Non-linearity Characteristics of the Analog-to-Digital Converter for Arase (ERG) Magnetometer (MGF)

Ayako MATSUOKA[*1], Reiko NOMURA[*2], Mariko TERAMOTO[*3]

ABSTRACT

The high-resolution magnetic field measurement in the intense field is required for the achievement of the Arase project. The magnetometer (MGF) onboard Arase has the digital resolution of 20 bit, which is realized by the 20-bit analogue-to-digital conversion (ADC). A delta-sigma ADC circuit has been developed to satisfy the 20-bit resolution, 256 Hz sampling and tolerance for the severe radiation environment in the radiation belt. We performed the ground experiment at a room temperature to evaluate the non-linearity characteristics of the delta-sigma ADC used for MGF. The non-linearity error for the full range was measured by obtaining continuously the output digital values from ADC for gradually varying input analogue voltage. The maximum non-linear error was 781 digits (0.07% of the full range) corresponding to 11 nT (84 nT) for ±8000 nT (±60000 nT) measurement range. The deviation was determined within 103 digits, corresponding to 1.5 nT (11.0 nT) for ±8000 nT (±60000 nT) range, when the environmental interference noise was not intense. It is within 213 digits, corresponding to 3.1 nT (22.5 nT) for ±8000 nT (±60000 nT) range, when the environmental noise was significant.

Keywords: Arase, MGF, Magnetic Field, Analog-to-digital Converter, Non-linearity

1. ANALOG-TO-DIGITAL CONVERTER FOR ARASE MGF

The Arase (also known as Energization and Radiation in Geospace, ERG) satellite was launched primarily to reveal the generation and loss mechanisms of relativistic electrons in the earth radiation belts (Miyoshi et al., 2018a). The high-resolution magnetic field measurement in the intense field is required for the achievement of the Arase mission. The Magnetic Field Experiment (MGF) magnetometer for the Arase mission was developed to conduct precise measurements of the static magnetic field and low-frequency magnetic field variations. The details of the MGF instrument design and characteristics are presented in Matsuoka et al. (2018).

MGF has two dynamic ranges, ±8000 nT and ±60000 nT, and the digital resolution of 20 bits. It is realized by the 20-bit analogue-to-digital conversion (ADC). Although there are popular commercial ADC ICs of 20-bit resolution or higher, their tolerance in the high radiation environment has not been well proved. A delta-sigma ADC circuit composed by discrete parts has been developed to satisfy the 20-bit resolution, 256 Hz sampling and tolerance for the radiation environment in the radiation belt.

Figure 1 shows the block diagram of the delta-sigma ADC designed for MGF. It has almost same design as that for BepiColombo MMO MGF-I (Baumjohann et al., 2010) except the output sampling frequency. It consists of an analogue delta-sigma modulator and a Finite Impulse Response (FIR) filter. The delta-sigma modulation circuit is made from a 14-bit ADC and a 12-bit Digital-to-Analogue Converter (DAC). It generates raw data with 16 kHz as the output of 14-bit ADC. The modulated data are fed back to the DAC and subtracted from the next input data value. The FIR filter implemented in a field-programmable gate array (FPGA) processes the digitised data and outputs the 256 Hz digital data with 20 bit resolution.

The error of ADC causes the error of the magnetic field measured by MGF. We carried a ground experiment of the MGF flight model to evaluate the non-linearity characteristics of ADC.

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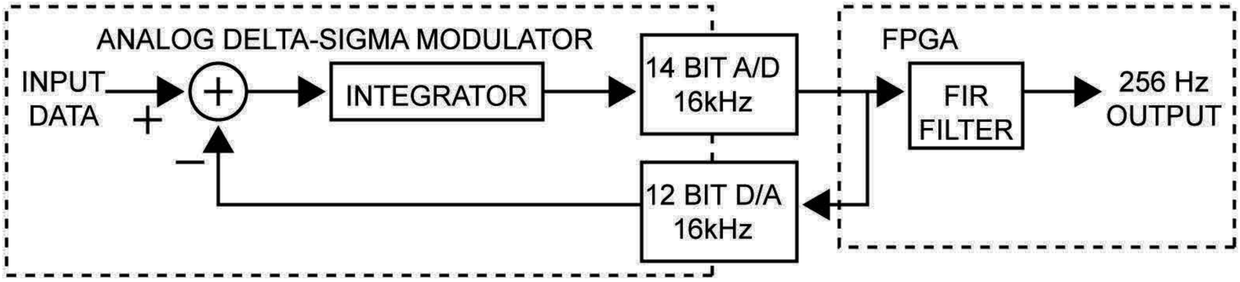


Fig. 1 Block diagram of the delta–sigma analogue-to-digital converter.

2. EXPERIMENTAL METHOD

Figure 2 shows a schematic diagram of the ground experiment to evaluate the non-linearity characteristics of the delta-sigma ADC. In the flight configuration of MGF, the signal from the sensor (MGF-S) is processed by the analog signal processing circuit in the MGF electronics part (MGF-E) and transferred to the ADC. For the experiment, the analog signal processing part was temporally disconnected from the ADC. We used a 12V battery and serially connected constant resistance as well as thermistor to input analogue voltage to the ADC. The input voltage changed continuously by heating and cooling the thermistor. There were three ranges of the input voltage; high (±5 V), middle (±2.5 V) and low (±1 V), and we changed the range by replacing the constant resistance. We performed the experiment 5 times for each range for both positive and negative input voltages. The input voltage was recorded with 1000Hz sampling frequency by a logger in which a 16-bit ADC is implemented. The recording started by the tick signal provided by MGF-E. The duration of the data recording for each experiment was 65.535 sec. The output 256Hz data from the ADC were stored in the mission data processor (MDP) emulator through CPU in MGF-E. The data are recorded together with the interval after the tick signal, which enables us to find the correspondence between the logged input voltage and the output data.

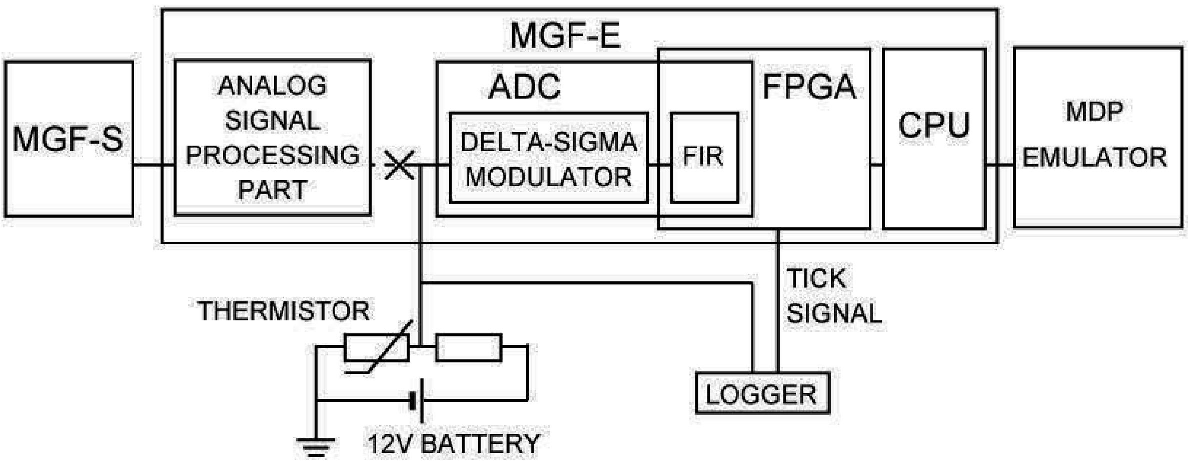


Fig. 2. Schematic diagram of the experiment to evaluate the non-linearity characteristics of ADC.

3. EVALUATION RESULT

3.1. ADC error versus input voltage

At first the output values from the ADC were fitted to a linear function of the input voltage. The deviation of the output values from the regression function was statistically analysed.

Figures 3 shows the devition of the output values versus the input voltage to the (a) x, (b) y and (c) z terminals of the ADC. The deviation of the individual output values is plotted by light-brue dots in the lower panels. The deviation obviously scatters for positive input values of the y and z components. The scattering is considered to be due to the environmental noise although the distinct reason is unclear. The data are divided into bins defined by the input voltage every 5 mV, and the output values are averaged for every bins. The numbers of data in every bins are plotted in the upper panels. The averaged output values are plotted by red and the standard deviation from the average is plotted by dark-blue in the lower panels.

The maximum deviation from the linear relation is 781 digits, 0.07% of the full range, which corresponds to 11 nT (84 nT) for ±8000 nT (±60000 nT) range. The maximum standard deviations from the average of each bin are 103, 80 and 74 digits for negative x, y and z input voltage, respectively, and 89 digits for positive z input voltage. 103 ditits correspond to 1.5 nT (11.0 nT) for ±8000 nT (±60000 nT) measurement range. The standard deviations for positive x and y input voltage are larger, 197 and 213 digits, respectively. 213 digits correspond to 3.1 nT (22.5 nT) for ±8000 nT (±60000 nT) range. By close inspection of the averaged data, the deviation shows steep changes every 0.19 mV of the input voltage. This indicates that the error value steeply changes when the 5th bit from MSB of the output value changes.

3.2. ADC error versus output value

We calibrate the in-flight data of MGF based on the output values, not the input voltage. Therefore we need to know the dependence of the deviation of the output values on the output value itself. Figure 4 shows devition of the output value for the three components again, but the holizontal axis is scaled by the output value. Because the output value has the revese sign to the input voltage, the features seen in Figure 4 are nearly horizontal inversions of those in Figure 3. Statistical bins are newly defined by the output value. As we noted in the last subsection, steep changes occur when the 5th bit from MSB of the output value changes, namely, every 32768 digits. The boundaries of the bins are defined as the factorial of 2, not to mix the data of different 5th bit value. The bin for the x and y components is defined every 1024 digits of the output value, v, for $|v| \geq 2048$ digits, every 8 digits for $-2048 \leq v \leq 256$ digits, every 256 digits for $256 \leq v \leq 2048$ digits. For the z component, it is defined every 1024 digits of v for $|v| \geq 2048$ digits and every 128 digits for $|v| \leq 2048$ digits.

3.3. Application to the MGF calibration

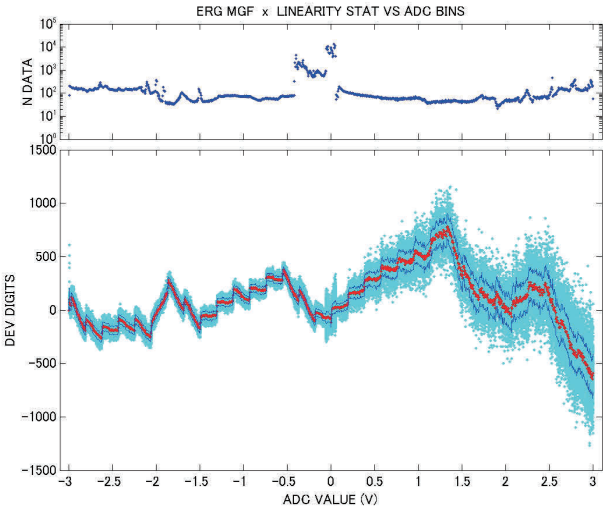
The non-linearity error of ADC presented here cause the inaccuracy of the magnetic field data obtained by Arase MGF. It results in quasi-static error along the spin axis and time variant error in the spin plane. The time variant error has the broad spectrum at frequencies from several hundreds mHz to several Hz. When we need the highly precise field data or study faint field variation in the space, the errors caused by ADC should be serious.

To remove the error by the ADC non-linearity, the deviation shown in Figure 4 is subtracted from the in-flight output values from MGF. The MGF Level-2 data stored in the data sever of ERG Science Center (Miyoshi et al., 2018b) have version numbers corresponding to the calibration method. The ADC non-linearity error is removed from the Level-2 data of version 02 and hereafter.

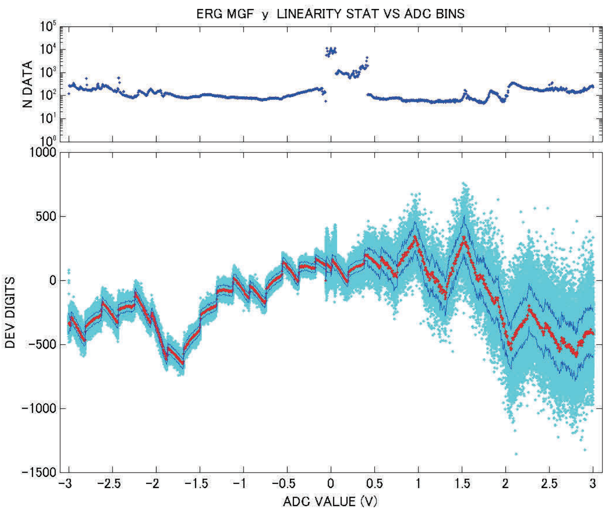
4. SUMMARY

We performed a ground experiment to evaluate the non-linearity characteristics of the delta-sigma ADC used for Arase MGF. The maximum non-linear error is 781 digits (0.07% of the full range) corresponding to 11 nT (84 nT) for ±8000 nT (±60000 nT) measurement range. The deviation is determined within 103 digits, corresponding to 1.5 nT (11.0 nT) for ±8000 nT (±60000 nT) range, when the environmental interference noise was not intense. It is within 213 digits, corresponding to 3.1 nT (22.5 nT) for ±8000 nT (±60000 nT) range, when the environmental noise was significant.

(a)



(b)



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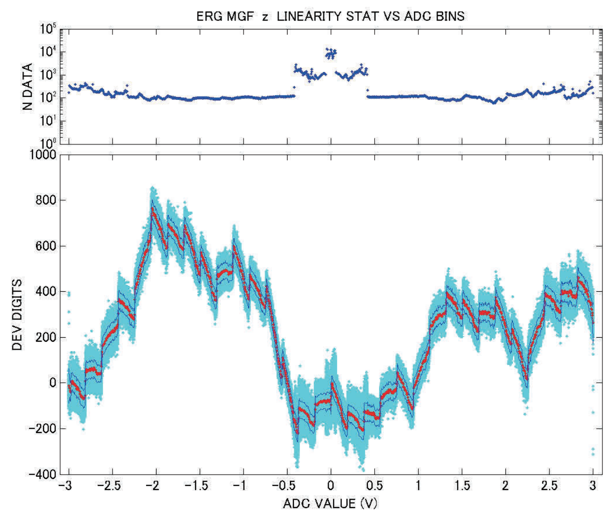
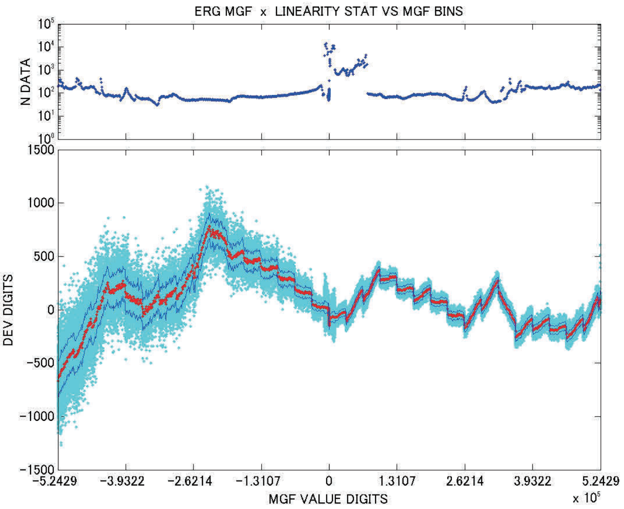


Fig. 3 The devition of the output values versus the input voltage for the (a) x, (b) y and (c) z components. Light-blue : the deviation of the individual output values, red : the averaged output values for every bins, dark-blue : the standard deviation from the average for every bins

(a)



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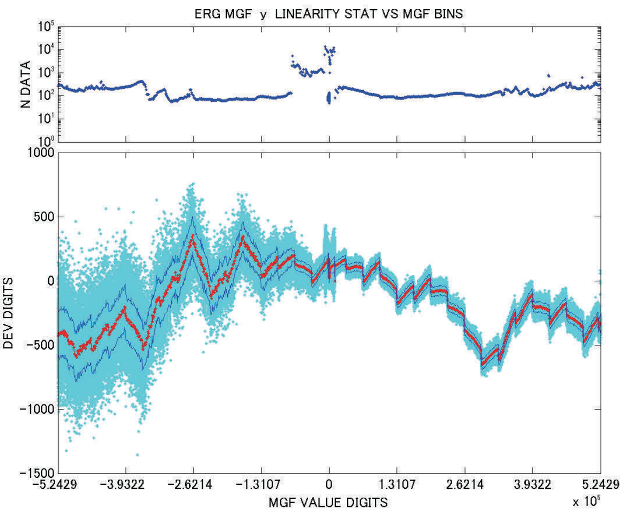

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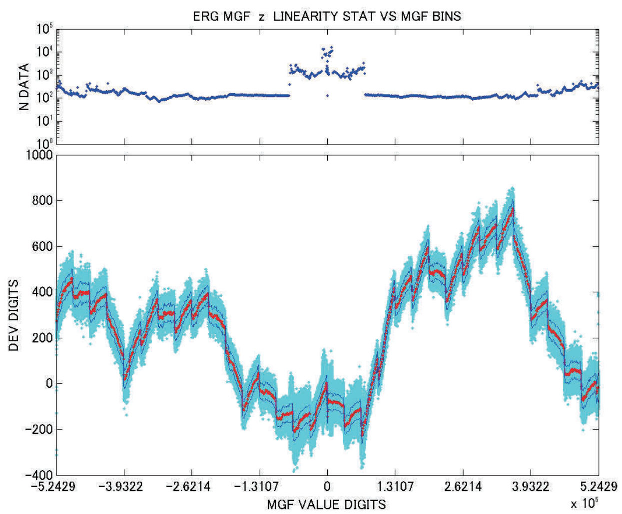

Fig. 4 The devition of the output values versus the output values for the (a) x, (b) y and (c) z components. The format is same as Fig. 3.

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