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Interactive Comment

Interactive comment on "A radiation hardened digital fluxgate magnetometer for space applications" *by* D. M. Miles et al.

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We would like to thank Anonymous Referee #1 for a detailed and helpful review of our manuscript. We will reply to each comment inline below:

1. The analysis of the modern state of the space borne, radiation tolerant fluxgate magnetometers would be very useful. It is particularly advised to compare the proposed magnetometer design with those reported in the following papers:

Highly integrated front-end electronics for spaceborne fluxgate sensors, by W. Magnes et al 2008 Meas. Sci. Technol. 19 115801 doi:10.1088/0957-0233/19/11/115801

The THEMIS Fluxgate Magnetometer, by H.U. Auster Space Sci. Rev. DOI

10.1007/s11214-008-9365-9

Miniaturized digital fluxgate magnetometer for small spacecraft applications, by Åke Forslund et al 2008 Meas. Sci. Technol. 19 015202 doi:10.1088/0957-0233/19/1/015202

All these instruments have the digital structure and the first two are radiation tolerant. Some data, e.g., correlation analysis principles, are already discussed there with better output. Necessary to compare also the advantages of principal solutions proposed in the paper.

Response 1: Agreed. The performance of the prototype instrument will be compared with other relevant instruments, including the two suggested, via a table of key performance metrics and the relevant key design choices.

2. Page 6, row 15. Eq. 2 is given without reference and probably is true only for the special case when the induction of the sense winding is much less than its active resistance Rwinding. For ordinal fluxgate sensor in short-circuit configuration shown in Fig.4 the amplifier output voltage Vout should be proportional to the relative permeability μr(t), but not to its derivative (d μr(t)/dt) as it follows from Eq. 2.

Response 2: Equation 2 follows from a derivation in "Ripka, P. (2001). Magnetic Sensors and Magnetometers. 685 Canton Street, Northwood, MA, 02062: Artech House, Inc." and should not have been presented without reference. Thank-you for pointing this out. This section will be expanded in the final manuscript.

3. Page 6, rows 21 – 25. The Vout could contain a number of the even harmonics (2f, 4f, 6 f, etc.) of the excitation frequency f, but not only 2f as it is claimed.

Response 3: Agreed – although with diminishing amplitude. The manuscript will be updated accordingly.

4. Page 7, rows 1-5 and Fig. 5. It seems that responses at the large fields (+24820 nT an -24430 nT) go into saturation and the shape of the signal is distorted. So, these

plots hardly indicate the true shape of the signal at large fields.

Response 4: Agreed – signal is badly distorted (clipped) in large fields as, among other things, the amplifiers cannot drive beyond their supply voltage. This signals do not correspond the external magnetic field beyond indicting out-of-range high/low. However, in the operating instrument the digital feedback would quickly return the field within the sensor back into the un-saturated region. The key feature, as noted in the text, is that "the amplitude of the error signal at the ADC trigger points is monotonic and strictly increasing with magnetic field. This is essential because any local extrema or out-of-range polarity inversion would cause the control loop to apply feedback in the wrong direction." The text will be adjusted to emphasis this point and acknowledge the limitation of the large-field signal output.

5. Page 7, rows 6-8. If I correctly understand the ADC samples the preamplifier output two times per excitation period and then the average value for even number of samples is calculated. Using such detection technique all low frequency fluctuations of the preamplifier and the ADC itself will be added to the useful signal. It is necessary to mention how much this contribution could increase the pure fluxgate sensor noise and zero offset temperature dependence.

Response 5: Agreed. The manuscript will be updated to reflect this.

6. Page 8, rows 15-22. For feedback field temperature compensation Acuna et al. (1978) used the temperature variations of the feedback coil resistance rather than its impedance. The inductivity of the feedback coil could also be temperature dependent. From this point of view the sentences "However, it is intentionally unbalanced so that the voltage to current conversion factor depends on the coil impedance. This dependence on coil impedance is then tuned until the temperature effects of the coil impedance and the coil geometry are equal and opposite." is not clear enough to understand what parameter of the coil is used for temperature compensation.

Response 6: The temperature compensation is based on the DC resistance of the coil.

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This will be corrected in the manuscript.

7. Page 9, rows 13-14. It is not clear what were the criteria for the selection of the instrument resolution 8 pT. The spectral density of the quantization noise at such resolution and frequency band is only 0.11 pT/rtHz (8 pT/sqrt(12*450 Hz)). Is it really needed to keep such small value (only 1 % of the sensor noise)? As the main parts of the magnetometer (Analog-to-digital and digital-to analog converters) strongly depend on resolution, its value should be properly selected.

Response 7: The 8 pT resolution, which is finer than required in the current application and using the current sensor, was selected in anticipation of ultra-low-noise cores such as those which may result from the ongoing research of Dr. Narod of Narod Geophysics Ltd. (Narod, Barry. "The origin of noise and hysteresis in permalloy ring-core fluxgate sensors." EGU General Assembly Conference Abstracts. Vol. 15. 2013.). The manuscript will be updated to include this motivation.

8. Page 9, rows 18-20. There is no proof of the 24 noise-free bits of digital-to-analog converter. Please, see the previous comment for the quantization noise estimation.

Response 8: Many subsystem test results were omitted in the interests of manuscript length. A new figure will be included showing the noise spectrum of the digital-to-analog converter.

9. Page 10, rows 3-6. It is not clear why sharing 2 bits from two 10-bit converters the16-bit converter instead of 18-bit one is obtained.

Response: Indeed. That sentence is incorrect and confusing as written. This will be rewritten and expanded for clarity.

10. Page 10, rows 7-9. Combining of two digital-to-analog converters may potentially produce a non-linear output. The results of the linearity tests are not presented in the paper.

Response: Agreed. There are also transient effects as the feedback filters settle from

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moving between even two adjacent feedback values if the relative contribution of the two PWMs changes (ie. The coarse PWM takes a step). The manuscript will be updated to reflect this.

11. Page 11, rows 15-17; Fig. 7. In the text it is declared that ". . . the amplitude of the sideband carriers is constant up to 1500 Hz . . . ", but in Fig. 7 these sideband amplitudes vary in the range – (24 . . . 44) dB.

Response 11: The reviewer is correct – the sidebands amplitudes in Figure 7 do vary as described. The text is based on an earlier version of the figure taken with a different bench top instrument. Figure 7, as presented, does not capture previously observed constant amplitude of the sidebands. More measurements of the raw sensor will be taken to verify the previously observed behaviour and Figure 7 and the text will be updated according. Thank-you for pointing this out.

12. Page 12, rows 21-24. The tests justifying the effective ADC resolution are not clear. As it is parameter of the ADC it has to be measured without influence of the sensor noise, but tests were performed with sensor. It is unclear also why the effective resolution is checked in the frequency domain, but not in the time domain.

Response 12: Section 4 was intended to describe the overall performance of the instrument so the test results are correspondingly for the coupled sensor/electronics system. For clarity, rows 14 to 21 describing the theory of the ADC oversampling will be moved to Section 2 (Instrument Design) and the intent of Figures 8 and 9 will be more clearly described. A figure showing the measured time series of a small amplitude magnetic square wave was omitted to reduce the length of the manuscript but will be re-inserted.

13. There is no the frequency response analysis of the magnetometer. Particularly, it is interesting how the 3-pole low-pass filter in the feedback loop (page 9, rows 5-6) influences on the frequency response. As this filter introduces a considerable phase shift, the magnetometer could become a self-oscillating system at some conditions. What measures were taken to avoid this? Maybe the irregularities of the noise spectra

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in the band 100-300 Hz (Fig. 8 - 10) are caused by this reason.

Response 13: The idea that the 100-300 Hz noise is related to self-oscillation is interesting. The odd double-peaked shaped seen in Figure 10 didn't seem suggestive of a self-resonance but the hypothesis is worth investigating. A new figure showing the frequency response of the magnetometer will be included in the final manuscript.

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