1 Introduction

The ASM shall provide scalar measurements of the magnetic field for the calibration of the VFM (Vector Field Magnetometer) using a technique based on a physical process which is directly related to the absolute scalar value of the B-field with high accuracy and stability.

In addition, on an experimental basis, the ASM will be able to operate as a vector field magnetometer.

LETI has been developing for many years very high resolution scalar magnetometers based on the nuclear magnetic resonance phenomenon. These sensors have been used for applications as diverse as geophysics (oil exploration), mapping magnetic (Oersted & Champ satellites) or the detection of anomalies (archaeology e.g. with the discovery of the San Diego wreck ship or magnetic anomaly detection -MAD- system aboard the French maritime patrol aircrafts). More recently, and to overcome specific drawbacks of this type of sensors (mainly the rapid deterioration of their performance in the presence of inhomogeneous fields and low bandwidth) a magnetometer based on laser optically pumped helium 4 has been developed. Our efforts have focused on the definition of an isotropic architecture (i.e. providing a measurement independent of the sensor orientation with respect to the magnetic field) and on the absolute accuracy of the magnetometer.

After a reminder of the functioning physical principle of the sensor, we present the architecture or the ASM and finally mention its performances.

2 Functioning principle of the helium 4 magnetometer

2.1 Physical principle

The helium magnetometer developed by Leti is based on the paramagnetic resonance of helium 4 in its metastable level 2^3S_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 (see Figure 1), by an energy ΔE that is directly proportional to the applied field. The determination of this separation is a direct method of measurement of B_0.

This is achieved through the magnetic resonance phenomenon: the application of an alternating magnetic field $B_1 cos(2\pi vt)$ induces transitions between these sublevels when the frequency v is close to the Larmor frequency v_0 defined by the relationship $h.v_0 = \Delta E$. Therefore it operates as a field to frequency converter, with a proportionality factor called the gyromagnetic ratio equal in our case to $\gamma_{He4} \approx 28$ GHz / T.

However, this resonance that tends to equalize the populations of the Zeeman sublevels is not directly observable because under normal conditions of thermodynamic equilibrium, these populations are already almost equal. Therefore at macroscopic level the resonance does not induce a detectable change of the helium vapour state.

So we use an optical pumping process to change significantly the atoms distribution of the three sublevels. The principle of this method is based on the angular momentum conservation between atoms and photons. In our case, the cell containing helium atoms is irradiated by a laser whose wavelength is locked on the transition D_0 (2^3S_1 - 2^3P_0). The transition probabilities, depending on the polarization of the incident radiation, are in general different for each of the three sub-levels so that this process results in a selective depopulation mechanism of pumping. The spontaneous radiative desexcitation on the other hand occurs with equal probabilities towards each of the three metastable sublevels, so that globally, the pumping cycle leads to a redistribution that can be very different from the thermodynamics equilibrium distribution. Resonance is therefore much more easily detectable; the amplification factor being of the order of 10^6!

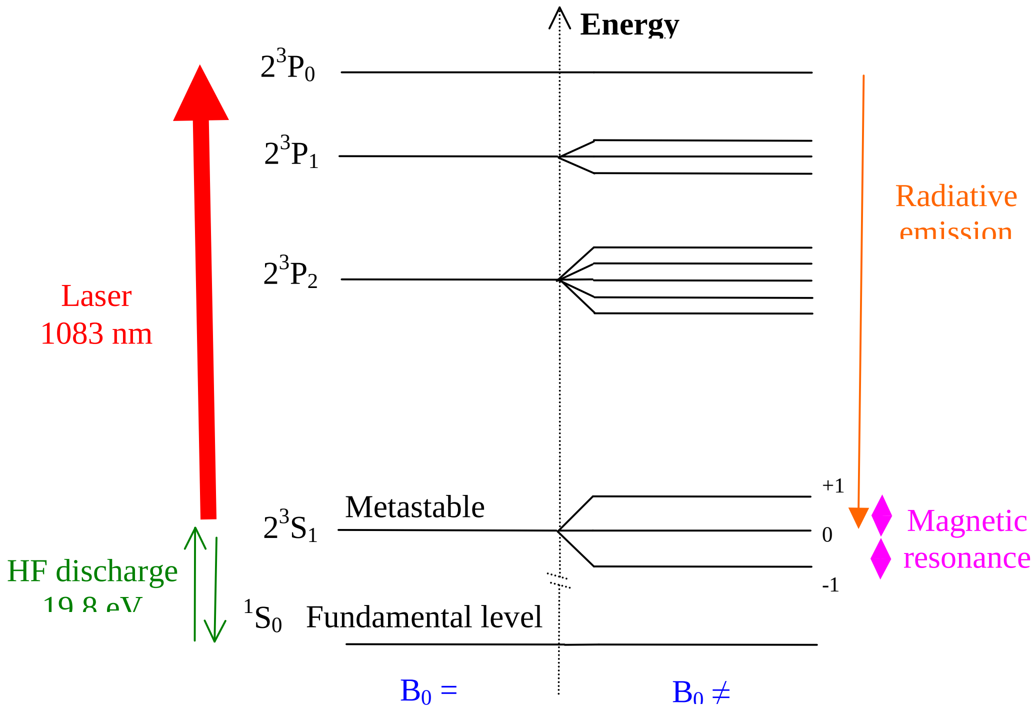

Figure 1. Energy levels of ^4He involved in the magnetic measurement. Not to scale

Finally, the resonance detection is carried out by measuring the transmitted light intensity. Its variations result from the superposition of three signals:

- A continuous signal reflecting the evolution of the populations of the Zeeman sub-levels (longitudinal detection)
- Modulations at both the RF value excitation and its double, corresponding to the evolution of coherences between sublevels (transverse detection).

The light source realizes two functions simultaneously for such a magnetometer: on one hand it enables the establishment of a distribution of atoms among the Zeeman sublevels significantly different from the Boltzmann distribution, and on the other hand it is used for the detection of the magnetic resonance. The performances of the magnetometer are directly derived from its characteristics.

2.2 Isotropic architecture

To take full advantage of scalar magnetometers performances in the context of mobile applications, it is essential to define an architecture free of the effects of orientation common to all standard scalar magnetometers based on magnetic resonance (for instance, in the case of the Oersted & Champ NMR sensors, that was achieved thanks to a specific coils geometry). As for instruments relying on the optical pumping technique, each of the following processes have to be considered:

- First the distribution of atoms on the three sublevels 2^3S_1 resulting from optical pumping cycle is directly depending on the relative orientation θ_F between the static magnetic field B_0 on one hand and the polarization of the laser E_0 (the case of linear polarization), or the direction k_0 of the propagation beam (case of circular polarization) on the other. Especially for certain directions (θ_F = 55 deg in the case of linear polarization for example), the optical pumping cycle does not change the thermodynamic equilibrium. In these circumstances, the magnetic resonance is no longer observable.

- Moreover only the component of the radiofrequency field B_1 perpendicular to the magnetic field B_0 actually induces resonating transitions among Zeeman sublevels, leading to a second potential source of resonance signal extinction.
- Finally, the chosen detection method can also be the origin of "dead zones" in which the measurement of the magnetic field amplitude B_0 can not be carried out.

Since all magnetic resonance magnetometers using optical pumping are potentially affected by these problems, various configurations have been proposed in the past to remedy to the situation. For example, Texas Instruments magnetometers used a combination of three cells arranged in three orthogonal directions to ensure that one of them at least provides a usable signal (on the SAC-C satellite, a 2 cells configuration was selected by the JPL, thereby solving only partially the problem), while CAE for its part manufactured a caesium optically pumped magnetometer whose attitude was permanently set in the most favourable direction with respect to the prevalent ambient magnetic field.

However, these architectures are quite cumbersome to implement. At LETI we have chosen to define an isotropic structure consisting of a single resonance cell that does not require a permanent active control of the overall sensor attitude.

Our method is based on the fact that for a linearly polarized pumping beam, the amplitudes of the resonance signals at the frequencies 0 (continuous absorption corresponding to the longitudinal detection scheme) and 2 v_0 reach an extremum when the polarization direction E_0 is perpendicular to the magnetic field B_0, while the signal at v_0 is equal to zero.

It is quite easy to demonstrate that this requirement can be met whatever the relative orientation of the sensor with respect to the magnetic field direction: it is possible to control the beam polarization direction through a rotation of a polarizer placed upstream of the cell, which is much simpler than implementing a rotation of the entire sensor (to our knowledge, all commercially available magnetometers exploit circularly polarized sources, for which the direction of propagation of the beam determines the anisotropies of the signal amplitude resonance).

Moreover since the radiofrequency field shall also be perpendicular to the static field for maximal efficiency, we have designed the excitation coils so that the resulting RF field is parallel to the linear polarizer, which imposes the light polarization direction E_0. The resulting magnetometer is then perfectly isotropic.

A piezoelectric motor has been chosen to drive the isotropic probe. The choice of this technology has been largely dictated by the imperative to use an actuator driven at a frequency of a few tens of kHz - both well above the sensor bandwidth and well below the excitation frequency corresponding to the minimum magnetic field likely to be met (approximately 500 kHz corresponding to a magnetic field slightly higher than 17 µT) - and which does not requires the use of any ferromagnetic material thus generating no magnetic disturbance although it is very close from the helium sensing cell.

Figure 2

The Figure 3 shows the resulting isotropic magnetometer functional scheme.

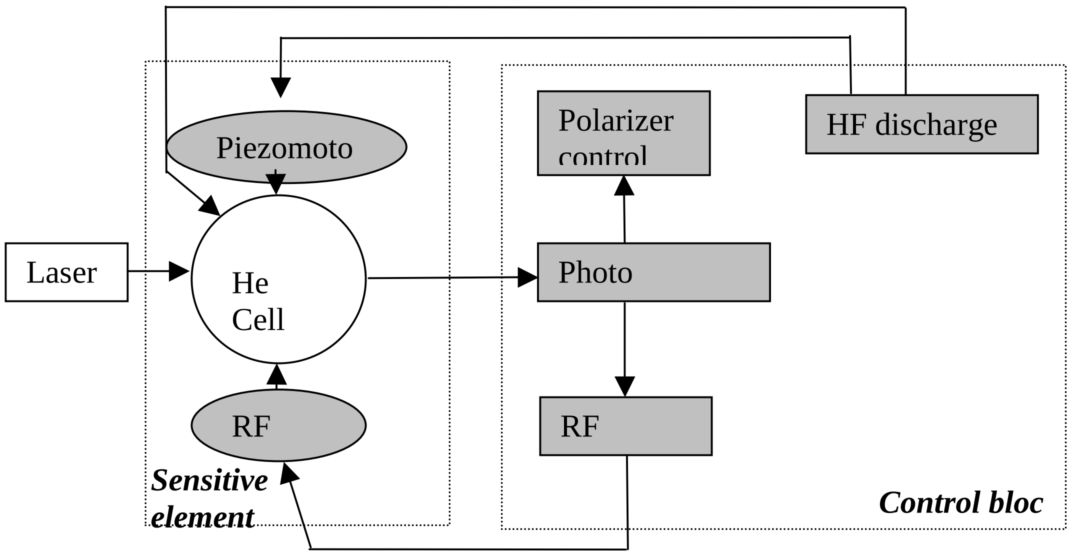

Figure 3. Isotropic magnetometer functional scheme

2.3 Vector measurement

The scalar and isotropic magnetometer can also provide a vector measurement of the magnetic field using the information provided by the superimposition of 3 low frequency (< 50 Hz) orthogonal magnetic fields by means of a set of 3 vector coils.

The principle used is quite simple to illustrate with a single oscillating field $B_\omega \cos \omega t$. If B_ω is parallel to B_0 the measured field B_M is $B_M = B_0 + B_\omega \cos \omega t$. If it is orthogonal to B_0 the measured field B_M is $B_M = \left(B_0{}^2 + (B_\omega \cos \omega t)^2\right)^{1/2} \approx B_0 (1 + \frac{1}{2}\left(\frac{B_\omega}{B_0}\cos \omega t\right)^2)$ considering that $\frac{B_\omega}{B_0} << 1$, which is the case in the Earth magnetic field with our B_ω value (≈ 50 nT). Therefore we see in the chosen cases that the modulation of the magnetic field at the frequency *ω* is “visible” when the modulation field is parallel to the magnetic field but not when it is orthogonal to it. The amplitude of the magnetic field at the frequency $\frac{\omega}{2\pi}$ is in fact an image of the magnetic field component along the magnetic modulation direction. It can be easily generalized to the generic case of 3 modulations. This technique allows simultaneous scalar and offset-free vector measurements. Further details are provided in *Earth Planets & Space*, ***53***, *949–958, 2001* *“On the calibration of a vectorial ^{4}He pumped magnetometer” by Gravrand & al. “.*