SSC18-III-06

Four-Magnetometer Board for CubeSat Applications

Leonardo H. Regoli, Mark B. Moldwin, Jacob Thoma, Matthew Pellioni
Department of Climate and Space Sciences and Engineering, University of Michigan
Space Research Building, 2455 Hayward St., Ann Arbor; 734-647-3755
lregoli@umich.edu

Bret Bronner
Space Physics Research Laboratory, University of Michigan
Space Research Building, 2455 Hayward St., Ann Arbor; 734-764-9532
bronner@umich.edu

ABSTRACT

A magnetometer board intended for CubeSat applications is presented. The board contains four PNI RM3100 magnetometers handled by a single MSP430 microcontroller. The low mass, size and power consumption of the individual magnetometers enables the inclusion of four sensors, thus improving the resolution of the system by a factor of two. The PNI RM3100 magnetometers have been thoroughly tested and characterized in a laboratory environment with the objective of detecting ULF waves in the Earth's magnetosphere. With the launch of the Michigan Bicentennial Archive (M-BARC) CubeSat scheduled for 2019, the magnetometer will be flown in space for the first time, increasing the TRL of the system to level 7.

INTRODUCTION

Measuring magnetic fields in space is of paramount importance in order to understand the dynamics of plasmas. From the interplanetary medium down to the upper layers of planetary ionospheres, the interaction between charged particles and magnetic fields defines the convection of plasmas in space as well as the generation and damping of waves[1].

An important limitation of traditional space missions when studying the dynamic nature of the space environment is the inability to sample more than one point in space at any given time. This makes it impossible to disentangle changes occurring in space and time.

In recent years, multi-spacecraft missions have been launched to study different aspects of the Earth's magnetosphere[2,3]. Given the prominent role of magnetic fields, all of these missions were equipped with high-resolution science magnetometers. Different technology developments led to smaller magnetometers with the capability of measuring fields with very high resolution, impossible to achieve a couple of decades ago.

The relative low costs associated with CubeSats makes them the natural choice for future multi-spacecraft studies. However, due to their small size, any system designed to be used in a CubeSat needs not only to be small, but also to have a very low power consumption (due to the limited area for solar panels). In addition, in order for a CubeSat mission to take advantage of the low-cost concept, the production price for any instrument needs to be taken to a minimum.

A number of different approaches have been taken in order to obtain magnetic field measurements with a resolution sufficiently high to perform scientific studies of the magnetosphere. In general, these efforts can be summarized in two main categories, namely miniaturization of traditional fluxgate and helium magnetometers[4] and the use of commercial-off-the-shelf (COTS) sensors[5].

In this contribution, we present the evaluation of a CubeSat form factor board containing four RM3100 magnetometers, designed to be flown aboard the Michigan Bicentennial Archive (M-BARC) CubeSat. M-BARC is planned to have a duration of 3 months on a GTO orbit with a period of 10.5 hours (Figure 1).

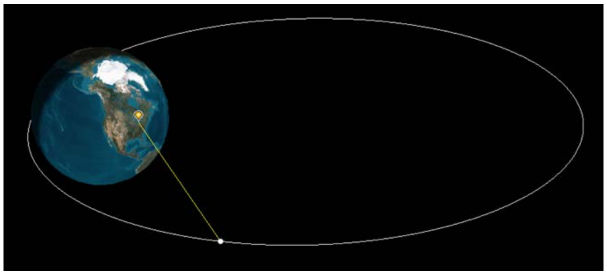

Figure 1: M-BARC's planned orbit

This flight opportunity will allow for the first magnetic field measurements to be taken in space with this relatively novel technology, increasing the Technology Readiness Level (TRL) of the instrument to level 7+, an important and necessary step towards the inclusion of the instrument in future space missions.

The inclusion of four magnetometers in a single board allows for an oversampling in space and a subsequent improvement in the resolution of the instrument by a factor of 2 without sacrificing the sampling frequency, necessary to detect ULF waves in the Earth's magnetosphere.

MAGNETO-INDUCTIVE SENSOR

The RM3100 magnetometer, manufactured by PNI Sensor Corporation, is based on a measurement principle known as magneto-inductive (MI) technology. The sensor consists of a resistor-inductor (RL) circuit driven by a Schmitt trigger oscillator (Figure 2).

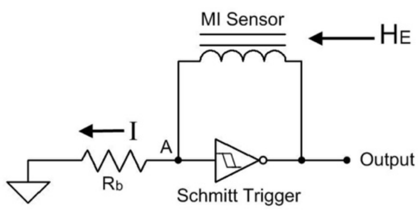

Figure 2: Schematic of the MI Sensor

The induction of the coil (MI Sensor in Figure 2) changes with the applied field, which is a combination of the external field (H_E) and that produced by the circulation of the electric current coming from the circuit (I). This change causes the charge and discharge times of the coil with the current circulating in opposite directions to vary from being symmetric (when no external field is applied) to being asymmetric (when an external field is present). By measuring the difference between the two times over a pre-defined number of charging and discharging cycles, the MI sensor is able to determine the value of the external field.

This simple working principle, in which the magnetic field value is determined by counting a specific number of cycles, directly provides a digital value and thus making the use of an analogue-digital converter (ADC) and an amplifier unnecessary. While the rest of the electronic components are still sensitive to temperature changes and radiation, the lack of an ADC and an amplifier eliminates one of the possible sources of error and also one of the most power-hungry elements in a traditional magnetometer.

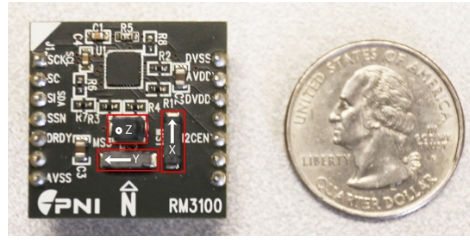

Figure 3: PNI RM3100 magnetometer shown next to a US quarter coin for size comparison. The red rectangles show the location of the sensing coils

In addition, the simple electronics involved in the design make the sensor very small and it is well suited to be produced in large quantities, allowing for a significant reduction in cost. All of this makes the MI technology a very promising candidate for future multi-CubeSat missions to study the dynamics of planetary magnetospheres and the solar wind.

Single sensor performance

The performance of a single sensor was extensively studied[6]. Although the tests presented in that study did not include thermal and radiation testing, the performance seems suitable for study of magnetospheric ULF waves in the PC4 to PC5 range as well as field-aligned currents. Table 1 summarizes the main characteristics of the sensor.

Table 1: Characteristics and performance of the PNI RM3100

Parameter	Value
Area	2.54 x 2.54 cm^2
Weight	< 3 g
Power consumption	< 10 mW
Amplitude range	± 100,000 nT
Frequency range	40 Hz
Resolution @ 40 Hz	8.7 nT
Resolution @ 1 Hz	2.7 nT
Noise floor	4 pT/√Hz @ 1 Hz

The area, weight and power consumption by themselves make the PNI RM3100 a very attractive option for CubeSat missions, as well as for ground-based magnetometers on power-limited applications (lunar and planetary landers, Earth-based in extreme environments).

The main limiting factor to study the full range of ULF waves in the magnetosphere right now is the resolution. While the frequency range is enough to cover even the PC1 range (up to 5 Hz[7]), the amplitude of these waves is on the order of 0.1 nT, meaning that an improvement of more than a factor of 10 in resolution is needed, as shown also in Figure 4, showing the resolution as a function of number of samples used for averaging.

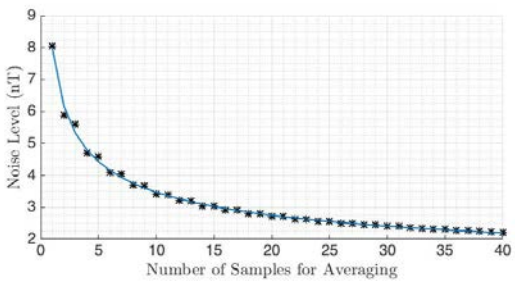

Figure 4: Noise level for different sizes of averaging window. The solid line represents a second-order polynomial fit to the data

Currently, the University of Michigan is working on the development of a completely new instrument based on the MI principle. As a first step though, a four-magnetometer board with a CubeSat form factor (10 cm x 10 cm) was built. The board is integrated in the Michigan Bicentennial Archive (M-BARC) CubeSat, scheduled to fly in 2019. The inclusion of four magnetometers on a single board allowed us to bring the resolution at 1 Hz closer to the nT mark without any further instrument development.

QUAD-MAGNETOMETER BOARD

Figure 5 shows the magnetometer board before integration into the M-BARC CubeSat. The board consists of four RM3100 magnetometers and an MSP430 microcontroller to synchronize the data acquisition and pre-processing. The software on the MSP430 continuously collects data from the four magnetometers and sends, once per second, the value of the averaged data collected by the four magnetometers. Specifically for M-BARC, the data are collected at a frequency of 30 Hz, and the reason for only sending back 1 Hz averages is the limited availability of data storage on the CubeSat as well as the limited bandwidth of the downlink connection.

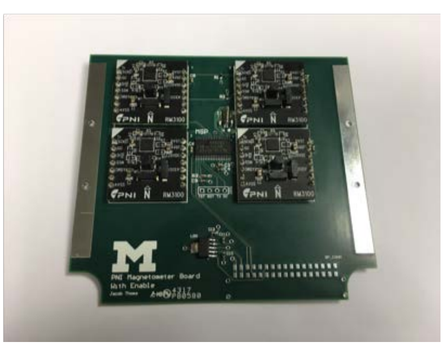

Figure 5: CubeSat board with four magnetometers to be flown on University of Michigan's MBARC

Including the MSP430 in the board facilitates the integration of the magnetometers with the rest of the CubeSat by providing a set of commands that can be sent to the board via UART communication and a pre-arranged formatted output provided by the board to the onboard computer. The same approach can be used for single-PNI boards (currently under preparation for a magnetometer comparison CubeSat mission) and also for the new MI magnetometer currently being developed at the University of Michigan.

Characterization tests

Based on the previous characterization of the single PNI sensor, new tests were carried out in order to characterize the performance of the quad-magnetometer board. In this section, a new resolution test particular to the board and a thermal test performed on an individual magnetometer are presented.

Resolution (quad-magnetometer board)

To determine the minimum fields that can be detected by the system, the quad-magnetometer board was placed inside a shield can that is in turn placed inside a copper room located in the Space Research Building at the University of Michigan[6].

The use of this equipment (depicted in Figure 6) provides a relatively well-controlled environment, where the Earth's magnetic field magnitude is significantly reduced. In addition, variable signals (such as that produced by the 60 Hz power line) are reduced to background levels.

Figure 6: Shield can (left) and copper room (right) used for resolution test

The system was programmed to take continuous measurements at 30 Hz for 30 s and the standard deviation of the signal is taken as the minimum signal to be detected (resolution). In this case, the value is calculated from the average of the measurements returned by the four magnetometers.

Figure 7 shows the results of the resolution test for the three axes. Each plot shows the individual measurement of each magnetometer in a different color (see legend) and the average of the four measurements in black. On top of each panel, the standard deviation of the measurements is shown, with the first four numbers corresponding to the magnetometers one to four in order, the fifth number being the average of the four individual standard deviations, and the last one corresponding to the average of the four measurements.

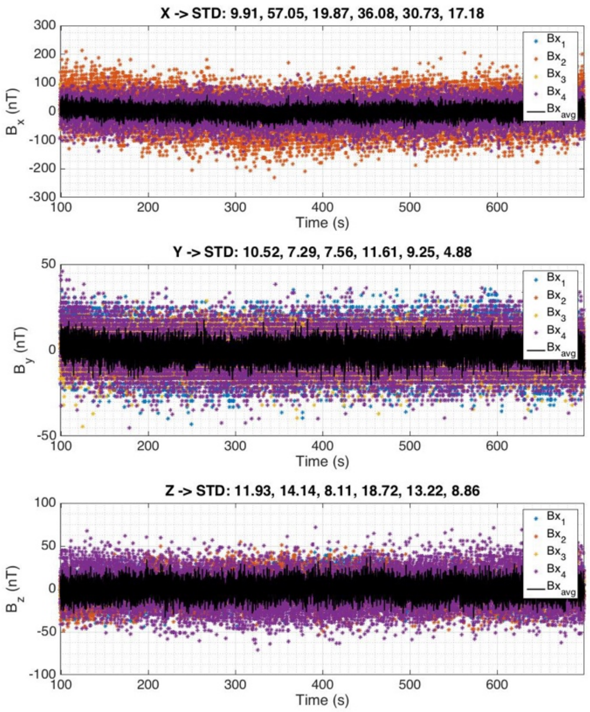

Figure 7: Data from the resolution test for the three axes. Numbers on the top of each panel correspond to standard deviation of the measurements (see text for more details)

The difference between the three axes is remarkable, with the X-axis presenting the highest noise level. In fact, the average of the four measurements is noisier than the first magnetometer. The reason for this is an error in the design of the board, with the microcontroller being placed too close to magnetometers two and four (the two bottom ones) and the oscillator placed too close to magnetometer three (the top right one).

The way the board is routed means that the noise is the lowest along the Y-axis, something visible in the standard deviations from the second panel of Figure 7. The four individual standard deviations are close to the values reported for a single magnetometer[6] and thus the standard deviation of the averaged signal is close to the expected reduction by a factor of two (square root of N, with N being the number of sensors being sampled).

Figure 8 shows the resolution (once again defined as the standard deviation) of the individual magnetometers and the average of the four values as a function of the size of the averaging window for the Y-axis. The reason for presenting only the Y-axis is, as already explained, that the two other axes contain magnetic noise that arises from an error in the design of the board and are not representative of the capabilities of the sensor.

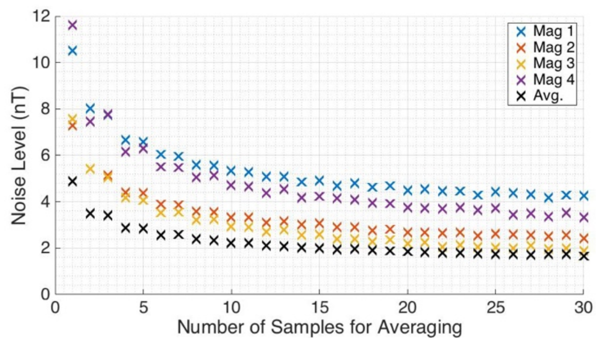

Figure 8: Resolution of the four individual magnetometers and of the average of the four values as a function of the width of the averaging window

From the plot it can be seen that the resolution of the board gets to an almost steady-state level below 2 nT at a sampling frequency of 2 Hz (averaging of 15 samples out of 30 per second) and reaches a minimum value of 1.65 nT at 1 Hz. This represents an improvement of 25% over the value for a single magnetometer[6] and, given the current redesign of the board and the expected reduction in magnetic noise, this is taken as an upper limit for the resolution improvement.

Thermal test

Due to changes in the performance of individual components with temperature, it is expected that any sensor presents a drift in the measurements when important changes in the external temperature occur. In order to quantify this, a thermal test is needed.

While a comprehensive characterization of the RM3100 magnetometer has already been performed, no thermal test has been carried out thus far. This subsection presents the results of a thermal test performed on a single magnetometer.

To determine how the measurement capabilities change with temperature, the sensor was placed inside a thermal chamber and a temperature sweep from ambient (23 °C) to +70 °C, down to -30 °C and back up to ambient was performed, while continuously taking measurements at 30 Hz.

Given that the external field can change during the experiment, a Meda fluxgate magnetometer[8] with resolution of 1 nT was placed outside the thermal chamber to keep track of it. The fluxgate magnetometer was placed in close proximity to the thermal chamber in order to account for field variations induced by the chamber itself (although a complete characterization of the noise produced by the chamber is not available).

The temperature was varied in steps of 10 °C, and the measurements with both magnetometers were taken once the temperature was stable at a given set point. For each set point, one-minute measurements were collected.

Figure 9 shows a plot of the field measured by the MI magnetometer and that measured by the fluxgate with respect to the temperature inside the thermal chamber. Both datasets were normalized to the field measured by each instrument at room temperature (23 °C) before turning on the chamber.

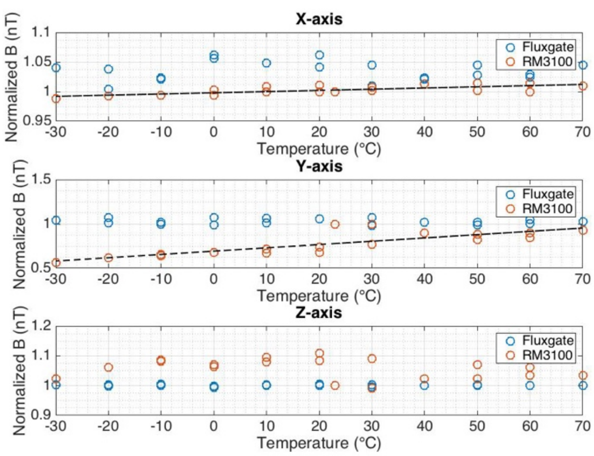

Figure 9: Magnetic field measurements in the three axes by a fluxgate magnetometer outside the thermal chamber (blue) and the PNI RM3100 inside the thermal chamber (orange) during the thermal tests (see text for more details)

The plots corresponding to the X- and Y-axes show a linear fit to the RM3100 measurements (dashed line) through the whole temperature range. For the X-axis, the slope of the line is 0.0002025 while for the Y-axis the slope is 0.003724. For the Z-axis, no fit was performed, since the data are much more scattered than for the other two axes.

While for the X- and Y- axes there seems to be a thermal drift present, based on the values of the slope and on the fact that the maximum deviation from the values measured outside the chamber with the fluxgate is less than 0.5 nT, with these preliminary tests we can conclude that the drift is negligible, taking into account that the value is below the resolution of the instrument at 1 Hz.

The deviation in the case of the Z-axis is also very small, of about 0.1 nT. These values can be taken as upper limit, given the lack of information about the magnetic noise introduced by the thermal chamber itself. When the chamber is cooling down, the magnetic noise can be quite high. This is visible in Figure 10, where the measurements taken by the RM3100 inside the chamber for a temperature of 30 °C going up (heating) and down (cooling) are shown.

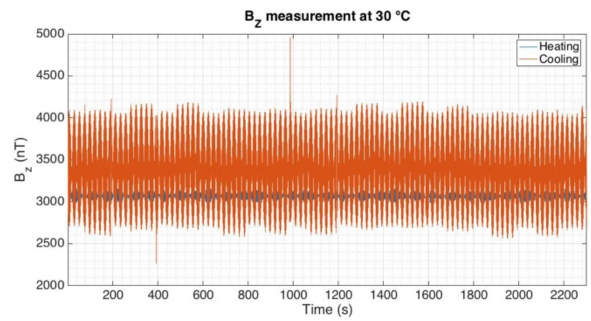

Figure 10: Z-axis magnetic field measurements taken by the PNI RM3100 magnetometer inside the thermal chamber at 30 °C (see text for more details)

From the two curves plotted, it is visible that both, the mean value and the standard deviation of the measurements (an indication of the noise present), are higher when the chamber is cooling down. This does not come as a surprise, given the fact that the chamber makes use of a compressor to reduce the temperature, producing a significant amount of magnetic noise.

Conclusions

A new board consisting of four MI magnetometers specifically designed for CubeSats was presented. The individual magnetometers have previously been characterized with the aim of using them for the detection of ULF waves in space.

During the first characterization steps of the board, an error in the design has been identified, leading to the presence of magnetic noise that can be corrected with a re-design of the board, currently in progress. However, an improvement of 25% in the resolution of the axis with the least amount of noise was achieved when compared with the resolution of an individual sensor, approaching the expected theoretical improvement of 50%.

Due to the already mentioned noise present in the board, the improvement in resolution is taken as an upper limit. Still, the current resolution of 1.65 nT at 1

Hz is approaching the sub-nT range needed for the detection of most of the waves in the PC1 to PC5 range. This further places the technology in a promising position for future CubeSat missions.

To complement the previously published results for the PNI RM3100, a thermal test was performed. The temperature was varied over a range between -30 °C and +70 °C. The results showed a very stable behavior with a difference of less than 0.5 nT between the values returned by the MI sensor and those returned by the control fluxgate magnetometer.

As part of the advancement in TRL, the redesigned version of the board presented in this paper will be flown in 2019 in two different CubeSat missions. This will raise the TRL of the individual sensors from the current level of 6 to more than 7 (possibly 9, depending on the performance during the missions).

In addition, further development is being carried out at the University of Michigan to produce a new magnetometer based on the MI principle. By implementing hardware and software changes, initial modeling suggests an improvement in resolution by about a factor of 10, which would bring it to a few hundreds of pT.

This resolution, together with the rest of the features (current ones listed in Table 1), particularly those related to resources like power and mass, make the technology one of the ideal candidates for magnetic field measurements in future small satellite missions.

For the same reasons, the MI magnetometer is also suitable for ground stations to be distributed in remote places, where extreme weather might require low power consumption to survive long winters. Currently, the first prototypes of such a ground station are being developed and plans for initial deployments are in place for this summer.

Acknowledgments

This work was supported by a NASA Heliophysics Technology and Instrument Development for Science grant (NNX16AH47G) and a NASA Small Spacecraft Technology Program grant (NNX16AT35A).

References

1. Baumjohann, W. and R. A. Treumann, “Basic Space Plasma Physics”, World Scientific Pub. Co. Inc., Dec. 1996.
2. Burch, J. L., T. E. Moore, R. B. Torbert and B. L. Giles, “Magnetospheric Multiscale Overview and Science Objectives”, Space Sci. Rev., 199(1-4).
3. Fear, R. C., S. E. Milan, R. Maggiolo, A. N. Fazakerley, I. Dandouras and S. B. Mende, “Direct observation of closed magnetic flux trapped in the high-latitude magnetosphere”, Science, 346(6216).
4. Miles, D. M., I. R. Mann, M. Ciurzynski, D. Barona, B. B. Narod, J. R. Bennest, I. P. Pakhotin, A. Kale, B. Bruner, C. D. A. Nokes, C. Cupido, T. Haluza-DeLay, D. G. Elliott and D. K. Milling, “A miniature, low-power scientific fluxgate magnetometer: A stepping-stone to cube-satellite constellation missions”, J. Geophys. Res. Space Physics, 121(11), 2016.
5. Matandirotya, E., R. R. V. Zyl, D. J. Gouws and E. F. Saunderson, “Evaluation of a Commercial-Off-the-Shelf Fluxgate Magnetometer for CubeSat Space Magnetometry”, Journal of Small Satellites, 2, 133–146, 2013.
6. Regoli, L. H., M. B. Moldwin, M. Pellioni, B. Bronner, K. Hite, A. Sheinker and B. M. Ponder, “Investigation of a low-cost magneto-inductive magnetometer for space science applications”, Geosci. Instrum. Method. Data Syst., 7, 2018.
7. Menk, F. W., “Magnetospheric ULF Waves: A Review”, in: The Dynamic Magnetosphere, edited by Liu, W. and M. Fujimoto, Springer, 2011.
8. MEDA: uMAG Series Handheld Fluxgate Magnetometers, available at: http://www.meda.com/pdf/uMAGDataSheetrevA.pdf (last access: March 2018), 2005.