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Geoscientific Instrumentation Methods and Data Systems Discussions

Interactive comment on "Radiation tolerance of the PNI RM3100 magnetometer for a Europa lander mission" *by* Leonardo H. Regoli et al.

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Response to Anonymous Referee #1:

- The authors should expand on the potential implications of placing a magnetometer inside a radiation vault with other instruments. In many applications it is necessary to separate the sensor from the supporting electronics and the spacecraft/lander to mitigate stray magnetic fields. Can useful scientific magnetic field measurements be made from within a radiation vault co-located with other instruments or would it be necessary to place the sensing element itself outside (the electronics could conceivably stay in the vault) thus dramatically increasing the expected dose experienced by the sensor?

Placing the sensor inside the vault could definitely increase the magnetic noise to a level above the signals that are to be detected. For this reason, the coils are expected to be separated from the electronics. The effects of radiation on the core material of the coils of this particular instrument have not been characterized, but in general, sensing coils are relatively insensitive to radiation compared to electronics. A few sentences explaining this were added at the end of section 2.

- The authors have not established metrics against which to assess the magnetometer performance. Rather, the analysis is primarily verifying gross function (the continuing measurement of a magnetic field rather than a complete loss of signal). The authors are assessing functional rather than parametric failure. It would be appropriate to have some context of notional measurement/instrument requirements for a Europa Lander mission (noise, range, sensitivity, stability, etc.) to evaluate the utility of the magnetometer's performance after irradiation.

The standard deviation is being used as a metric to evaluate the quality of the measurements being taken by the sensors. The requirements of a Europa Lander mission in terms of strength and bandwidth of the signal are not well constrained and modeling of the expected induced signals is required. The scope of this paper is to evaluate the radiation tolerance of the sensors and the standard deviation provides a measurement of the smallest signal that the magnetometers can detect.

- Can the authors quantify the impact of irradiation on the sensitivity and/or baseline stability of the magnetometer? The results for Sensor 9 in Figure 8 suggest a gain and/or offset error ofâĹij3% after irradiation which seems very high by magnetometer standards – particularly in a Jovian application where presumably in-situ calibration may be challenging as the main field is not well understood.

This is an excellent remark, but unfortunately no measurements of the offsets were taken during the experiments presented so it is impossible for us to provide this number at this point, so this will have to be left as an open question for future test campaigns.

- Can you quantify the impact of irradiation on the noise performance of the instrument beyond what appear to be standard deviation ("std:")? For example, average spectral transforms of the data of pre and post irradiation date (Figure 9) would be useful to assess the noise floor and determine the standard pT/sqrt(Hz) at 1 Hz figure of merit.

We calculated the noise floor for all the sensors before and after irradiation and the values were added in a table (Table 1 in the updated manuscript). Similar behavior can be observed, with no clear degradation of the performance present after the irradiation.

Minor comments:

- Line 49: Is the dosage accumulated during transit from Earth to Europa significant compared to the dosage accumulated on the surface? Is the transit dosage included in these estimates?

The orbit of Europa lies close to the center of the Jovian radiation belts, which are by far the strongest source of high-energy particles in the solar system. Badhwar et al. (1994) analyzed the dose that would be received by astronauts in interplanetary space under different solar wind conditions and found an average value of 0.46 Sv/year or 46 rad(SI)/year, which is negligible when compared to what is expected at the surface of Europa.

- Figure 1: Could the authors speculate on what portion of the magneto-inductive instrument is primarily susceptible to TID?

The logic of the instrument is concentrated on the ASIC, with the rest of the circuit corresponding to analogue components and the sensing coils, so the failure is most probably at the level of the ASIC. This speculation was added as part of the conclusions.

- Line 81: Is there any concerns about Enhanced Low Dose Rate Sensitivity (ELDRS)?

As stated in the text, two of the sensors were irradiated at 260 rad(SI)/hr, which corresponds to 72 mrad(SI)/s. The idea of this tests was precisely to evaluate the effect of

low dose rate sensitivity and see whether the rate made a difference in the response of the sensors or not. Although these were passive tests, no difference was noted between the response of these and the rest of the sensors in the study.

- Figure 7: Can the intermittent failures shown for Sensor 5 be corrected by power cy-cling? i.e., are this single event upsets/latchups or TID failures?

Power cycling was tried for the sensors that completely stopped working during the tests with no success. No power cycling was tried for the intermittent failures. The fact that some of the sensors resumed normal functioning might be an indication that these were latchup events, but without dedicated tests it is hard to say.

Response to Anonymous Referee #2:

- Does the attitude and orientation of the lander affect the accuracy of the measurements?

The measurements taken by the magnetometer are independent of the attitude and orientation of the lander. For the measurements to be of any scientific value, the relative orientation between the magnetometer and the lander, as well as the orientation of the lander with respect to the surface are required.

- Does the sensor measure the magnetic field in three directions? Please clarify.

Yes, the sensor contains three orthogonal coils. A clarification has been added to the text as well as an extra figure showing the PNI RM3100 magnetometer with the three sensing coils. We show the magnitude of the field as a representation of the performance of the magnetometer throughout the tests. We could show individual axis measurements, but this would unnecessarily increase the length of the paper. A small clarification on this point was added towards the end of the first section.

- The test show that the sensors meet the TID requirement. What is the requirement in term of science performances? If the sensor works well but is not able to measure the magnetic field with enough accuracy, it is not very useful. Please comment in the article.

The signals to be detected at the surface of Europa are a combination of electromagnetic waves from the surrounding environment (e.g. ion cyclotron waves arising from the mass loading of the co-rotating plasma) and induction signals generated by the presence of the subsurface ocean and, possibly, water flows near the landing site. The induction signal is quite strong (estimated to be about 12-20 nT as reported in Khurana et al. 2009), well within the measurement capabilities of the PNI RM3100 (Regoli et al. 2018). The induction signals from water flows is expected to be much smaller, but no published estimates are available (to the best of our knowledge), and assessing the suitability of the PNI RM3100 for those measurements is beyond the scope of this paper. For this reason, we evaluate the performance of the magnetometer and its degradation with TID making use of the standard deviation of the detected signal. As an additional metric (and following a suggestion of Anonymous Reviewer #1), we are adding calculations of the noise floor. All these points were added in the "Radiation exposure in space" section for clarification.

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