so that the values mentioned here are in fact upper value limits.

The last important feature of the OVM is its susceptibility to the electromagnetic environment. Due to the differential architecture, the pick-up coils reject on the first order the ambient radiated fields. However, despite the care that has been devoted to the matching of the coils characteristics, the residual imbalance at low frequencies between these coils gives rise to a remaining magnetic field susceptibility which prevents the magnetometer operation in standard laboratory environments, mostly due to the mains harmonics emissions. Moreover, the Overhauser NMR magnetometer's narrow resonance line, which is clearly an advantage in terms of magnetometer accuracy and long time stability, turns out to be a problem during the satellite integration operations: whenever the instrument is submitted to spatial magnetic gradients, its performances degrade quickly, preventing it from operating under most environment tests conditions (in particular for all stowed boom configurations). These susceptibilities, which are no longer of concern once the satellite is in orbit, contribute to make it quite cumbersome during all ground activities.

THE SWARM LASER PUMPED HELIUM MAGNETOMETER

To overcome the limitations of the Overhauser magnetometers identified during the Oersted and Champ programs, a new magnetometer has been designed for the Swarm mission [5]. It relies now on a low pressure helium vapour as the sensing medium (see Fig. 4), with the optical pumping process the counterpart of the dynamic nuclear polarization.

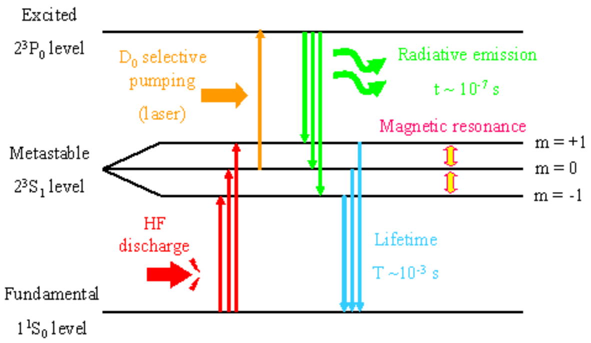

Fig.4: Relevant helium energy levels involved in the ASM magnetometer

One important difference is however due to the fact that the optical pumping is a much more efficient polarization method, leading to an almost complete polarization. As a consequence, the signal amplitude does no longer depend on the magnetic field strength and a resolution of 1 pT/√Hz is now obtained over the complete measurement range.

As compared to most optically pumped magnetometers, the Absolute Scalar magnetometer (ASM) operates with linearly polarized pumping light instead of circularly polarized light. The main reasons for that choice are the following:

- the strong interaction between the laser pumping beam and the helium atoms can in general affect their energy level and result in so-called light shifts [6] whenever the pumping light wavelength is detuned from the helium transition center wavelength. Now using linearly polarized light suppresses this effect, thus significantly increasing the instrument's accuracy.
- the key parameter governing the optical pumping angular dependence is then the direction of the laser polarization, whereas it is the propagation direction of the pumping beam that matters in circularly polarized light. Now when trying to design an isotropic instrument, i.e an instrument whose performances are independent of the sensor attitude, it is obviously easier to control the direction of the linear polarization than to rotate the whole sensor in order to align it properly with respect to the magnetic field direction. In our case the isotropy is thus simply achieved thanks to the use of an amagnetic piezoelectric motor which permanently

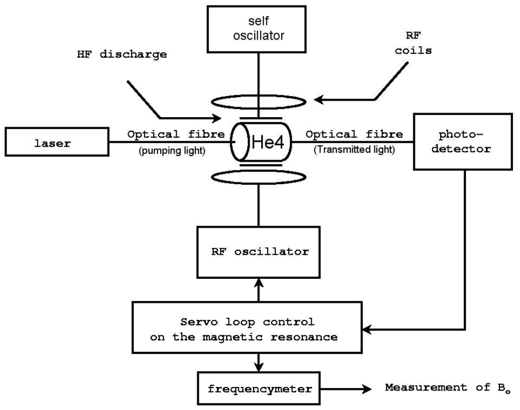

Fig.5: Isotropic helium magnetometer architecture

controls the laser polarization and the RF magnetic field directions so that they are both perpendicular to the static magnetic field [7]. The resulting magnetometer architecture is illustrated on Fig.5.

Contrary to the Overhauser solution based on a design trade-off between instrument's resolution and omnidirectionality, the helium magnetometer is always operated in the optimal operational conditions thanks to this servo loop, but this is achieved at the expense of the use of a dedicated mechanism. As for the sensor anisotropy, resulting from a combination of induced and remanent contributions, a typical signature corresponding to the flight configuration is presented on Fig.6.

As for the environment susceptibility, the ASM significantly broader resonance line (close to 70 nT as compared to less than 7 nT for the OVM) reduces the impact of inhomogeneous magnetic fields on the magnetometer performances, while the principles of operation and architecture of the helium device makes it robust to low frequency radiated magnetic fields, thus making the EMC specifications much easier to meet in that respect.

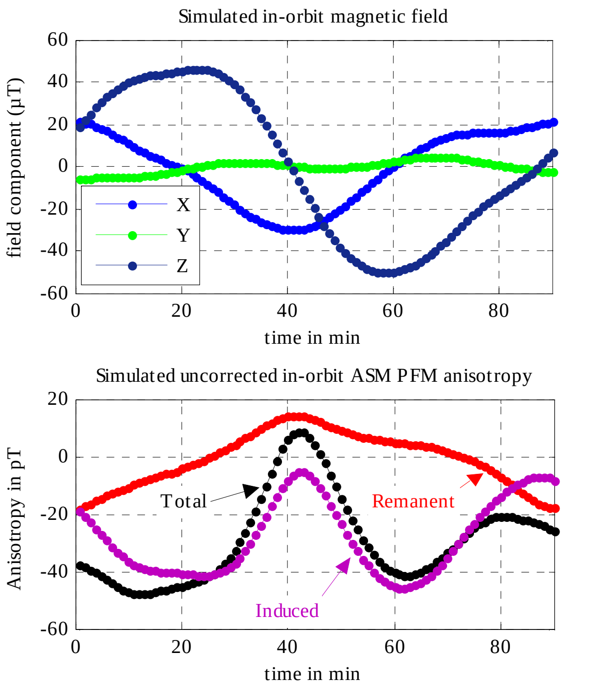

Fig.6: residual anisotropy for the in orbit ASM configuration

Last but not least, the short metastable helium relaxation time (of the order of one millisecond) results in a much higher bandwidth for the helium magnetometer than was the case for the NMR sensors. While this feature is of no direct interest for the calibration of the vector instruments (the scalar data are sampled for that purpose at a fixed 1 Hz frequency), it opens new opportunities for the exploitation of the scalar instrument.

NEW CAPABILITIES OF THE ASM

First of all, the scalar magnetometer can intrinsically be operated at an increased sampling rate (a burst mode at 250 Hz, corresponding to a 100 Hz measurement bandwidth, is available on the Swarm magnetometers, but will be operated only for a short duration during the commissioning phase except if a scientific interest for high data rate measurements is expressed). Now, the combination of high resolution and extended bandwidth, apart from delivering additional data for potential new study fields, also makes it possible to deliver simultaneously scalar and vector data with a single instrument. [8]. To achieve this, three orthogonal low amplitude AC excitations are applied to the helium cell, and the spectral analysis of the scalar resulting output provides an estimation of the projection of the static magnetic field along the modulation directions. The corresponding architecture has already been described in detail in several previous papers (see for instance [9]). The obvious advantages of that configuration derive from the fact that the very same instrument simultaneously delivers both absolute scalar and vector data, thus suppressing elaborate synchronization requirements between different instruments or any concern about the spatial magnetic gradients between them. Moreover, contrary to the intrinsically vector instruments, it does not exhibit any offset, thus considerably simplifying its calibration process. Last but not least, it offers auto-calibration capabilities and the calculation of a scalar residual (difference between the static field modulus and the field amplitude deduced from the estimation of its three components) provides an easy means for real time data quality assessment. The design performances for these indirect vector data are a resolution of 1 nT/√Hz for a 50 µT ambient field, and an accuracy of 10^{-5} for the determination of the vector data scale factors. The Table 2 and the Fig.7 show respectively the noise level and the scalar residual characteristics of one of the ASM flight models for various magnetic field intensities and the residuals between the scalar measurements and the corresponding values deduced from the vector estimation during thin shell runs at 10, 20, 40 and 60 µT.

Magnetic field amplitude (µT)	10	20	40	60
Vector resolution (nT/√Hz)	0,3	0,7	1,1	1,8
Scalar residual standard deviation (nT)	0,19	0,17	0,24	0,35

Table 2: Evolution of the vector resolution and scalar residual characteristics (model FM1b)

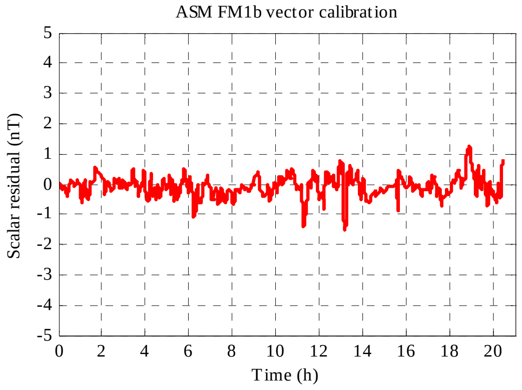

Fig. 7: Scalar residual for the FM1b vector calibration.

These preliminary results confirm that our initial design goals are met, and both scalar and vector data will be the nominally delivered by the three ASMs on board the Swarm satellites. It will thus provide for the first time the possibility to cross calibrate in flight two different types of vector instruments (the Vector Fluxgate Magnetometer and the ASM in vector mode).

CONCLUSION / PROSPECTS

For the past ten years, several Earth magnetic field mapping satellites have been launched. In each case, their magnetic payload consisted of a combination of a vector instrument and a scalar magnetometer to provide an absolute reference for their in-flight calibration. While the vector sensor technology was basically always the same (the CSC fluxgates manufactured by the Danish Technical University), two types of scalar magnetometers have been developed by Leti. The Overhauser magnetometers flown on Oersted and Champ have largely met the missions' specifications, especially in terms of lifetime (the Oersted OVM is still in working order after more than 11 years in orbit, and the Champ one delivered data up to the end of the mission in 2010) and thus contributed significantly to these missions' successes. A new type of scalar magnetometer with increased metrological performances and additional functionalities has been space qualified for the Swarm mission. The six flight models have been delivered to the project at the beginning of 2011 and have been successfully integrated on the Swarm satellites. These three satellites are presently undergoing the final qualification tests at system level and will be ready for the launch scheduled for mid 2012. The ASM characteristics make it ideally suited not only for the traditional role of scalar magnetometers as absolute references for the calibration of the on-board vector instruments, but also for extended operational capacities, such as higher frequency scalar measurements (of potential interest for magnetosphere studies for the low frequency part of the spectrum) or autonomous scalar / vector operations. Last but not least, the helium magnetometer can be operated in a zero field configuration with only very minor evolutions in the sensor overall design, thus extending its initial capabilities to new missions in planetary exploration.

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