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Geoscientific Instrumentation Methods and Data Systems Discussions
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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 #2 for a detailed and helpful review of our manuscript. In the interests of clarity we have added numbers the referee's comments and will reply to each comment inline below:

1. The authors present a novel concept of a fluxgate magnetometer (i.e. direct digitisation combined with a new feedback system based on two cascaded PWM stages) for space application. However, the new concept is not compared with already existing similar fluxgate magnetometer designs and a potential weakness (non-linearity) as well as the dependence of the transfer function on the new feedback design are not discussed.

Response 1: Agreed. The performance of the prototype instrument will be compared with other relevant instruments, including the suggested papers, via a table of key performance metrics and the relevant key design choices. The potential non-linearity and dependence on the feedback design will be acknowledged in the text.

2. Two topics which are not so relevant for the application are discussed with too much detail (text and figures). The output voltage at large applied magnetic fields is not so important in a loop configuration (Fig. 5) and the scientific need for a very large bandwidth of 100Hz and more with the (limited) sensitivity of a fluxgate sensor is not made clear (Fig. 7).

Response 2: The key feature of Figure 4, 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 as this is important to the control system. The 8 pT resolution and potential for high-bandwidths was developed 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.

Specific Comments:

3. Abstract, 16-19: The novelties of the new design should be compared with already published fluxgate magnetometers instead of with a precursor model.

Response 3: The abstract will be updated accordingly.

4. Ch. 1, p. 3, 20-21: The science objectives only require a 10 Hz bandwidth. There seems to be no need for an instrument with a bandwidth of 450 Hz (and more)?

Response 4: This is true. The text will be updated to include the future-compatibility motivation described in Response 2.

5. Ch. 2, p. 4, 20-22: Reference to an earlier publication of a two ring-core sensor design should be included.

Response 5: The manuscript will be updated accordingly.

6. Ch. 2, p. 5, 5-8: This paragraph somehow briefly describes the core of the instrument design. The measured magnetic field is obviously the sum of the two PWM stages and the remnant field digitised by the ADC. How is this realised in the FPGA? What elements are limiting the linearity and determining the overall transfer function? The inclusion of an additional block diagram of the required logic in the FPGA should be considered.

Response 6: A block diagram showing major elements of the FPGA logic will be created for the final manuscript including further details on how the final data product is assembled.

7. Ch. 2.1, p. 6, 22 and p. 7, 14: In principle, only odd harmonics should couple from the drive to the sense windings. Coupling of even harmonics would result in large offsets.

Response 7: Figure 5 shows the significant (but constant) 1f tone. This is removed by decimating over an even number of samples and removing an experimentally determined offset from each channel. This will be further described as part of Response 6.

8. Ch. 2.1, p. 7, 18: Is an 'out-of-range polarity inversion' in the analog domain a realistic scenario?

Response 8: Signal inversion near the amplifier supply rails would be possible in large signal if the amplifiers were poorly chosen. This isn't an issue in normal operation but could interfere with the initial servo to the instrument's operating point when initially turned on in a field large enough to clip the analog system. This point will be made

more explicitly in the manuscript.

9. Ch. 2.2, p. 8, 6-7: There is a low-pass filter in the feedback of the OBrien et al. design!

Response 9: The reviewer is correct. The O'brien et al. design used a "simple RC". The manuscript will be updated accordingly. Thank-you for catching this.

10. Ch. 2.2, p. 9, 15-16: It is not understood why 2 bits are lost due to the drive residuals?

Response 10: Even in a constant field, the value of two successive ADC values can vary by more than half the +/- 2.5V total ADC input range due to the significant 1f tone. If the input value is too large or too small then the half of the samples will be clipped and invalid. This restricts us (accurately) usable input range of the ADC. This will be explicitly explained in the revised manuscript.

11. Ch. 2.2, p. 10, 6: The design should in principle lead to a (10 - 2) +10 = 18 bit design. But it obviously is not having the linearity performance of an 18 bit DAC. What happens at the transition from the low range to the high range PWM DAC at multiples of about 256nT? Is there a significant differential non-linearity error at the 0 nT transition?

Response 11: Indeed. This was noted by the other referee as well. The sentence is incorrect and confusing as written. This will be rewritten and expanded for clarity. Both PWMs are operated and summed continuously so there isn't a transition between PWM modes. However, there are transient effects as the feedback filters settle when 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 limitation.

12. Ch. 3: As pointed out above, the scientific relevance should be made clear.

Response 12: Agreed. The manuscript will be updated accordingly to reflect the future compatibility motivation in Response 2.

13. Ch. 4.1, p. 12, 8-10: Noise, offset and linearity (with applied sine signal) are ideally tested in a magnetic shielding can. It is not understood why the described facility is too noisy.

Response 13: Offset and linearity and linearity can indeed be measured in a multilayer magnetic shielding can at the CARISMA laboratory. The CARISMA laboratory has several significant local noise sources (nearby elevator, large compressor for a walk-in freezer, and overhead air-conditioning and ventilation fans) which make noise measurements, particularly at low frequencies, difficult compared to the NRCan facilities. This will be more fully explained in the updated manuscript.

14. Ch. 4.2, p. 12, 16-17: One shouldn't speak of an error measurement. The remnant field is a consequence of the overall design. Furthermore, are the 57.6 ksps just decimated or digitally filtered and then decimated. A simple decimation would lead to a serious aliasing problem.

Response 14: "Error Signal" is used in the control system sense since the measured output of the sensor is used as the input for the control system driving the digital feedback. This will be noted in the manuscript. Currently, the 57.6 ksps data stream is simply decimated which, as the referee notes, makes the instrument vulnerable to aliasing. A digital filter was to be added in future work; however, this current limitation will be acknowledged in the manuscript.

15. Ch. 4.2, Fig. 8 and 9: This is not a representative discussion of the magnetic resolution. When the time series is long enough, even much smaller periodic signals can be resolved with an FFT.

Response 15: 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.

16. Ch. 4.3, Fig. 10: The 10, 7 and 5 pT/rt(Hz) lines are misleading since the values

are just valid at 1 Hz.

Response 16: The three lines show 1/f reference spectrums which typically dominate fluxgate noise at low frequencies. Although typically quoted at 1 Hz these are valid at any frequency and are, in our opinion, a useful reference to interpret noise plots.

17. Ch. 4.4: What exactly is meant with RMS error? Is it the overall non-linearity of the instrument? Is it dominated by either integral or differential non-linearity? Residual plots should demonstrated what is meant here exactly. Is the presented number compliant with the performance required for the scientific missions?

Response 17: The RMS error provides an estimate of the expected absolute error of the instrument at any point in it's +/-65,536 nT range. It is calculated by using the known absolute current measurements driving the Helmholtz coils creating the test measurement to create a set of ideal instrument measurements. The difference between each measured point and the ideal measurement are then averaged by a RMS calculation. Each datum is taken as the arithmetic mean of 900 samples (1 second) to cancel out the 60 Hz contamination. This test, and how it meets the requirements of the mission, will be expanded in the manuscript.

18. Ch. 5: Offset stability tests with sensor and electronics temperature should be important tasks in the future.

Response 18: Agreed. These will be added to Section 5 – Future Work.

Technical corrections:

19. Ch. 4.1, p. 11, 22-23: ... National Resources Canada (NRC) ...

Response 19: Agreed – However I will continue to use the abbreviation NRCan as, in Canada, NRC is typically used to refer to the National Research Council instead.

Ch. 4.1, p. 12, 8: ... than the NRC facility ...

Response 20: See Response 19.

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