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 #2 on 20 July 2018

We thank the referee for the constructive comments which we have incorporated into the manuscript. Referee #2 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 authors argue to provide a proof-of-concept of a hybrid magnetometer design which is meant to be a fluxgate and a search coil sensor at the same time. The work performed is certainly interesting to the community but strictly speaking, the proof-of concept has not been accomplished. This must be made clear in the abstract and the conclusion. The lack of a feedback circuit, which is essential for a highly linear and stable fluxgate magnetometer, combined with the fact that the search coil mode is just 6 dB better than an air core based sensor make this concept useless even for cubesat applications as long as a science case is missing which could provide the rational for the acceptance of the poor performance ("Search coil reconstruction provides superior gain and noise only above 1kHz").

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."

Specific comments to slicing, filtering and non-linearity:

Slicing is equivalent to decimation of sampled data to sample streams with identical core saturation. This decimation happens without ant-aliasing. Consequently, the resulting 4 data streams (slices) are subject to spectral folding from the original 20 kHz spectrum down to the new sampling frequency of 5 kHz. All distortion, harmonics and noise in the frequency band from 2.5 to 10 kHz is therefore folded into the used spectrum of each of the sliced data sets. This is only somewhat reduced by the first order analog input filter with a cut-off frequency of 5 kHz.

Both, sliced and “all” data sets are subject to different magnetic gains within the core. These gains are time dependent on excitation. If “magnetic data” was directly sampled at the core, one could try to just use the slices that are not subject to saturation to avoid the resulting nonlinearity. Unfortunately, the signal crosses sensor output (RLC network), input amplifier, analog low pass and sampling stage before the digitiser. All of these stages have transfer functions that mix up data from different saturation states unless their combined phase delay is below half a sample. The resulting transfer function has to be considered as nonlinear system with fading memory and cannot be handled easily, if at all.

At the same time, averaging multiple slices means to mix up different gain states which will result in nonlinearity.

This is an excellent description of the mixing of the different saturation states though the transfer functions of the instrument and likely helps to explain the results of the sliced searchcoil data. We have inserted an explanation of the saturation state mixing, based on the referee’s comments, into Section 4 and referenced them in the discussion.

Change made. The following text has been inserted in Section 4 and is now referenced in the discussion:

“If it were somehow possible to sample the magnetic field at the core directly then these saturation states could be accessed independently and without interference. However, since the magnetic field is accessed via its induction of current/voltage in the sense coil, the signal from the different magnetic states must pass through the RLC filter formed by the sense winding, the preamplifier, the antialiasing filter, and the analog to digital converter. Each of these stages has a transfer function which will, to varying degrees, blend the different saturation states unless the combined phase delay of all the stages is below half a sample which does not appear to be the case here. Consequently, the various saturation states are likely somewhat mixed and cannot be separated perfectly. Nevertheless, we will explore treating the various saturation states separately to see if any performance benefit can be gained.”

“However, slicing the data to use only the phase with highest magnetic gain produced a higher instrumental noise floor than simply using all samples – potentially due to the mixing of the saturation states by the combined transfer function of the sense winding and electronics.”

Specific comments to feedback-less operation:

The fluxgate does not include a feedback circuit, but regular operation will presumably require it. Feedback reduces the non-linearity of the fluxgate and a trade-off is required between fluxgate linearity and feedback bandwidth. This means that the fluxgate feedback will certainly have an impact on the search-coil action. A digital compensation by modelling will be needed which drives the complexity of the instrument.

Agreed. As the reviewer notes, all presented data were taken with the instrument operating in open loop. Magnetic feedback will be required for a complete instrument and the search coil action is likely to be particularly sensitive to updates in the magnetic feedback.

Change made. A discussion of the need for and likely complexity of magnetic feedback has been added in the new Section 8.

"All data presented here were taken with the instrument operating in open loop. For most practical applications, magnetic feedback will be required to extend the magnetic range, linearize the instrument, and potentially to provide temperature compensation. In a primarily digital design, such as presented here, this magnetic feedback is typically accomplished using a digital to analog converter to force current either into the sense winding or into a separate feedback winding and drive the field in the sensor towards zero. The range of the instrument is then set by the maximum amount of feedback current, the instrument's linearity is primarily dependent on the feedback circuit, and feedback current can be made temperature sensitive to compensate for changes in sensor geometry (Acuña et al., 1978; Miles et al., 2017). Updates to the fluxgate feedback will undoubtably impact the search coil action, particularly in instruments with high bandwidth feedback used either to maximum instrument linearity or to track rapid changes in the magnetic field such on spinning platforms. Characterisation, modelling, and compensation will be required to correct for the dynamic behaviour of the magnetic feedback. Although compensating for the dynamic behaviour of magnetic feedback is required in most fluxgate magnetometers, the additional search coil action in the hybrid magnetometer is likely to be particularly sensitive which will drive instrument complexity."

Specific comments on noise scales:

The initial assumption is that the core is more or less free of excitation between the pulses. However, Figure 7 shows that the noise floor is much higher for the excitation free slice "C". This is counter-intuitive and requires explanation.

Slice B contains the majority of the fluxgate action, so it seems plausible that, during the following Slice C, the core is still somewhat energized. As the core returns to its unsaturated state, Barkhausen jumps may be contributing to the high noise floor observed in Slice C. We have added explanatory text to clarify the alignment of the slices and comment on the higher noise observed in Slice C.

Changes made. The follow two pieces of text have 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..."

"Slice B contains the majority of the fluxgate action, so it seems plausible that, during the following Slice C, the core is still somewhat energized. As the core returns to its unsaturated state, Barkhausen jumps may be contributing to the high noise floor observed in Slice C."

The noise floor and sensitivity of the search-coil part are only slightly better than the fluxgate part. In principle one could assume that operating the fluxgate sensor up to 3 kHz (page 3, line 11) could deliver comparable results with only a minor loss in sensitivity. The importance of this loss needs to be discussed in the context of potential scientific requirements.

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.*

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Editorial:

It would be of advantage to use the same colour code for the slices in Figure 10 and 11.

Change made. The line colours in Figure 10c now match those used in Figure 11 and elsewhere in the manuscript.