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Discussions

Tri Axial Square Helmholtz Coil system at the Alibag Magnetic Observatory: Upgraded to Magnetic Sensor calibration facility

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Abstract. A Tri Axial Square Helmholtz Coil system for the study of palaeomagnetic studies was successfully commissioned at the Alibag magnetic observatory in the year 1985. This system was used for few years after which the system encountered technical problems with the control unit. Rectification of the same could not be undertaken as the information document related to this system was not available and as a result the said system had been lying in an un-used state for a long time until 2015 when the system was re-commissioned and upgraded as a test facility for calibrating the magnetometer sensors. We have upgraded the system with a constant current source and a data logging unit. Both these units have been designed and developed in the institute laboratory. Also re-measurements of the existing system have been made thoroughly. The upgraded system is semi automatic, enabling non-specialists to operate it after a brief period of instruction. This facility is now in broad use for the parent institute and external institutions to calibrate their magnetometers and also serves as a national facility. Here the design of this system with the calibration results for the space borne fluxgate magnetometers is presented.

1 Introduction

The Helmholtz coil system which is a useful laboratory technique is normally used to generate magnetic field levels of specified volume and uniformity. These coils provide accurate means to perform numerous experiments and testing functions that require a known ambient magnetic field. The field generation can be either static, time-varying DC or AC or depending on the applications requirements. Typical applications include magnetometer calibration, magnetic compass calibration, satellite characterization and bio-magnetic studies (D. Herceg, A. Juhas and M. Milutinov, 2009). Square Helmholtz coils can be utilized instead of circular Helmholtz coils in the design as they provide a wider uniform field parallel to the coils as compared to circular coils. The governing equation for the magnetic field B at the center point of a square coil pair is

$$B = \frac{2\mu_o NI}{\pi a} \frac{2}{(1+\gamma^2)\sqrt{2+\gamma^2}} \tag{1}$$

Where μ_o is the permeability of the vacuum, 4.95e-5 Tesla-in/Amp, *N* is the number of wrappings, *I* is the current passing through the coils, *a* is half the length of a side of the coil, and γ is the ratio of the distance between the two coils *2b* and the length of the side of a coil *2a* as shown in Figure 1. In order to achieve a homogeneous field at the mid-point of the square Helmholtz coil pair γ is 0.5445 which is Helmholtz spacing ratio. Eqn. 1 relies on the coils being orthogonal, centered, and

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properly spaced. "If the coils are not properly spaced, a profile similar to that of Figure 2 is achieved" (M. Brewer, 2012).

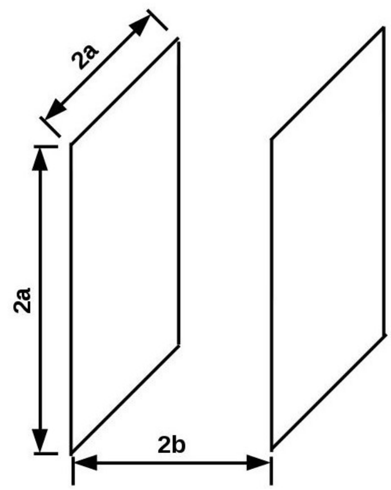

Figure 1. *Square Helmholtz Coil Pair.*

Square Helmholtz Coil utilize 2 pairs of square Helmholtz coils or 3 orthogonal pairs of Helmholtz coils which permits 3-axis control of a magnetic field within the coils. This configuration of 3 orthogonal square coil pairs is often referred to as a "Helmholtz cage". Commercial cages are manufactured by Bartington Instruments Limited (Bartington), Serviciencia and Macintyre Electronic Design Associates, Inc. (MEDA). Several universities have built Helmholtz cages to develop and test sensors for space applications. Also the Naval Post Graduate School (NPS) in Monterrey, CA, the University of Michigan (U-M) in Ann Arbor, MI (A. Klesh, S. Seagraves, M. Bennett, D. Boone, J. Cutler and H. Bahcivank, 2010), and the Delft University of Technology in the Netherlands (F. Poppenk and R. Amini, 2006; F. Poppenk, R. Amini and G. Brouwer, 2007) all have built Helmholtz cages (M. Brewer, 2012).

One such Helmholtz cage for the study of palaeomagnetic studies had been commissioned at the Alibag Magnetic Observatory in the year 1985. After few years of operation this system encountered technical problems associated with the feedback mechanism of the closed loop system and had to be abandoned. This being a Square Helmholtz coil system we realized its importance for calibrating ground and space based magnetometer sensors and with this purpose the said system was re-designed by introducing a Constant Current Source (CCS) and a Data Logger. Also all the technical parameters of the system were re-calculated. This compact unit is now referred as the Tri Axial Square Helmholtz Coil System. This system generates uniform, accurate and precise magnetic fields in a volume about the center of the coil system and is serving as a calibration facility for both space and ground borne magnetometer sensors. The schematic of the system is shown in Figure 3.

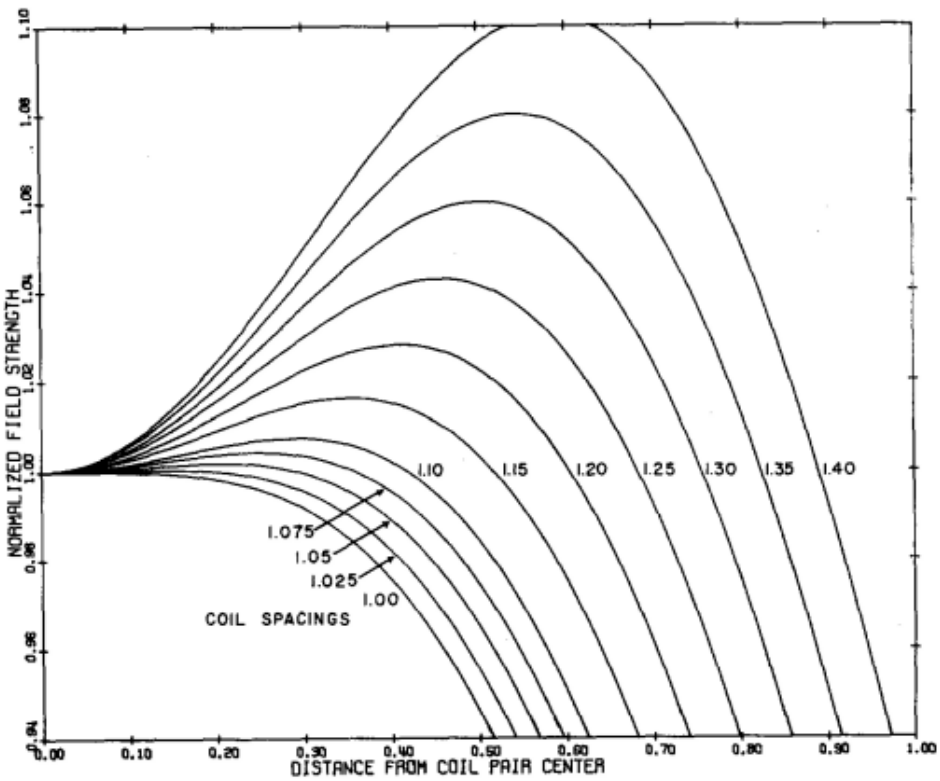

Figure 2. *Magnetic Field Uniformity for a Circular Coil (M. Rudd and J. Craig, 1968).*

2 Description of the Tri Axial Square Helmholtz Coil System

The Tri Axial Square Helmholtz Coil System (cage) here is a three component device using three pairs of square field coils to produce homogeneous magnetic field in the working space in the center of the system. The individual coil pairs are spaced to fulfill the familiar Helmholtz condition that the second-order derivative of the field produced along the axis of the coil pairs is zero at the pair centre. This appropriate spacing of the square field coils is 0.5445 of the side of the square. These dimensions provide optimal uniformity over a region. This system yields a working space volume of approx. 5 liters (considering a cubic sensor of 17 cubic cm) with max. ±2 nT homogeneity deviation and is realized by using the square-shaped coils of 2-2.5 m size. The coils are supported by a borosilicate glass piping construction to electrically isolate the coils from the support structure. The primary glass support structure at the end corners is joined using a female square design 6 way cross aluminum connector to which a Bakelite bracket is fixed using a nut and a bolt. Borosilicate glass is selectively chosen as it possess outstanding corrosion resistance and low coefficients of thermal expansion. The piping appears clear and color less as borosilicate glass shows no appreciable absorption in the visible region of the spectrum (Borosilicate). The coefficient of thermal expansion of aluminum (Aluminum) is less than that of borosilicate glass as a result the corners remain to be intact for years. The Bakelite bracket is a triangle quarter round and each quarter radius is 149.86 mm and 124 mm thick. This bracket is used for rolling the

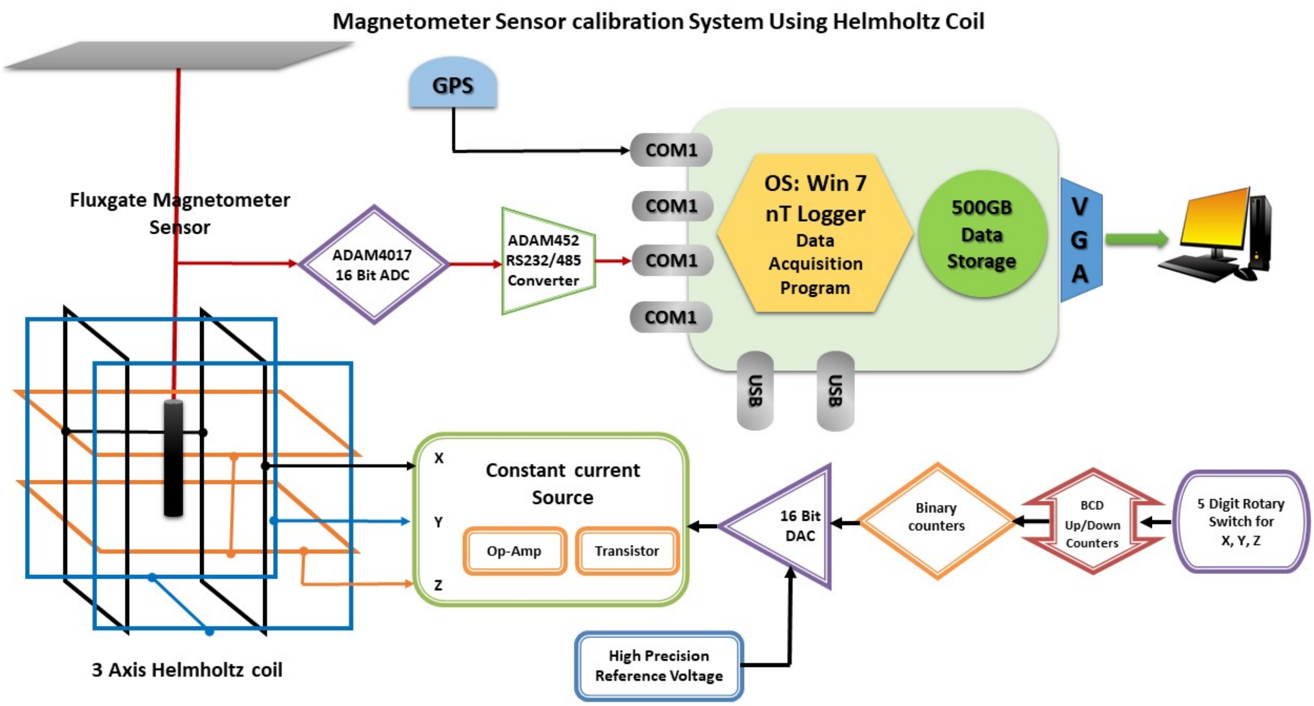

Figure 3. *Schematic of the re-designed Helmholtz coil calibration facility.*

coil at the edges and ensures additional stiffness at the edges. Additional strength to the primary glass assembly is provided by implementing a triangular structure design where the apex of the triangle joins the corner most edges and the three corners of the base meet the adjacent sides of the primary glass frame Figure 4. Also thin Bakelite blocks for holding the coils have been fixed to the support frame using a strong adhesive. These serve as an intermediary between the coil and the support frame and are uniformly spaced all along the length of the frame. Such a construction design yields a cage that ensures stability of the system geometry independent of the environmental parameters and time. The diameter of the primary glass tube is 172 mm and for the glass tube implemented in the triangular structure is 146 mm. The surface area of the aluminum connector is 2053.5 cm^2. Bakelite is used for its electrical non conductivity and heat-resistant properties (Bakelite).

The coils consist of 12 AWG copper wires wound to attain the shape of a cuboid. The wind is parallel to the length of the cuboid. The thickness of the wound is 127 mm. The wires are laid in neat rows so that the magnetic field is completely perpendicular to the flow of current. There are 2 such electrically isolated windings in each coil. However the number of turns was not known. The final coil is wrapped with an insulation of 0.7 mm thickness. The outermost coil is a pair of coils and is perfectly a square of area 62500 cm^2 (a = 250 cm). The spacing between the pair is 136 cm. The inner pair is also a square with area of 40000 cm^2 (a = 200 cm) and nests within the outer coil. The spacing between the pair is 110 cm. The innermost pair is again a perfect square of area 50625 cm^2 (a = 225 cm) with 123 cm spacing between the pair and nest within the other

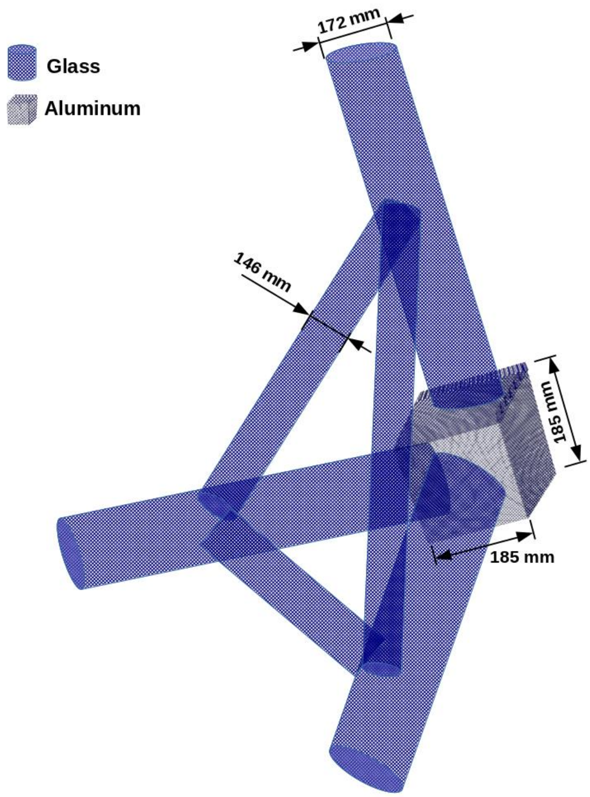

Figure 4. *Triangular structure design at the corners ensures additional stiffness at the corners of the cage.*

two coils. The wrapped coils were installed into the cage in a certain orientation based on several factors. First and foremost was the consideration of the ambient magnetic field at the proposed cage location. The geomagnetic field is commonly defined with +X pointed North, +Y pointing East, and +Z pointing down. The cage axes were selected to match this definition (Brewer, 2012). The coils controlling the Z axis are the largest coils. The next consideration involved the X or North component of the ambient magnetic field which is larger than the Y or East component. If the direction of the X component needed to be reversed a higher magnitude magnetic field would be required than that required to flip the Y direction magnetic field. Larger magnetic fields are generated by smaller coils thus the smallest coil was selected to control the X direction. Therefore, the remaining middle sized coil controls the Y direction (Brewer, 2012). The final cage is shown in Figure 5.

3 Tri Axial Square Helmholtz Coil System: Control and data Acquisition

The system includes a Constant Current Source (CCS) and a Data Logger. The CCS which has been developed in house is an electronic unit which feeds ultra stable and accurate current to coil by which a known and stable magnetic field is generated.

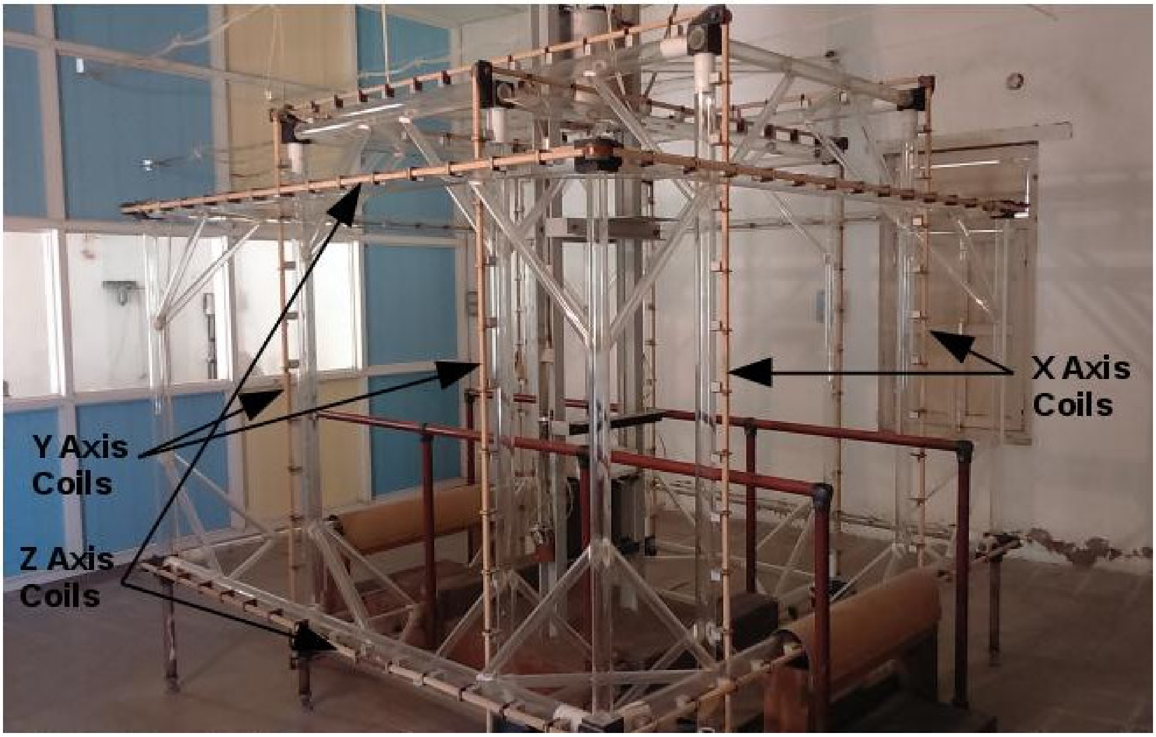

Figure 5. *Tri Axial Square Helmholtz Coil calibration facility at Alibag Magnetic Observatory.*

This magnetic field is then sensed by the magnetometer and logged into data logger. The CCS is designed to provide current at a stability and resolution of 10 μA. It can supply a maximum of 1A current to the coil which can produce enough magnetic field to calibrate any magnetometer (Fluxgate, Proton Precession Magnetometer, Overhauser etc) with the range of nT to mT. The CCS mainly consists of 3 components of which DAC LTC1657 is the key component providing ultra stable current. LTC1657 is a Parallel 16-Bit Rail-to-Rail Micro power DAC, and provides an ultra stable analog voltage output for the given 16-Bit digital inputs. LTC1657 is chosen because of its very low deglitched voltage output of 8nV max and Differential Non-Linearity (DNL) of $\pm$1LSB max (refer data sheet of LTC1657). The other useful feature of LTC1657 is the stable internal reference voltage and internally buffered output voltage that makes this IC very appropriate for our application. The second key component is the op-amp LT1014 and 2N3055 power transistor. These deliver a constant current to the coil system. The 2N3055 power transistor is NPN silicon with high power rating with very low temperature drift. The op-amp and transistor configuration makes very accurate constant current source whose input is fed by the DAC. The third component is the digital inputs feeding to the DAC. It comprises of 5 digit rotatory BCD switches for human input to set current value, CD4510 presettable up/down counters and CD4040 ripple binary counters. The CCS circuit operates on a stable $\pm$12V DC supply, although a few of the integrated circuits (ICs) work on +5V DC which is provided by the main +12V supply through a +5V voltage regulator. It is very important to have a high quality ground for this circuit to work efficiently. Here ground noise is kept below 1mVpp. There are 3 electronic boards for each coil of Helmholtz coil system and all 3 are identical in design. Provision is made to reverse the current in all the 3 coils by using a 2 pole 2 way toggle switch. This enables the CCS to generate magnetic field in every possible direction in the coil and thus calibration accuracy improves.

4 Calibration of the Fluxgate magnetometers using the Open Loop Tri Axial Square Helmholtz Coil System

Very precise Earth magnetic field measurements in space have been made using fluxgate magnetometers in combination with scalar magnetometers (G. Musmann and Y. Afanassiev, 2010) but only a few detailed descriptions about the theory and how to design and calibrate space fluxgate magnetometers have been published. The goal of this experiment was to determine whether the fluxgates can be calibrated using this system or not. The fluxgate sensors under test referred to as the EUT (Equipment Under Test) is a triaxial fluxgate magnetometer procured from Watson Industries Inc., 3035 Melby St., Eau Claire, WI 54703, USA (Watson Industries, 2015). The sensor is mounted on a non-magnetic table referred to as the test stand which is placed at the centre of the Helmholtz cage. The test stand is made out of non magnetic material and can be adjusted to various heights using a spirit level of 6 sec sensitivity. The sensor is mounted so that sensor axes are aligned along H, D and Z directions. Using a CCS (Constant Current Source) the magnetic fields along the 3 directions can be varied. A set of measurements is tabulated by passing currents ranging from 50 mA to 500 mA through one of the coils in the forward and reverse directions. The input field in nT is calculated by the following formula. Similarly the other 2 components can be calibrated.

$$\text{Input Field} = \text{Initial Field} + (\text{Input Current} \times \text{Coil Constant})$$

The fluxgate provides all three axes of magnetic field data as analog voltages in the range of ± 10V o/p which corresponds to $\pm 60{,}000$ nT (Since 1V $\Rightarrow$ 6,000 nT). This o/p is fed to a data logger referred to as the nTLOGGER. ADAM-4017 which is a part of the nTLOGGER which is a 16-Bit commercially available A-D converter converts inputs from 3 fluxgate sensors to digital form. It gives a resolution of ± 4 nT. The nTLOGGER is a Dual-Core Intel Atom processor based small size data acquisition computer equipped GPS timing module developed in-house. It runs on a Windows operating system, containing the LabVIEW based nTLOG data acquisition program. Since the o/p of ADAM-4017 is in RS-485 format it is converted in to RS-232 format by using ADAM-4520.

Figure 6, Figure 7 and Figure 8 shows the comparison plots of input field and the measured field obtained for the three different coils and for one particular sensor. These results confirm that the field measured by the sensor is in agreement with the input current (input field) with a difference of few nT at small currents and increasing to $\leq$ 100 nT at higher inputs. This behaviour is attributed to the sensor alignment at the centre of the cage. The similar trend is seen in 3 more sensors.

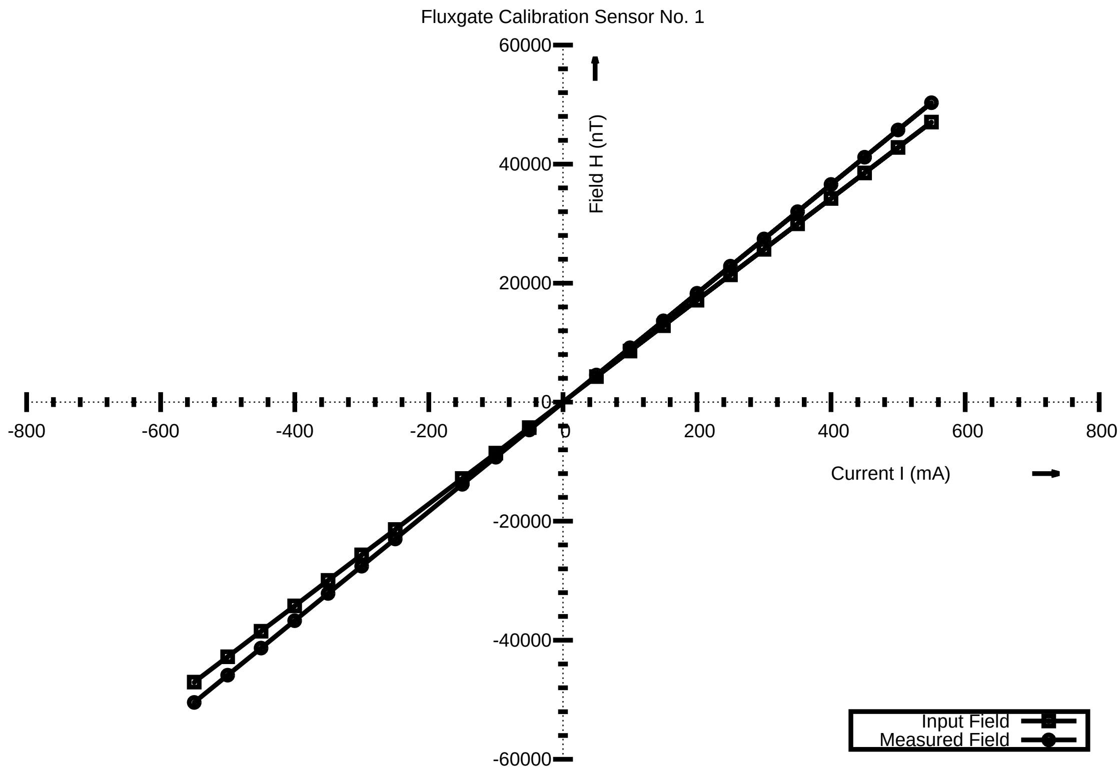

Figure 6. *Fluxgate calibration using H Coil.*

5 Conclusions

The measured fields in the cage volume are influenced by the natural variations due to the geomagnetic field. This system being an open loop system has no feedback mechanism for the cancellation of these variations. To negate the effects of these geomagnetic fields a closed loop system has to be implemented. We are in a process of designing such a closed loop mechanism. Further the mechanical structure of a tri axial system necessarily becomes rather complicated, and the systems described so far have a tendency to be heavy and bulky. This problem is believed to be overcome by a compact spherical coil system. We are also in the design stage of the Circular Helmholtz Coil system.

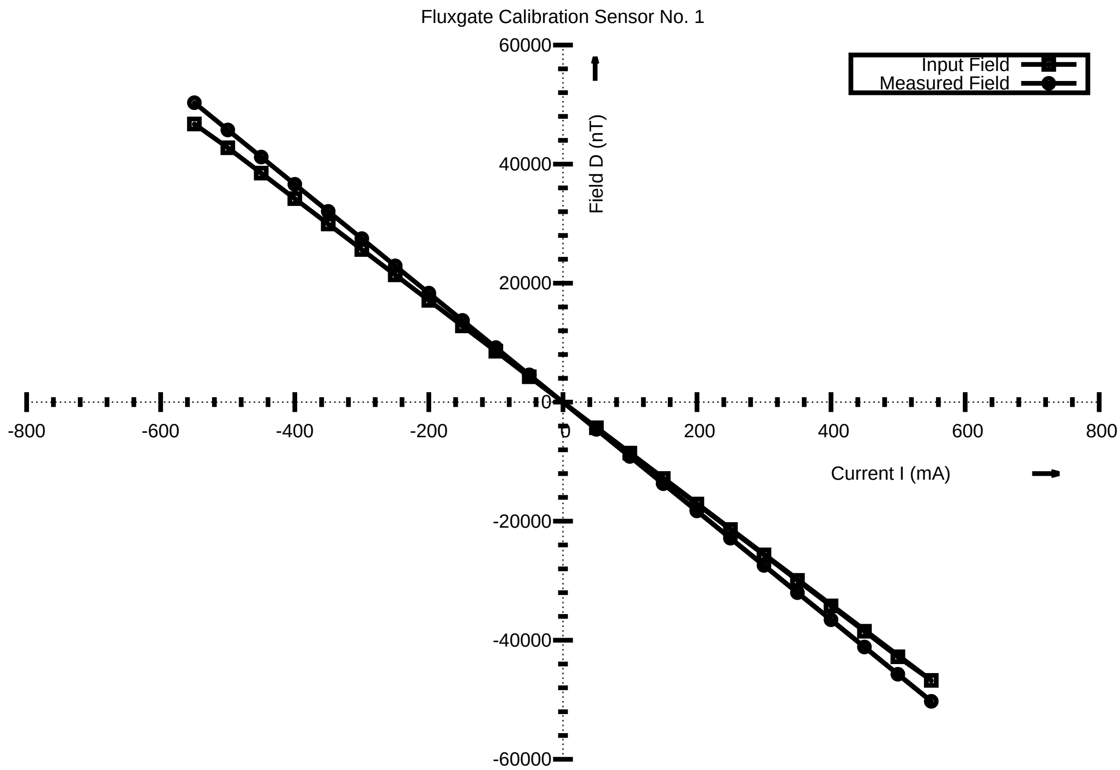

Figure 7. *Fluxgate calibration using D Coil.*

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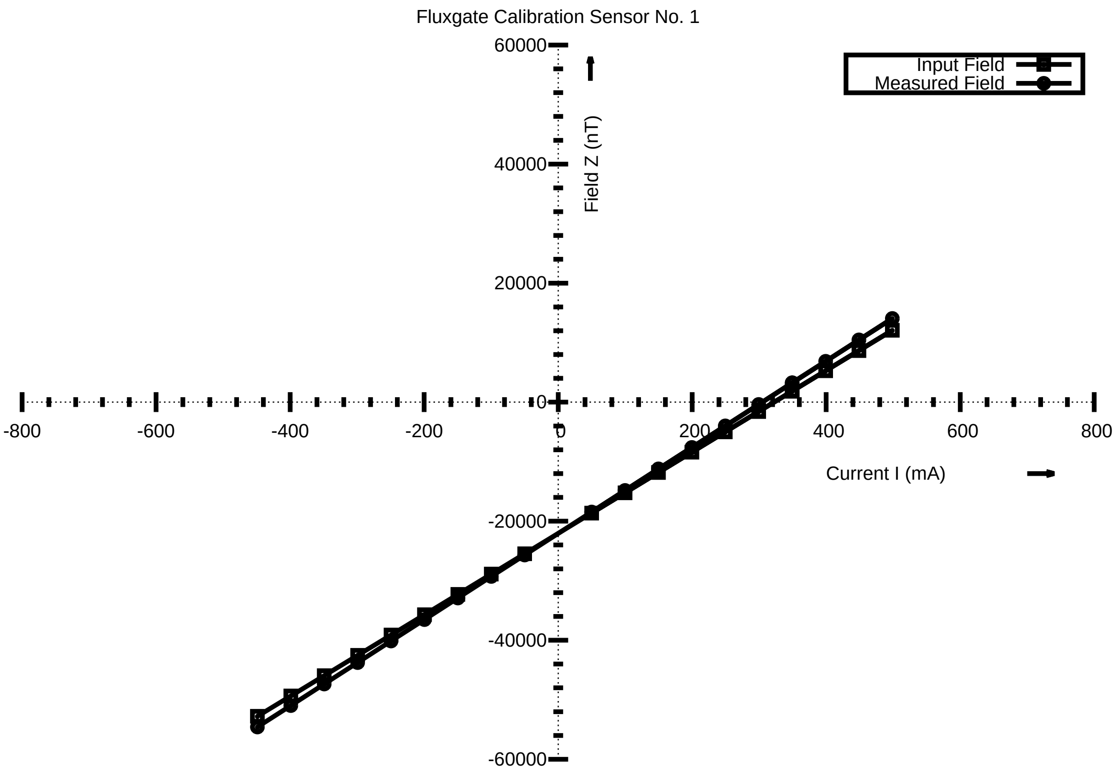

Figure 8. *Fluxgate calibration using Z Coil.*

References

D. Herceg, A. Juhas and M. Milutinov, "A Design of a Four Square Coil System for a Biomagnetic Experiment," *Facta universitatis - series: Electronics and Energetics*., Vol. 22, no. 3, pp. 285-292, Dec. 2009.

M. Rudd and J. Craig, "Optimum Spacing of Square and Circular Coil Pairs," *Review of Scientific Instruments*., May, 1968.

Bartington Instruments Limited. [Online]. Available: www.bartington.com/Literaturepdf/Datasheets/DS2613%20Helmholtz%20Coil%20System.pdf

Macintyre Electronic Design Associates, Inc. [Online]. Available: www.meda.com/Catalog/hcs-01%20data%20sheet54.pdf

A. Klesh, S. Seagraves, M. Bennett, D. Boone, J. Cutler and H. Bahcivank, "Dynamically Driven Helmholtz Cage for Experimental Magnetic Attitude Determination," in *Proc. Advances in the Astronautical Sciences*, Vol. 135, pp. 147-160, 2010.

F. Poppenk and R. Amini, "Delfi-C3 Control System Development and Verification," in *Proc. 57th International Astronautical Congress, Valencia, Spain*, pp. 1-9, 2006.

F. Poppenk, R. Amini and G. Brouwer, “Design and Application of a Helmholtz Cage for Testing Nano-Satellites,” in *Proc. 6th International Symposium on Environmental Testing for Space Programmes, Noordwijk, The Netherlands*, pp. 1-9, 2007.

[Online]. Available: http://www.goelscientific.co.in/Borosilicate-Glass.php

Peter Hidnert, “Thermal Expansion of Aluminum and various important Aluminum Alloys,” [Online]. Available: http://nvlpubs.nist.gov/nistpubs/ScientificPapers/nbsscientificpaper497vol19_A2b.pdf

[Online]. Available: https://en.wikipedia.org/wiki/Bakelite

M. Brewer. (2012, March). Master Thesis: Cubesat Attitude Determination and Helmholtz Cage Design. Air Force Institute of Technology, Air University, U.S. [Online]. Available: http://www.dtic.mil/dtic/tr/fulltext/u2/a557488.pdf

G. Musmann and Y. Afanassiev, *Fluxgate Magnetometers for Space Research*, ISBN 978-3-8391-3702-4, Herstellung und Verlag, January 26, 2010.

Watson Industries. [Online]. Available: http://watson-gyro.com/wp-content/uploads/delightful-downloads/2015/06/fluxgate-magnetometer-FGM-301-spec.pdf