Response to Peer Review Referee Comments

Response to RC1 "Tesseract – A High Stability, Low-Noise Fluxgate Sensor Designed for Constellation Applications" by Kenton Greene et al. by Mark B. Moldwin on May 10, 2022:

We thank the referee for the constructive comments which we have incorporated into the manuscript. Mark B. Moldwin raised an important issue, 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".

<u>Technical Changes:</u>

Line 26: Change made. Text now reads: "Constellation satellite missions to have an important role in the future of space plasma science."

Line 27: Change made. Text now reads: "The NASA Heliophysics Science and Technology Roadmap for 2014–2033, states a driver of scientific discovery will come from a constellation mission of 30 or more spacecraft (Heliophysics Roadmap 2014)."

Line 29: Change made. Text now reads: "Space Technology 5 (ST-5) (Slavin et al., 2008), Time History of Events and Macroscale Interactions during Substorms (THEMIS) *(Auster et al., 2008) and The Magnetospheric Multiscale Mission (MMS) (Torbert et al., 2016)"*

Line 276: Change made. Text now reads: "Prototype #1 was lowest power consumption configuration; Prototype #2 was the lowest inhomogeneity and Prototype #3 was chosen for a balance of low inhomogeneity and low power consumption."

<u>Specific Comments</u>

1. Define "Stability" here. In Abstract the 2nd half discusses thermal stability. Also differentiate between what is examined here and long-term gain and offset stability. The other issue of thermal stability is assumed here is that the gain is linear with temp and that the 'test' field is Earth field of 60000 nT to get units of ppm/C. Can (nT)/C also be given?

The reviewer raises the important point that there are different ways to quantify stability. Fluxgate Stability is often described in terms of the stability of its individual calibration parameters: offset, orthogonality, and sensitivity. These parameters can change over temperature but can also drift over time (with a constant temperature). In the context of magnetospheric applications, stability is sometimes defined in part per million (ppm) of the total measured field.

In this paper, we focus on the stability of the sensor itself. The stability of a fluxgate instrument's sensitivity and orthogonality is determined primarily by the structural stability of the sensor (Acuna et al., 1978; Miles et al., 2017).

The stability of the instrumental zeros or offsets (nT/C) is also important to evaluating the overall stability of a fluxgate; however, the changes in offsets are thought to come primarily from the changes in cores and driving electronics over temperature rather than changes in the sensor itself (Ripka et al., 2014). We are *currently in the process of integrating the electronics and cores with the sensor base and will address the offset stability of the Tesseract Magnetometer in a future manuscript.*

We have added context to clarify this on line 44: "Fluxgate magnetometers do not measure the magnetic field absolutely and therefore must be calibrated in order to make absolute measurements. However, the calibration parameters, sensitivity, orthogonality and offset, vary with changes in sensor temperature or over time. Fluxgate stability is the degree to which these calibration parameters remain constant."

In line 46 we have added a distinction between Sensor stability and core/electronics stability: "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. In this paper, we are concerned with the stability of the sensor."

2. Is the Ripka result with respect to thermal stability of gain or long-term stability of the gain at a given temp or both? I couldn't find in a quick read of the paper.

The Ripka 1992 review article states that inhomogeneity of the feedback magnetic field could be one of the causes offset drift. Here is the link to a quick read of the paper: https://doi.org/10.1016/0924-4247(92)80159-Z

In addition to offsets, inhomogeneities in the feedback magnetic field has been shown to effect the stability of sensitivity or coil constant (Korepanov and Marusenkov 2012) and orthogonality (Petrucha et al 2015)

We have also made the following changes to clarify this at line 112: "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)."

3. Are there other examples that used a Merritt coil for the nulling with fluxgates or is this the first use?

The only other example of a Merritt coil feedback topology used for a fluxgate that the authors are aware was by Petrucha et al., (2015). They built a bench top prototype of sensor laboratory prototype that used a Merritt coil feedback winding and two ring geometry cores. However, limited by the ringcore geometry, Petrucha et al., (2015) places the ringcores asymmetrically inside the Merritt coil. As a result, the cores immersed in a field that is inhomogeneous by as much as 8%.

Tesseract is the first to use of a Merritt coil feedback windings that uses the racetrack core configuration (shown in Figure 3). This combination of Racetrack geometry cores and Merritt Coil feedback topology has the advantage of keeping the cores in a very homogenous region (shown in Figure 4b) and ease of manufacturing. Tesseract's design draws inspiration from the aforementioned SMILE sensor (Forslund et al., 2008), which used three equally spaced square feedback coils and a parallel rod sensor in each axis to create a miniature cube-shaped, three axis nulled sensor.

We have added a more detailed background of previous feedback winding designs on line 108: "The idea of more complex feedback winding is not new. Designs such as Primdahl and Jensen 1982 and Chulliat et al., 2009 used stacked circular coils to create a three-axis null. A study by Petrucha et al., (2015) experimented with a laboratory prototype sensor that used a Merritt coil feedback topology with ring *geometry cores. Tesseract's design draws inspiration from the aforementioned SMILE sensor (Forslund et al., 2008), which used three equally spaced square feedback coils and a parallel rod sensor in each axis to create a cube-shaped, three axis nulled sensor."*

4. Have you ran a test to verify or is the surmise really based on previous work suggesting homogeneity is important? Does small gradient have any impact on sensitivity/noise or only temp stability?

We base this hypothesis off of past experimental studies (i.e Korepanov and Marusenkov (2012); Ripka (2014); Marusenkov (2006)) that have demonstrated that sensors with more homogeneous winding topology have less dependence on changes in the sensor's excitation behavior over temperature, which contributes to temperature instability.

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 temperature instability, could raise the instrumental noise floor.

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 along the core by as little as 1.3%, can alter the measured alignment of the sensor's axes by +/- 0.12 degrees. Brauer et al (1997) demonstrated that inhomogeneities as little as 1% causes large 25 nT deviations from linearity when an uncompensated earth field is applied in a transverse axis.

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 along the core 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."

5. Have you demonstrated that the configuration is better than just three cores? (or is 'expected based on previous research that can be cited?

The authors have not demonstrated this experimentally. Cores with shape anisotropies that have opposite polarities like that of the rod core fluxgates have been shown to produce smaller stray fields, than ring-core geometry fluxgates (Ripka and Billingsley 2000). The authors hypothesize that shape anisotropies and symmetry of the Tesseract's two cores per axis with opposite polarities will further suppress stray fields that can cause cross-axis contamination.

We have changed the language to clarify in line 150-151: "We hypothesize that pairing of identical cores with opposite polarities in each axis may further reduce the tendency for cross-axis contamination due to mutual cancellation of their stray fields (Ripka and Billingsley 2000)."

6. What is the notional average magnetic field created by the 20-mA current?

For the engineering model Tesseract sensor (Prototype #3 in section 3.1.2) the field generated by the 20-mA current was ~190,000 nT. The field was intentionally large so that small differences (Inhomogeneities) would be easily resolved.

A change was made on line 282. The text now reads: "Each prototype sensor was placed within a single axis solenoid within a three-layer mumetal magnetic shield and constant current of 20 mA was applied to the feedback windings creating a magnetic field of about 190,000 nT"

7. It should be clearly stated that the temperature dependence you are looking at is on the "structure" and not the cores and electronics in the conclusions.

The reviewer makes a very important point. This paper is concerned with the stability of the sensor's structure alone independent of the effects of cores and electronics. Changes in the sensor structure are thought to be a primarily cause of instability of sensor orthogonality (Acuna et al., 1978) and sensitivity (Miles et al., 2017) over temperature. Therefore, in this paper, we focus on temperature dependence of the geometry of the sensor (sensitivity and orthogonality over temperature).

We are currently in the process of integrating the electronics and cores with the sensor base and will characterize their effect on the stability of the Tesseract Magnetometer in a future manuscript.

We have added this clarification in several places to highlight the importance of this distinction:

In the introduction; lines 59-63: "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."

At the end of line 335: "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 425) we have changed the text to "We used a low-cost method to analyze the gain and orthogonality of the sensor over temperature without any dependance on cores or electronics."