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Radiation Tolerance of Low-Cost Magnetometer for Space Applications

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ABSTRACT

Knowing the three-dimensional magnetic field configuration and dynamics in space environments is key to understand the physical processes taking place. Plasma dynamics depend on the local orientation of the magnetic field, and key quantities such as pitch angle and dynamical processes such as waves and reconnection cannot be studied without in-situ measurements of the fields. For this reason, magnetometers are one of the most important instruments for space physics-focused missions. This is true both for spacecraft and also for landed missions, particularly on atmosphere-less bodies, where the space environment interacts directly with the surface. To enable the next generation of small spacecraft and landers, sensors need to be low-cost and withstand the harsh radiation environment present in space. Here we present the latest advances in the characterization of a commercial-off-the-shelf three-dimensional magnetometer, summarizing previous and new results from radiation tests. The sensor shows tolerance up to a total ionization dose (TID) of 300 krad, levels well beyond those typical for a low-Earth orbit mission, and compliant with those expected during a landed mission on the Jovian moon Europa.

INTRODUCTION

The central role of magnetic fields in space was already recognized before the beginning of the space age. For instance, at the beginning of the 20th Century, Kristian Birkeland already proposed in 1908 that a system of currents linked to the magnetic field of the Earth was responsible for the visible aurorae[1]. Nowadays, it is well known that the structure and dynamics of the magnetic fields in space play a central role in determining the plasma dynamics and in governing many of the physical processes taking place at the different domains of the heliosphere, including planetary magnetospheres and the surface of airless bodies such as our own Moon and moons of the outer planets.

Placing a magnetic field sensor (magnetometer) on a rover or spacecraft can significantly increase the cost of a mission. The cost of the sensor itself normally represents an important part of the increase, and the magnetic cleanliness requirements represent the rest. While the cleanliness program (the requirements placed upon other instruments and the bus of the spacecraft itself to reduce the magnetic noise at the sensor) remains a necessary challenge, the development of new measurement techniques and the widespread interest in magnetometers, partly driven by the popularization of mobile phones and the use of these sensors in the automotive industry, has led to the availability of commercial-off-the-shelf (COTS) sensors with ever-increasing sensitivity, reaching levels that are adequate for scientific studies in space.

The Magneto-Inductive Principle

The magneto-inductive principle is a novel measurement technique[2] that takes advantage of the symmetric nature of the permeability curve of a core material. This is the working principle of the PNI RM3100 magnetometer, the sensor used during the characterization results presented in this paper.

At a basic level, the PNI RM3100 consists of a simple inductor-resistor (LR) circuit driven by an oscillator logic gate known as a Schmitt trigger. This configuration is shown in Figure 1.

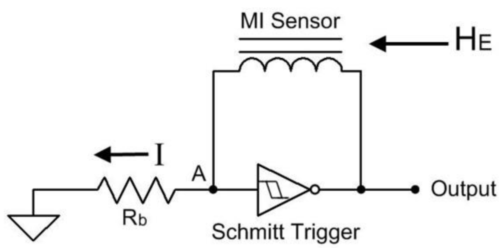

Figure 1. Basic electronic circuit of the magneto-inductive sensor[2].

During operation, a current (I) is driven through the circuit, inducing a positive or negative voltage (depending on the direction of the current) at the entrance of the Schmitt trigger (point A). Whenever a trigger level is reached, the output of the Schmitt trigger is switched changing sign, which causes the current to flow in the opposite direction, until the same trigger level but with opposite sign is reached, and the process is repeated.

This happens continuously during operation, causing the sensing coil (MI Sensor) to be driven at positive and negative currents alternatively. The current levels are designed so that the coil is excited at the quasi-linear section of the permeability curve, as shown in Figure 2. The magnetic field intensity sensed by the coil (H_E) is the sum of the self-induced field produced by the circulating current and the external field being measured.

Since the permeability curve is symmetric around the x-axis (induced field), when no external field is present, the inductor will be driven at symmetric regions in the positive and negative sides of the permeability curve, producing equal charge and discharge times. However, if an external field is applied, the regions of operation in the curve will be shifted in either direction (depending on the sign of the external field), causing the charge and discharge times in each direction to differ by a small amount. By repeating this operation several times and taking the average of the different between the positive and negative charge and discharge times, the magnitude of the external field along the direction of the sensing coil can be determined.

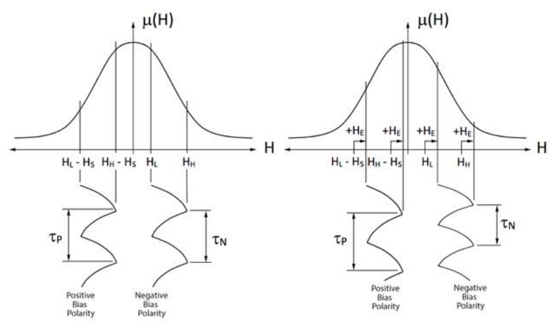

Figure 2. Permeability curve and functioning logic[2].

This process is cyclically repeated along the three axes (with three separate orthogonal coils) and this way the three-dimensional magnetic field can be determined. In order to decrease the noise, a large number of samples are taken for each measurement. This number of samples is determined by an internal variable parameter known as the cycle count. For all the experiments presented here, the cycle count was set to 800, and the operation frequency (closely linked to the cycle count) was 40 Hz.

Radiation Environments in Space

The space environment is filled with different types of electromagnetic (photons) and particle (neutrons, electrons and ions) radiation. This radiation can be harmful for living organisms, depending on its energy. The development of life on Earth was possible due to the shielding effect of its atmosphere and, to a lesser extent, of its intrinsic magnetic field.

The main concern for instruments and electronics in space is related to particle radiation. High-energy particles can penetrate the silicon of electronic components creating transient and permanent damage[3,4]. This is normally addressed with the use of specifically designed electronics (known as radiation hardened) and by mechanical shielding of the instrument, using layers of insulator material such as aluminum of different widths.

Different factors determine the particular spectrum of particles at a certain location. The most energetic particles that can be encountered in space are known as galactic cosmic rays (GCRs). These are ions (usually protons) that have been accelerated outside the solar system by astrophysical processes such as supernova shocks[5], and that reach the Earth environment after traveling extremely large distances at relativistic velocities (typical energies range between 10 MeV to 10 GeV).

The effect of particle radiation on electronics, though, does not only depend on the particle's energy, nor does it increase monotonically with it. The important factor is a combination of the flux (number of particles per second per centimeter squared) and the energy. However, since the cross section (the interaction area between a target material, in the case of electronics usually silicon, and the incoming particle) changes with energy, extremely energetic particles can travel through the material without ever interacting with it (see for instance the cross section for electron impact ionization of molecular nitrogen in Figure 1 of the study by Bug and coleagues[6]).

Apart from astrophysical shocks and other acceleration processes outside our solar system, particles can be accelerated at interplanetary shocks (localized shocks in the solar wind)[7], magnetospheric shocks (the bow shocks located upstream of the planets where the supersonic solar wind is decelerated)[8] and processes internal to the magnetospheres, such as wave-particle interaction[9] and magnetic reconnection[10], among others.

All of these acceleration mechanisms increase the energy of particles to levels that become dangerous for electronic systems. In terms of flux, the most effective mechanism to increase it to significant levels is the trapping of charged particles[11]. This occurs in the inner region of planetary magnetospheres, where the quasi-dipolar configuration of the magnetic field provides the necessary structure to create what is known as magnetic bottles.

This accumulation of energetic charged particles (mostly protons and electrons) is commonly referred to as radiation belts (also Van Allen belts in the case of Earth). The strongest radiation belts in the solar system are those of Jupiter, due to a combination of efficient acceleration mechanisms and a strong magnetic moment[12].

Europa

Due to the existence of subsurface oceans and the possibility of these oceans to harbor extraterrestrial life, the icy moons of the outer planets are particularly interesting subjects of study, currently drawing significant attention among the space physics and the exobiology communities.

One of the Jovian Galilean moons, Europa, has been at the center of this growing interest due to a combination of factors, including the relative accessibility (Jupiter is located at 5 AU, while Saturn, host of another interesting icy moon, Enceladus, is located at 10 AU), the possibility of oceanic material being expelled to the surface through water vapor plumes[13] facilitating its study, and a relatively good understanding of its surface structure and composition, derived from close flybys by the Galileo spacecraft and remote observations with space- and ground-based assets.

Currently, there are two planned missions to further study Europa's surface and space environment. NASA is planning to launch Europa Clipper in 2024 while ESA is planning to launch JUICE in 2022. The data returned by both missions will provide sufficient details of the surface structure to pave the way for a future landed mission.

A recent study by NASA in preparation for a possible landed mission[14] has provided constrains on the radiation environment expected at the surface of Europa. While Europa is not in the middle of the radiation belts, it is located at a region of trapped particles that create an extremely complex environment to operate any electronics. Inside a 7.62 mm Aluminum shielding vault, the radiation dose over a mission lifetime of 20 days would be of 300 krad. As a comparison, at Low-Earth Orbit (LEO) the dose rate is typically significantly less than 1 krad per year[15].

SENSOR PERFORMANCE

The PNI RM3100 has a performance that meets the requirements to detect ultra-low frequency (ULF) waves in space[16]. The sensor has a sensitivity of ~2.2 nT at 1 Hz, and it can be pushed to sub-nT values by adjusting the sampling frequency and averaging to frequencies below 1 Hz[17].

Thus far, the PNI RM3100 sensor had not been characterized for radiation tolerance. Understanding the instrument's response to the high levels of radiation encountered in space is of key importance to take the step to use it for scientific measurements in space. This paper gives a high-level summary of the response of the sensor to a set of radiation experiments in the context of space physics applications.

Temperature Response

One of the characteristics of the space environment is the extreme temperature ranges that are present, depending on the location (illuminated or eclipse) and distance from the Sun. For instance, with Saturn being located at 10 astronomical units (AU), and the solar power decreasing according to an inverse square law, the amount of radiation would be 1/100th of the level perceived at Earth.

Initial tests for the temperature response were carried out[17], with the results shown in Figure 3. The test consisted in placing the PNI RM3100 sensor inside a thermal chamber and changing the temperature inside from room temperature down to -30 °C, then up to +70 °C and then back to room temperature. At the same time, measurements with a well-calibrated fluxgate magnetometer with 1 nT sensitivity were taken outside the chamber.

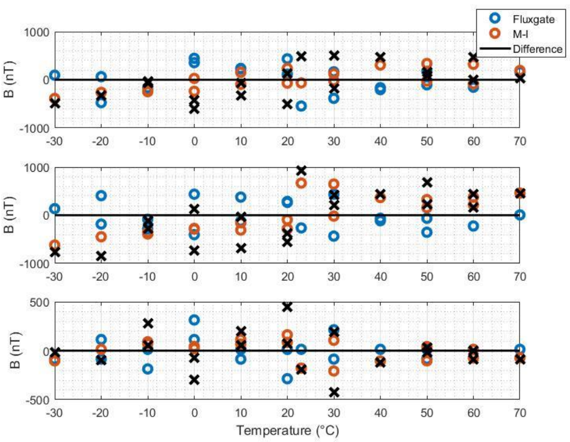

Figure 3. PNI RM3100 and fluxgate measurements of three-dimensional field vs. temperature.

The plots in Figure 3 show the magnetic field readings for the three axes (X, Y and Z for top, middle and bottom panel respectively), with the blue circles showing the readings of the fluxgate (outside the chamber, at room temperature) and the orange circles those of the PNI RM3100 inside the chamber. The black crosses show the difference between both readings. Two readings per temperature are shown, since the measurements were taken going up and down. Overall, the results show an increase in the offset with temperature, but new experiments under a more controlled environment need to be carried out before deriving an analytical model to correct for the deviations. These experiments are planned to take place later this year.

Radiation Response

In order to determine the sensor response under an environment similar to that expected at different space environments, nine different sensors were tested at two separate irradiation facilities, exposing them up to a total ionization dose (TID) of at least 300 krad[18]. Of the nine sensors, seven survived the exposure without any failure during or after the experiment. Two sensors failed during the exposure, one of which completely recovered afterwards, and one never did (complete damage).

The two sensors that failed did so after reaching 150 krad. This means that up to 100 krad, all of the sensors were able to function without any issues. This level of tolerance places the instrument in an excellent position for low-Earth orbit and Lunar exploration applications. For the Moon, a slow transfer and 30 days on the surface behind 0.04 cm of Aluminum shielding was estimated to produce a TID of about 1 krad[19] and up to 110 krad with no shielding during a slow transition to the Moon[20].

For Europa, the Science Definition Team report6 estimated 150 krad for a total duration of 20 days at the surface, and they suggested a factor of 2 safety, hence the need to test for up to 300 krad. In order to guarantee the survivability of all the sensors up to the 300 krad level, based on the results of the exposure experiments[18] a shielding of approximately 5 mm extra beyond the proposed 7.62 mm would be sufficient.

CONCLUSIONS

Based on the performance of the sensor under laboratory and relevant environments[16,17,18], the PNI RM3100 presents itself as an excellent candidate to perform magnetic field measurements in space missions. Its low cost, size, mass and power consumption[16], together with its response to temperature changes and tolerance to radiation means that the magnetometer can be used in difficult environments without significant extra shielding.

Further laboratory experiments are needed to fully determine the response under strong temperature gradients. These experiments are currently being designed and will be carried out later this year. Another aspect relevant for space exploration is the separation of the sensing coils from the electronics. This is a relatively straightforward approach to increase the tolerance to harsh environments, by placing the electronics, which are the sensitive part of the sensor, under further shielding. Due to the importance of the time high frequency accurate time measurement required for the functioning of the sensor, carefully validation is needed to guarantee that no degradation in performance takes place. Initial results separating the coils from the electronics by a few tens of cm (not reported in this paper) showed no significant impact in the measurements, but further experimentation is needed in this particular area as well.

Acknowledgments

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