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Interactive comment on "A Hybrid Fluxgate and Search Coil Magnetometer Concept Using a Racetrack Core" *by* David M. Miles et al.

Anonymous Referee #3

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General Comments

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 feed-through signal.

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.

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.

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 flux-gate 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".

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/Hz$^{0.5}$) 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 un-sliced 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.

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.

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 ..."

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."

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?

p. 7, Fig. 6 caption, *"Drive current into the racetrack ringcore."*
Probably, it should be "Drive current into the racetrack core."

p. 7, l. 14, *". . . of the ringcore magnetisation cycle."*
Probably, it should be ". . . of the racetrack core magnetisation cycle."

p. 8, Fig. 7 caption, *". . . of the ringcore magnetisation cycle."*
Probably, it should be ". . . of the racetrack core magnetisation cycle."

p. 8, l. 13, *"...(2,500 and 5,000 Hz respectively)."*
Probably, it should be ". . . (2,500 and 7,500 Hz respectively)."

p. 11, l. 16, *"The ringcore is driven ..."*
Probably, it should be "The racetrack core is driven ..."

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