Response to Interactive comment on “A Hybrid Fluxgate and Search Coil Magnetometer Concept Using a Racetrack Core” by David M. Miles et al. by M. Moldwin (Referee) on 9 July 2018

We thank Dr. Moldwin for his constructive comments which we have incorporated into the manuscript. Dr. Moldwin raised several questions about earlier work, methodology, and the anticipated performance of a complete instrument. We have addressed each question below; Dr. Moldwin’s comments are in plain text, our responses in *italics* and any content added to or changed in the manuscript are in *“quoted italics”.*

The paper describes an interesting concept of using a single sensor to act independently as a DC and AC magnetometer using both the traditional search coil and fluxgate techniques.

1) The paper doesn’t currently discuss the approach in context of earlier work looking at making hybrid magnetometers that combine fluxgate and search coils. Examples of two groups (one in China and one in Japan) that have been developing such sensors are below.

Shi et al., 2017 Review of Scientific Instruments 88, 125001 (2017); doi: 10.1063/1.5013015 View online: https://doi.org/10.1063/1.5013015

F. Han, S. Harada and I. Sasada, "Fluxgate and Search Coil Hybrid: A Low-Noise Wide-Band Magnetometer," in IEEE Transactions on Magnetics, vol. 48, no. 11, pp. 3700-3703, Nov. 2012. doi: 10.1109/TMAG.2012.2196762

The references to Shi, Han and two other relevant publications have been added to provide better context to the presented research.

Change made. The relevant section now reads:

“The complementarity of the two sensor technologies has led several authors to investigate creating hybrid instruments which can exploit both the fluxgate and the search coil effects. Two groups (Han et al., 2012; Shi et al., 2017) are developing hybrid instruments by embedding a fluxgate within the hollow core of a searchcoil and electrically fusing the outputs. This same technique can be used for other DC magnetometer technologies such as by embedding a Hall sensor at the centre of a search coil core (Leroy et al., 2008). Ripka, (1995) investigated whether the feedback coil in a fluxgate could also be used as a search coil magnetometer. This paper extends that concept by changing the geometry of the fluxgate sensor to mimic that of a search coil such that both effects can be extracted from a common sense winding. Zhang et al., (2010) used a similar sensor design but interleaved at ~1 s intervals and switched off the fluxgate excitation when operating the search coil. The paper also examines the search coil signal extraction to see if it can be improved by interleaving its capture with the fluxgate action on the timescale of the excitation of the core.”

2) Are there any issues anticipated with building a 3-axis sensor in terms of cross-talk, offsets or other interference that can be described? What would be an expected possible dimensions for such a hybrid magnetometer (size, mass, power)?

The hybrid magnetometer design will likely be affected by the same cross-coupling effects as traditional fluxgate and searchcoil designs exacerbated by the bandwidth and sensitivity of the searchcoil path potentially picking up transients from updates the magnetic feedback used in the fluxgate path. We have added text to the discussion describing this, the anticipated process for scaling to a 3-axis sensor, and our estimates of the size, mass, and power of such a flight instrument.

Changes made. The following new text has been added:

"Developing a complete vector spaceflight sensor based on the proof-of-concept work described here will require addressing several design issues: the addition of magnetic feedback to linearize and extend the range of the fluxgate path, robust and highly orthogonal mounting of three sensor axes, and likely the development of real-time processing firmware for the search coil and fluxgate paths to avoid telemetering the raw digitized data."

"Fluxgate and search coil magnetometers build up a vector magnetic field measurement from three nominally orthogonal projections. Small misalignment of these axes can be mitigated using an orthogonality matrix correction. However, a secondary effect which can be difficult to characterise and calibrate out is the potential for cross-talk between the channels. The presence of a ferromagnetic core and/or magnetic feedback are expected to create cross-talk offsets in the same way as in standard fluxgate or searchcoil sensors. A potentially trickier issue is whether the broader bandwidth and higher sensitivity of the searchcoil path will cause it to pick up transients from dynamical fluxgate behaviours such as, in an offsetting instrument, updating the magnetic feedback in one of the other sensor axes. Such effects will need to be carefully characterised and potentially compensated for within the instrument."

"The racetrack ring core and the glass-tube based solenoidal winding used in the proof-of-concept prototype mass 6 g and 46 g respectively. Allowing for some mass optimisation of the sense winding, three sensor axes, and a mount to hold the axes orthogonal we estimate that a complete vector hybrid sensor based on the current racetrack cores would likely mass ~250-300 g and extend ~10 cm in each direction. Extrapolating from the current laboratory electronics, a complete three channel instrument would likely consume ~400-500 mW of power during normal operation."

3) What is the telemetry rate at the appropriate samples per second to extract both DC and AC signals? Would the processing be done within the FPGA or would an actual CubeSat system down load the full telemetry to be processed on the ground?

Telemetering the raw samples required to extract the fluxgate and searchcoil signals in post-processing on the ground is likely impractical for most spacecraft missions.

Change made. A paragraph to this effect has been added to the manuscript.

"A flight version of the hybrid magnetometer would likely need to implement both fluxgate and searchcoil reconstruction in onboard processing. An instrument with three channels sampling to 24

resolution at 20,000 sps would require ~1.4 Mbps of bandwidth for the forward loop, with some lower but non-trivial bandwidth required to telemeter the magnetic feedback applied to each sensor axis. For spacecraft applications with telemetry constraints, this bandwidth could be significantly reduced by processing the raw samples onboard the spacecraft into a lower cadence fluxgate stream (three channels of 24-bit fluxgate data at 100 sps requires ~7 kbps) and compressed spectral products such an averaged spectra or filter banks from the searchcoil path. This processing could be accomplished either in real-time in the FPGA or in software on an embedded computer in the spacecraft."

4) End of section 5 indicates that the racetrack core optimization is to blame for the lower sensitivity. Could the difference be due to the shape of the core instead of manufacturing or drive circuit tuning? Would you expect the same noise level solely on the material properties of the foil and its manufacturing process?

Previous authors have demonstrated low-noise and high sensitivity using racetrack geometry cores. However, to our knowledge, there has not been a systematic comparison of noise performance for a equivalent amount and type of ferromagnetic foil in ring and racetrack geometry. It is possible that the drive circuit was not optimally tuned; however, we followed the same process that we have used for rings in a variety of sizes and geometries in the past with good results. We have added some appropriate caveats in the text.

Change made. The relevant text now reads:

"Other authors (e.g., Hinnrichs et al., 2001; Ripka, 1993) have achieved good noise and sensitivity using race-track geometry cores so we interpret these results to suggest that something about the manufacture or drive of the racetrack core presented here is not yet optimised. This is beyond the scope of this manuscript and is the subject of ongoing work."

5) Any comment on reasons for the flat gain/response seen in Figure 11 below 100 Hz?

We infer that the flat gain/response seen in Figure 11 is a frequency folding artefact caused by insufficient antialiasing.

The existing text in the manuscript states:

"The constant gain below ~40 Hz for the hybrid search coil reconstructions appears to be a frequency folding effect caused by insufficient antialiasing before digitisation. The ringcore is driven at 2,500 Hz so the fluxgate modulation will manifest as sidebands around the even harmonics at 5,000, 10,000, 20,000 Hz, etc. A 1 Hz magnetic test signal will therefore create a sideband at 20,001 Hz (eight harmonic). The sensor is sampled at 20,000 sps creating a 10,000 Hz Nyquist frequency. Therefore, the 20,001 Hz sideband will frequency fold over the Nyquist frequency and 0 Hz down to an aliased 1 Hz which will dominate compared to the small sensitivity of the search coil at low frequencies."

Change made. We have added an explanatory caveat to the caption of Figure 11.

"The constant gain/noise below is believed to be an aliasing artefact."