Response to Peer Review Referee Comments

Response to RC2 comments on “Tesseract – A High Stability, Low-Noise Fluxgate Sensor Designed for Constellation Applications” by Greene et al. made by Hans-Ulrich Auster on May 10, 2022:

We thank the referee for the constructive comments which we have incorporated into the manuscript. Hans-Ulrich Auster raised a few important issues about comparison to other sensors in the literature, which we address below. Referee comments are in plain text our responses in italics and any content added to or changed in the manuscript are in “*quoted italics*”

1. Features of magnetic field experiments on constellation mission are discussed in the introduction. Please add a brief statement, why particularly these applications are used as reference for the new developed magnetometer. An argument could be, that these missions are representative for almost all space born magnetometers; wide range is required (low field at apogee, high field at perigee), exposed to radiation, temperature changes due to eclipse crossings.

The Referee raises an important point about the instruments discussed in the introduction. The constellation missions mentioned in the paper have exposure to a wide range of environmental conditions such as a large range magnetic field strength, abrupt temperature changes and exposure to radiation. One or more of these conditions are characteristic of the environmental considerations that affect magnetometers in most applications in space.

We have added a brief statement to highlight this point on line 31-33 which reads: “Magnetospheric missions are representative of the conditions experienced by many spaceborne magnetometers; they are subject to a wide range of magnetic fields (low field at apogee, high field at perigee), as well as radiation exposure, and temperature changes due to eclipse crossings.”

2. The comparison is made disordered, some parameters are listed for the one, others for the second type of magnetometer. This should be harmonized, may be supported in a table format. Noise, mass, scale value and axis stability vs. temperature shall be given for all of them. All constellation missions mentioned in this paper (Themis, MMS, SWARM) are since many years in space. Long period data for offset and axis stability should be available from inflight calibration. Contact magnetometer PI’s for these data (if not published) and include the inflight measured drifts into your comparison.

We have rearranged in section 1.2 so that the sensor parameters are synergized: Size in mm^3, mass in g, sensitivity over temperature in ppm/℃, orthogonality stability in degrees, and noise in pT/√Hz are listed in order so that comparisons can be more easily made.

Lines 80 – 94 now reads: “Potentially the most stable magnetospheric field fluxgate measurements to date were taken with the Compact Spherical Coil (CSC) Sensor aboard Swarm which implements a nested three axis feedback coil wound on a MACOR shell to create a very homogenous a three-axis null at the location of the cores. From Primdahl and Jenson (1982), we estimate that the CSC’s feedback coils hold their ring-cores in a field that deviates from uniformity by 1.5%. The 100x100x50 mm, 500g CSC sensor has *maintained a sensitivity stability over temperature of 10 ppm/°C and very high axis stability of 0.002 degrees from -20°C to 40°C while achieving a noise floor of 6.6 pT/√Hz at 1 Hz (Merayo et al., 2008).*

The THEMIS mission incorporated a small 70×70×45 mm, 75g fluxgate sensors that achieved a sensitivity stability of 22 ppm/°C, an axes' stability within 0.017 degrees from -100°C to 60°C and a noise of 10 pT/Hz at 1 Hz (Auster et al., 2008). The 42.4×44.3×48.7 mm, 88g Magnetospheric Multiscale Mission DFG instrument achieved a sensitivity stability over temperature of 30 ppm/°C, an an axis stability of about 0.03 degrees between -50°C and 30°C a noise floor of 8pT/√Hz at 1 Hz, (Russell et al., 2016)."

Lines 110 -113 now reads: "One of the best small sensors to date appears to be the Small Magnetometer in Low-mass Experiment (SMILE): a 20×20×20 mm, 40 g cubic sensor based on three rod cores within a three-axis feedback winding, which achieved a thermal sensitivity stability of 11 ppm/°C, an axis stability better than 0.02 degrees from -30 to 45°C, and 30 pT/√Hz at 1Hz (Forslund et al., 2008)."

3. The presented sensor design is impressive. In contrast to the straightforward OERSTEDT/SWARM design (feedback system over three single ringcores) and the more compact THEMIS design (feedback system over crossed ringcores) the cores (racetracks) are accommodated symmetric and identical for all three components. It is made similar to the very innovative Xavier Lalanne design from the 1990th. He placed six ringcores at the six planes of a cube. Please refer to it.

The Authors would like to thank the Referee for bringing this work to our attention. The VM391 magnetometer developed by Lalanne and Chulliat (Chulliat et al., 2009) is a clever sensor design that uses circular, concentric feedback coil geometry with several ringcores placed symmetrically in order to create a sensor with three axis compensation. This design is still used in the ground-based magnetometer community including at many INTERMAGNET ground observatories.

We have added a reference to this work where we discuss previous feedback winding designs. Line 145 now reads: "The idea of more complex feedback winding is not new. Designs such as Primdahl and Jensen (1982), Auster et al., (2008) and Chulliat et al (2009) have used different methods of stacking concentric circular coils to create a three-axis null sensor."

4. Promoting the presented sensor is ok, however, the comparison with a user defined ringcore sensor, which should imply that the presented sensor is much better than ringcore sensors in general is not acceptable. The comparison has to be made with the vector compensated ringcore sensors you have studied in the introduction.

The Authors include this comparison because it illustrates what we think are interesting features such as the effects of sensor asymmetry on sensitivity and orthogonality (Shown in Figure 11). It was not the intention of the Authors to infer that the ringcore sensor that is tested in this paper is representative of a state-of-the-art instrument.

We concur that referring to second sensor tested for comparison in this manuscript as 'the ringcore sensor' creates unintended confusion with sensors discussed in section 1 that use ring-cores. The ringcore sensor tested in this manuscript is the design from Miles et al., (2013). To avoid this confusion with other sensors *that use ringcores, we now refer to the ringcore sensor tested in the manuscript as the 'Miles (2013) ringcore sensor design' everywhere in the text:*

Line 141- 142 now reads: A two-axis null ring-core sensor design based on (Miles et al., 2013) was used in the testing described section 3 and is shown for comparison.

Line 159 now reads: "The Tesseract Sensor's specifications as measured in the laboratory compared with the specifications of a more traditional ring-core sensor design described in Miles et al., 2013. Tesseract is marginally larger than the Miles et al. 2013 ring-core sensor design"

Line 217 now reads: "*Torlon is lighter and much easier to machine than the traditional Inconel ring-core bobbin or MACOR used in Miles (2013)"*

Line 367 now reads: "We performed the same test again, this time using our prototype feedback winding for the Miles (2013) 1" ring-core sensor (Figure 1b)"

Line 374-375 now reads: "The maximum that the measured feedback field deviates from uniformity along the x axis of the Miles (2013) ring-core sensor is 5.62%. The Miles (2013) sensor's feedback windings generate a field the along the center axis of the ring-core that is ten times more inhomogeneous than that generated by the Tesseract sensor."

Line 523 now reads: "The Miles (2013) ring-core sensor design (Figure 1b) was also temporarily configured as an air-core search coil"

Line 529 now reads: "The u_3 *Angle (blue) changes the most, presumably because the Miles (2013) ring-core sensor base is most asymmetric between the Y and Z Axes (Figure 1b)."*

To avoid misrepresenting or overstating the comparison between the two sensors, we have rewritten several lines in the text:

In the abstract, lines 16 and 20, we have taken out comparisons to the 'ringcore' sensor. The section now reads: "The thermal stability of the sensor's feedback windings is measured using an insulated container filled with dry ice inside a coil system. The sensitivity over temperature of the feedback windings is found to be between 13 ppm/°C and 17 ppm/°C. The sensor's three axes maintain orthogonality to within at most 0.015 degrees over a temperature range of -45 °C to 20 °C. Tesseract's cores achieve a magnetic noise floor of 5 pT/√Hz at one Hz."

This paper is a study of the sensor's geometry without cores or driving electronics. The tests described are concerned with of the effect of sensor structure on stability, such as the feedback topology and axis alignment. The sensor is currently in the process of being integrated with cores and flight electronics. The full driven, vector compensated, magnetometer and calibrated results will be discussed in a forthcoming manuscript.

In the introduction we line 53: "Fluxgate offsets are thought to originate primarily from the cores and driving electronics (Ripka et al., 2014), while changes in sensitivity and orthogonality are caused predominately by changes in the geometry of the sensor (Acuna et al., 1978; Miles et al., 2017). In this paper, we are concerned with the stability of the sensor. Factors suspected of degrading a fluxgate sensor's stability include an inhomogeneous magnetic null (Ripka, 1992) and skewing of the axes due to mechanical and thermal strain (Primdahl, 1979)."

5. Quantities are mixed up. It shall be clearly distinguished between stability of offsets, scale values and orthogonality. The vector compensation stabilizes the orientation of the magnetic axis while the offset stability depends on core properties only. Thus, for scale value and axes stability it is fully unimportant which type and geometry of magnetic material is used as core.

We agree with the reviewer that past studies (i.e. Acuna et al., 1978; Petrucha et al., 2015; Primdahl and Jensen 1982) have clearly demonstrated that the stability of the orthogonality is determined by alignment feedback windings that provide vector compensation, while the offset stability depends on cores and driving electronics (Ripka et al., 2014).

This paper is concerned with the sensor and therefore we do not focus on cores, or offset stability, instead we focus on sensitivity (scale value) stability and orthogonality (axis alignment) stability. Once the sensor and the electronics are fully tuned, we plan to extensively calibrate and characterize the full instrument including offset stability over time and offset over temperature.

We have added new text to the introduction of the manuscript to highlight this distinction between offsets, sensitivities and orthogonality and define the scope of the paper in lines 59 – 63: "Fluxgate offsets are thought to originate primarily from the cores and driving electronics (e.g., Ripka et al. 2014), while changes in sensitivity and orthogonality are caused predominately by changes in the geometry of the sensor. In this paper, we are concerned with the stability of the sensor."

And on lines 120 – 122: "An inhomogeneous magnetic null at the cores is thought to contribute to degrading the stability of a fluxgate's offset (Ripka, 1992) sensitivity (Korepanov and Marusenkov 2012) and orthogonality (Petrucha et al 2015). "

We have also made clear the distinctions between sensitivity, orthogonality, and offsets Section 3. In line 364: "Here, we describe a test to measure the stability of the Tesseract sensor's feedback windings over temperature by temporarily configuring it as an air-core search coil magnetometer to directly access the attributes of the sensor base and feedback windings without any dependence on cores or electronics."

In the conclusion (line 448) we have changed the text to "We used a low-cost method to analyze the sensitivity and orthogonality of the sensor over temperature independent of cores or electronics."

6. The analysis of the uniformity of the feedback coils has been intensively discussed. No question, high homogeneity is better than low homogeneity, however in case you want to underline the importance of the uniformity, you have to quantify it. What is the impact on offset, scale value, linearity, and orthogonality behavior really? Particularly racetracks with a significant length/diameter ratio might disturb the uniformity you have hardly achieved by the sophisticated feedback coil design.

We agree with the reviewer that it is important to quantify the impacts of homogeneity on sensor stability. We base this off past experimental studies that have demonstrated that an inhomogeneous feedback field can negatively affect temperature stability of orthogonality and instrumental linearity.

A study by Petrucha et al (2015) determined that in a three-axis null sensor, changing the inhomogeneity of the magnetic feedback by that deviates from average along the core by 1.3%, can alter the measured alignment of the sensor's axes by as much as +/- 0.12 degrees.

Brauer et al (1997) demonstrated that inhomogeneities as little as 1% causes 25 nT deviations from linearity when an uncompensated earth field is applied in a transverse axis.

Several studies have demonstrated that sensors with more homogeneous winding topology are less dependent on changes in the sensor's excitation behavior over temperature, which contributes to sensitivity (Marusenkov 2006) and offset (Ripka 2014) instability over changes in temperature. Felch and Potter (1953) demonstrated that an inhomogeneous feedback field causes a residual out-of-phase cosine signal to appear at the output, that in turn causes baseline to drift. This signal can also leak into the 2f, which in addition to causing offset and temperature instability, could raise the instrumental noise floor. However, these effects are slightly more difficult to quantify because they have a dependance on the magnetization of the core.

We have cited previous work that highlights the importance of feedback homogeneity by adding the following text on line 190: "A homogeneous magnetic null around the cores improves stability over temperature by reducing in dependance of the sensitivity on the temperature dependance of the excitation current (Korepanov and Marusenkov 2012). A study by Petrucha et al (2015) determined that in a three-axis null sensor, changing the inhomogeneity of the magnetic feedback by 1.3%, can alter the measured alignment of the sensor's axes by as much as +/- 0.12 degrees. An inhomogeneous feedback field can also degrade instrumental linearity. Brauer et al (1997) demonstrated that inhomogeneities as little as 1% causes 25 nT deviations from linearity when an uncompensated earth field is applied in a transverse axis."

We agree with the reviewer that disturbances caused by changes in core geometry can affect the stability of fluxgate measurements. This problem can be more pronounced in cores with a large length-diameter ratio such as a racetrack core. According to Marusenkov (2006), if the compensation/feedback field as a function of position length H(z) satisfies the conditions:

$$\frac{1}{l}\int_0^l H(z)dz = H(l),$$

$$\left.\frac{dH(z)}{dz}\right|_l = 0,$$

Where l is half of the effective length of the fluxgate core,

Then small deviations of the length or/and position of the core have practically no influence on the value of the compensation field averaged by core length (Marusenkov 2006). We assert that since the racetrack cores are held in a very uniform homogeneous three axis null (as shown in Figure 4b cores are outlined in maroon), that roughly satisfies these conditions, the length/diameter of the core may not have a significant effect on the stability of the measurement sensitivity. We will investigate this issue in a future manuscript once the cores and electronics have been integrated with the sensor.

7. The authors present a nice sensor with an excellent performance. The only drawback is the mass, which may be a little bit too heavy for constellation missions or small satellites. However, with respect to the mass of boom and harness, a few 100g should be acceptable for the most important part of a magnetic field experiment, the sensor.

The Authors agree with Referees assessment that the Tesseract Sensor is on the heavier side to be accommodated on a small satellite. Tesseract could be a good fit for small-medium scale constellation satellites (missions like the proposed Geospace Dynamics Constellation (GDC) and MagneToRE).

8. The discussion of thermal expansion of the feedback system is not as simple. A high scale value stability of <10ppm/K, achieved by a combination of materials with different expansion coefficients must not be better than a scale value stability of 20ppm/K, if this one is linear over the whole temperature range and has a lower hysteresis. Thus linearity, the reaction on fast temperature changes (e.g. during eclipse) and the hysteresis are criteria which have to be discussed and compared, not the number itself.

We agree with the reviewer that the linearity of the dependance of gain on temperature matters more than the magnitude of that dependance (in ppm/K). We understand that the time varying effective temperature, sometimes described as thermal gradient, is of great interest to the community and has been observed in-situ (Bromund et al., 2021) and in the laboratory (Brauer et al., 1999). We are interested in addressing this issue are currently running an entirely separate set of tests, that are out of the scope of this paper.

In this paper, we focus on thermally homogenous effects. We test this by changing the sensor temperature very gradually (roughly one degree Celsius per hour as shown in Figure 10). However, in an uncontrolled warming there is always the possibly for thermal gradients or transients. We are currently building a new purpose-build testing facility similar to the one used in Magnes et al (1998) that will allow thermal controlled testing environment and limit the possibly for thermal 'gradients', 'shocks' or 'transients'.

We have added text to address the concern of a hysteresis effect due to thermal gradients in section 4.1 from lines 556 – 561: "The accuracy of these measurements is limited by the magnetic noise of the laboratory setup and in an uncontrolled warming there is always the possibly for thermal gradients or transients. A more sophisticated experimental set up will be required to characterize the stability of Tesseract's calibration parameters to an accuracy acceptable for most space science applications (greater than ± 0.1 nT). We are currently developing a new calibration facility at the University of Iowa that will be purpose built for controlled temperature characterization fluxgate sensor's calibration parameters which will incorporate better shielding and limit the possibly for thermal gradients or shocks."