Response to Interactive comment on "A Hybrid Fluxgate and Search Coil Magnetometer Concept Using a Racetrack Core" by David M. Miles et al. by Anonymous Referee #3 on 29 July 2018

We thank the referee for the constructive comments which we have incorporated into the manuscript. Referee #3 raised several questions and issues which we address below; the referee'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 considers an interesting approach to extend functionality of a flux-gate magnetometer adding to the existing hardware the software data processing procedure exploiting a search coil mechanism. A hybrid magnetometer is expected to have the wider operation frequency band and/or better noise performance, what is especially beneficial for space-born instruments. There are key challenges for successful design of this kind of instruments. First of all, the periodical saturation of the magnetic core, necessary for flux-gate operation, could degrade the noise performance of the search coil channel. A hybrid magnetometer would be operationally useful, only if the noise level of the search coil path is lower, in some frequency band, than that of the flux-gate path.

It seems for the hybrid magnetometer described in the paper the search coil channel brings no benefits to the instrument noise performance – the same results could be achieved using the flux-gate mechanism solely. So, further efforts are necessary in order to prove the proposed concept of a hybrid instrument.

Specific Comments

p. 6, l. 11-13, "The phase offset between the drive current pulses (Figure 6a) and the sensor output waveform (Figure 6b) is believed to result from the RLC behaviour of the sense coil and preamp."

It is unclear why the authors assume that there is "the phase offset between" these signals. In my opinion, Figure 6b depicts mostly the feed-through signal, the shape of which depends on symmetry of the magnetic core/drive winding. Generally, one can expect weak similarity between waveforms of the drive current pulses and the feedthrough signal.

We agree with the referee that much of the sensor output is feed-through from the drive signal. In hindsight, the referenced "phase offset" is ambiguous in the text. It refers to the fact that Slice B, which is offset by one sample from the drive current pules in Figure 6a, contains the majority of the fluxgate action. We have added explanatory text to clarify the alignment of the slices and created the new Table 1 (described below) to specify the mapping.

Changes made.

The following text has been inserted: "Slice 2/B and 6/B contain the majority of the fluxgate action produced by the current pulses forcing the core into saturation…"

The new Table 1 (details below) has been added to explicitly define the mapping.

p. 8, Fig. 7. The signals at frequencies 20, 40, 80 Hz are clearly seen in the spectra of the 'sliced' steams. At the same time the spectrum of the raw ADC samples does not contain at these frequencies any signals exceeding the noise background. This could be a sign that the spectral folding occurred during separating the raw record to the slices.

We agree with the referee that spectral folding is occurring as we separate the raw record into slices. This is now explicitly acknowledged in the text.

Change made. The following text has been inserted below Figure 7:

"Note the presence of narrow spectral content at 20, 40, and 80 Hz in the sliced spectra which are not present on the spectra generated from the raw ADC samples. This is consistent with spectral folding which would be expected as the raw ADC samples are not band-limited via an anti-aliasing filter before the slicing as that would further mix the core saturation states."

p. 10, l. 12-14. "The raw ADC Samples are also sliced into four time series (Slice A-D) corresponding to the four phases of the magnetisation cycle of the core, low pass filtered at 1,000 Hz to remove the second harmonic modulation, and independently detrended to remove the static offset caused by that phase of the magnetisation cycle (Figure 10b)."

During the slicing procedure raw ADC samples are decimated without anti-aliasing. The Nyquist frequency of the sliced time series is 2.5 kHz. So, the signals in the band 2.5-10 kHz generated mostly by the flux-gate mechanism are folded down to the band DC-2.5 kHz. It is hardly possible "to remove the second harmonic modulation" applying 1 kHz low pass filter to the decimated data. The static offset in the sliced time series is one of consequences of the aliasing.

Agreed. As described in the response to the previous comment this frequency folding is an unavoidable consequence of the slicing process. We have added an explicit acknowledgment of how the signals associated with the fluxgate mechanism will be folded into the search coil bandwidth.

The referee's point is well made that the low-pass filter of the sliced data cannot "remove the second harmonic modulation". We have removed that text.

*Change made: The following text was added below Figure 7:*

"This will have the practical effect of folding signals in the 2.5-10 kHz band, mostly associated with the fluxgate mechanism, down into the search coil bandwidth."

Change made: The text "to remove the second harmonic modulation" has been removed from the first paragraph in Section 6.

p. 11, Fig. 10a/b. What is the reason of the 180 degrees phase shift in the responses on the same test signal? If these responses appeared due to the search coil mechanism, how to explain it using the first

term in the Eq. 1. The value of the relative permeability varies significantly during an excitation cycle, but it always remains a positive number. In my opinion, the responses based on the sliced streams are mainly generated by the fluxgate effect and the spectrum folding. The weak dependence of the gain and the noise level on the frequency for the sliced time series (Fig. 11) also supports this conclusion. If so, the results obtained for the sliced streams should be given in the section "Fluxgate Reconstruction".

This is an insightful observation by the reviewer – the permeability varies significantly during the excitation cycle but is always positive so how can it create the polarity inversion / 180 degree phase shift seen in Fig 10. We have re-analysed this data based on the reviewer's comments and agree that the behaviour shown appears to be dominated by the aliased fluxgate signal. We have recreated the figure using data for a 500 Hz test signal where, in Fig. 11, all search coil slices show sensitivity above the flat response attributed the aliased fluxgate signal.
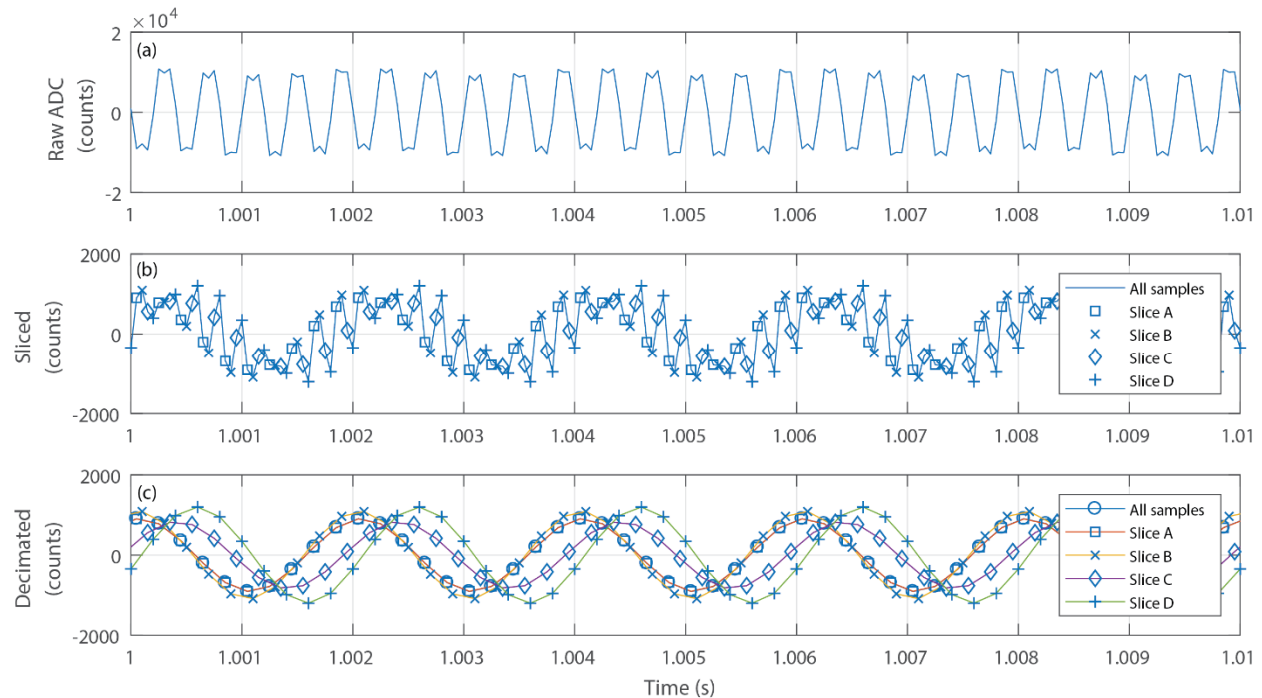
At 500 Hz the reconstructions from all data and from the four slices are more in phase and show variation in gain consistent with various states of core saturation. We suspect that this data is still somewhat contaminated with residual aliased fluxgate signal. However, at higher frequencies the coil response dominates which will also mask the effect of core saturation. The 500 Hz test signal was taken as the best compromise available from the current data showing the effect of core saturation.

Change made. Fig. 10 has been recreated using data with a 500 Hz test signal to mitigate the influence of aliased fluxgate signal. The following text has been added:

"The 500 Hz test signal was selected as it illustrates the region where the magnetic gain of the coil is significant to the search coil effect – above the frequencies where the fluxgate effect dominates and below frequencies where the coil response dominates."

p. 12, Fig. 11, l. 4-7, "A standard figure of merit for search coil performance is the power spectral density noise floor of the instrument (Figure 11b) using quiet data taken inside a magnetic shield normalised by the frequency dependent gain. As expected, the solid mu-metal core provides the lowest noise followed by the unsaturated racetrack core. The air core and the continuously saturated racetrack core provide the poorest result. The un-sliced hybrid search coil path performs between the solid- and air-core limits as expected."

At the linear part of the transfer function (80 – 250 Hz) the gain ratio between the unsaturated core search coil and the un-sliced hybrid search coil is approximately equal to 3.6. Is this value correlates with decreasing of the relative permeability averaged over flux-gate driving cycle in respect with that of the non-driven core? The ratio of the noise levels (expressed in nT/Hz0:5) at 100 Hz for the un-sliced hybrid search coil and the unsaturated core search coil is equal to 5.3. It means that the noise level of the unsliced hybrid search coil could not be explained only by its lower gain. Probably, there are other noise sources including Barkhausen irregularities at cyclical driving of the core. In my opinion, to figure out and to minimize these additional noise sources is the main challenge for successful designing a hybrid flux-gate/search coil magnetometer. Unfortunately, the authors did not apply sufficient efforts in this area.

This is a useful piece of analysis which we have adapted into the manuscript. We agree with the referee the Barkhausen jumps due to the energization of the core are a likely candidate for the additional magnetic noise source. A detailed examination of the potential contributions of Barkhausen noise and the de-energisation of the core is beyond the scope of this proof-of-concept instrument. We have added references to these tasks under future work.

Change made. The following text has been added below Figure 11:

"In the frequency range of ~50-250 Hz, where the search coil gains can be accurately measured but are not yet dominated by the sense coil, the gain ratio between the unsaturated coil and the saturated coil is approximately 3.6. However, the ratio of noise levels at 100 Hz for the unsliced hybrid search coil and the unsaturated racetrack core is larger, approximately 5.3. The noise level of the hybrid search coil therefore cannot be entirely due to lower magnetic gain. This implies the presence of an additional magnetic noise source – potentially Barkhausen jumps due to the excitation of the core."

Change made. The following text has been appended to Future Work:

"Finally, the noise floor of the hybrid searchcoil data implies the presence of an additional magnetic noise source which we speculate may be due to Barkhausen jumps due to excitation of the core. This needs to be confirmed and, if this is the case, the thickness, number of layers, and heat treatment should be explored to see if the core can be engineered to de-energised more rapidly."

p. 13, Fig. 12. It would be very informative to increase the operation frequency band of the flux-gate channel (let say till 1 kHz?) and compare its noise performance with that of the search coil channel. It seems for this case study there is no benefits from the search coil path.

We have expanded the operational frequency band of the fluxgate channel to 500 Hz (1 kHz would have required more invasive changes to the filter/demodulation implementation) and have regenerated all the affected figures to aid in the comparison between the fluxgate and search coil performance.

We agree that, in the current proof-of-concept instrument, the search coil action provides limited practical utility ("modestly superior gain and noise above ~ 1 kHz"). The intention of this manuscript was to assess if it was feasible to simultaneously extract both the search coil and fluxgate actions from a common sensor. As described in the Discussion and Future Work sessions, we anticipate that significant optimization will be required before the search coil action is "operationally useful". We have further acknowledged the current limitations of the hybrid search coil data under Discussion and Conclusion.

Change made. The following text has been added to Discussion and Conclusion.

"At present, the noise floor and sensitivity of the hybrid search coil data is only modestly better than the fluxgate data and only at frequencies above ~1 kHz. In principle, the fluxgate could be operated at higher (kHz) frequencies to provide similar data with only a modest loss in sensitivity. However, since it has been demonstrated that the fluxgate and search coil actions can be extracted separately it may be possible to optimise the search coil behaviour of the sensor to provide high frequency sensitivity and noise floor beyond that which is possible with current fluxgate technology."

Change made. The *operational frequency band of the fluxgate channel was increased to 500 Hz and Figures 5, 8, 9, and 12 and their descriptions have been updated accordingly.*

Technical corrections

p. 3, Fig. 2 caption, "(d) Racetrack fluxgate ring core similar in geometry ..."

Probably, it should be "(d) Racetrack fluxgate core similar in geometry ..."

Change made.

p. 4, Fig.3 caption, "Racetrack foil bobbin used in the magnetometer ringcore for the hybrid magnetometer."

Probably, it should be "Racetrack foil bobbin used in the sensor for the hybrid magnetometer."

Change made.

p. 7, Fig. 6 and l. 4-11. Correspondence between a slice number and an interval in the magnetization loop of the core (saturated, unsaturated, transitions to/from saturation) is unclear, in my opinion. I suggest to give a table, which maps the different phases of the magnetization

loop to the slice numbers.

I assume the following correspondence:

the group A of the slices 1 and 5 - the deep saturation;

the group B of the slices 2 and 6 – transition from saturation to an unsaturated state;

the group C of the slices 3 and 7 – the unsaturated state;

the group D of the slices 4 and 8 – transition from an unsaturated state to saturation.

Is it correct?

As described in the response to the first comment, and now clarified in the text, there is a phase offset between the saturating current observed in Figure 6a and the output of the sensor in Figure 6b/c. The majority of the fluxgate modulation is observed in group B (Slice 2 and 6). We have summarized our inferred core saturation state in a table as suggested.

Change made. The following table has been inserted after Figure 6.

Table 1: Correspondence of Slice Number and Core Saturation State

Group	Slice #	Inferred Core State
A	1 and 5	Unsaturated
B	2 and 6	Entering saturation, fluxgate action observed
C	3 and 7	Recovering from saturation
D	4 and 8	Mostly unsaturated, still somewhat energised

p. 7, Fig. 6 caption, "Drive current into the racetrack ringcore."

Probably, it should be "Drive current into the racetrack core."

Change made.

p. 7, l. 14, "… of the ringcore magnetisation cycle."

Probably, it should be "… of the racetrack core magnetisation cycle."

Change made.

p. 8, Fig. 7 caption, "… of the ringcore magnetisation cycle."

Probably, it should be "… of the racetrack core magnetisation cycle."

Change made.

p. 8, l. 13, "… (2,500 and 5,000 Hz respectively)."

Probably, it should be "… (2,500 and 7,500 Hz respectively)."

Change made.

p. 11, l. 16, "The ringcore is driven …"

Probably, it should be "The racetrack core is driven …"

Change made.