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Dynamically driven a Helmholtz cage for ground testing of attitude determination and control system (ADCS) of nanosatellites

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Abstract

ADCS is one of the subsystems of nanosatellites that goes through ground testing before launching. By emulating magnetic fields experienced by nanosatellites in their orbits is modelled by a Helmholtz cage made of three pairs of orthogonally connected Helmholtz coils. The magnetic field in a certain orbit was modeled by implementing algorithms using the World Magnetic Model (WMM) in MATLAB (2018b). Using MATLAB Aerospace Toolbox, implemented algorithm acquired the orbit's magnetic field as components in 3-axes which could be assigned to the three sets of coils in the Helmholtz cage. One of its three coils was selected and supplied a current through an Arduino-based driver. The resulting magnetic field at the center of the coil was measured by Honeywell's HMR2300 magnetometer by increasing pulse width. Using this data, a relationship between pulse width and the created magnetic field was obtained. For modelling the orbital magnetic field inside the cage, the magnetic field experienced by a Nanosatellite in its orbit was calculated using the implemented algorithm by taking a Two-Line Element (TLE) dataset. The pulse widths related to the magnetic field values in one particular axis throughout one period of the Nanosatellite were calculated using the derived relationship and the related current variation was applied to the corresponding coil. The magnetic field created by the coil was measured and plotted. The plotted expected magnetic field variation and the experimentally implemented magnetic field variation are fairly similar and within the range of the Earth Magnetic Field. While the theoretical variation was smooth, the experimental variation had discontinuities.

Keywords: ADCS, Helmholtz cage, Nanosatellites, TLE, WMM

Introduction

An artificial satellite is an object that has been placed into an orbit with a purpose. Since 1957, the first artificial object place in orbit around the earth, thousands of various artificial satellites are sent to space for different purposes such as Earth observation, communication, Navigation, weather and disaster detection, Telemedicine, Space telescopes, Space station and etc. (Theoret, 2016).

When a Nanosatellite is launched into an orbit, it rotates about its centre of gravity called "tumbling" which is a 3-axis spinning around its centre caused by gravitational forces acting on the antennas and satellite body and the disturbances created by magnetic fields. Due to tumbling, satellites are unable to perform their duties effectively. To prevent this, a subsystem called Attitude Determination and Control System (ADCS) was introduced to satellites to detumble itself to perform their missions with accuracy. Within the shortest period, the detumbling process must be arranged to steady the satellite according to the mission. So, to determine the satellite's attitude, the ADCS system consisted of sensors that gather data on the orientation of the satellite. One of those onboard sensors is a magnetometer which collects 3-axes real-time data of the Earth Magnetic Field (EMF) of a satellite's orbit. Implementations have been done to control the detumbling of Cube satellites (CubeSats) since their capabilities differ from bigger satellites. B-Dot Algorithm is such an implementation to determine the angular rate of the satellite and detumble it using three orthogonal magnetic torquers which produce electromagnetic fields to stabilize the deviation of the satellite after orbital insertion by passing a current through each actuator coil (Regulinski, 1962 & Want 1998).

Within the last decade, CubeSats got popularized over bigger satellites due to lower cost, a shorter period for fully building and testing. But the problem is not having a facility to investigate the performance of real-time 3-axes magneto torquers for the ADC System within Sri Lanka. So, this ADCS of CubeSats must go through a ground-testing before it is launched into the actual orbit. Therefore, a system that is capable of simulating a uniform region of a magnetic field that the satellite will be experiencing in its orbit should be built for ground testing.

The specific objectives are to generate a real-time on-orbit magnetic field for any CubeSat anywhere at any time using MATLAB coding and Simulink as well as to power up the cage and supply the current as a Pulse Width Module (PWM) to the X-coil of the Helmholtz cage through the driver circuit and compare the theoretical values and experimentally implemented values.

This research was carried out for a RAAVANA – 1, which was launch to space by Sri Lanka in 2019. It's a 1U CubeSat which has a 10 cm length on each side. The Biot-Savart law implies that the radius of the coils, and the distance between the coils, is proportional to the size of the magnetic field volume that should be produced. Therefore, a cubic contact magnetic field of 20 cm on each side of the volume was necessary to be generated to cover the whole volume of the CubeSat and more.

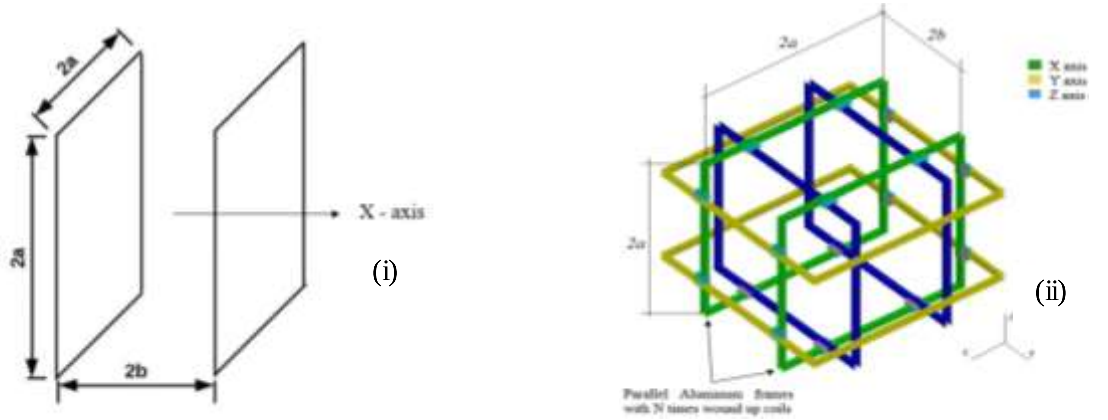


Figure 1. *(i) X-axis square Helmholtz coil pair (ii) The Helmholtz cage design (Cayo 2019)*

When there is a pair of identical circular magnetic coils parallel to each on the same axis, the setup of these coils is called the Helmholtz coil pair proposed by the German physicist Hermann von Helmholtz (1821-1894). Instead of a plane magnetic field, they generate a uniform volume magnetic field along the axis (Theoret, 2016). A wider uniform field can be generated by utilizing square coils instead of circular coils (Regulinski, 1962 & Want

1998). And it got greater central accessibility and the computations of the field are easier than circular coil pairs (Want 1998).

By using the traditional form of the Biot-Savart law, the scale of applicability was broadened up while implementing it to the Helmholtz Cage. So, a Helmholtz cage can be designed to create such a dynamic and uniform magnetic field using three pairs of orthogonally connected Helmholtz coils (Theoret 2016, Mahavarka 2018 & Pastena 2002).

Keplerian elements are a set of parameters used to express an orbit of an Earth-orbiting satellite. Therefore, these are called orbital elements or orbital parameters. This set of elements consisted of eight parameters that demonstrate the size, shape and orientation of the orbit (Rogers 2008). The TLE set is the way the above orbital elements are presented to describe the location of an Earth-orbiting satellite. A TLE includes three lines which can be divided into two parts. The first line shows the name and the other two lines express the “address” of the referring satellite (Chatters 2009). The inputs of the algorithm are based on the TLE dataset which describes the location of a satellite using Keplerian Elements. Many fitted reference frames consist of a group of unit length, right-handed and three correlatively perpendicular vectors which is called “Dextral Orthonormal Triad” to express the position and the orientation of a satellite (Hughes 2012).

Based on three reference frames which are Perifocal Coordinate System, Earth-Centered Inertial (ECI) frame and Earth-Centered Earth Fixed (ECEF) frame the position and the orientation of a satellite are expressed here.

Methodology/materials and methods

Software and Hardware

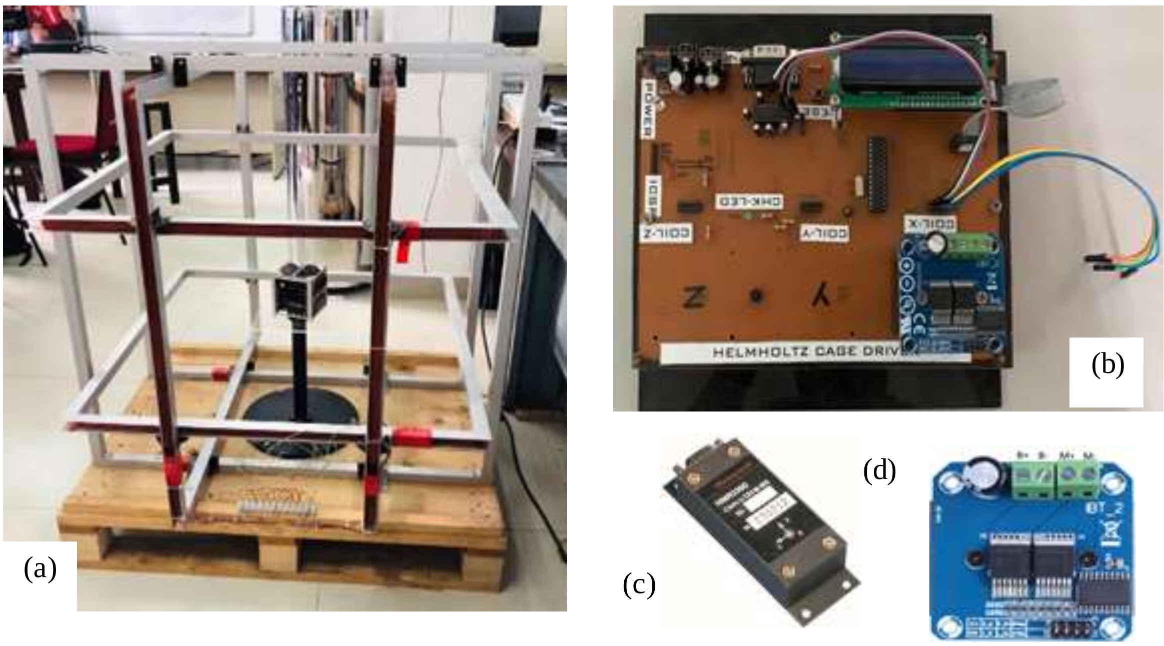


Figure 2. *(a) The Helmholtz cage design, built at Arthur C. Clarke Institute for Modern Technologies (b) The Driver Circuit (c) HMR2300 Smart Digital Magnetometer (d)BTS7960 High Current H-Bridge module*

MATLAB (2018b), Arduino - 1.8 and Realterm_2.0.0.70 were the software utilized. The algorithms were implemented using MATLAB (2018b). The magnetic field in a certain orbit can be modeled using the World Magnetic Model (WMM) in the MATLAB Aerospace Toolbox when the orbit information is given. Mainly four hardware were used in case of emulating the on-orbit magnetic field into the Helmholtz cage.To measure magnetic fields and communicate with a computer HMR2300 Smart Digital Magnetometer was used. The Realterm_2.0.0.70 software was used for this purpose. A BTS7960 High Current H-Bridge module was applied for taking a PWM signal as input and making a current output according to the duty cycle of the PWM signal. A Driver circuit was made for supplying the current to the cage. To code the motor driver, Arduino - 1.8 was used. Finally, the Helmholtz Cage was the test subject.

Calculation of the orbital coordinates (Longitude, Latitude & Altitude/ LLA) from TLE.

```
0 Raavana-1
1 44330U 98067QF 19345.06705768 .00006175 00000-0 99589-4 0 9998
2 44330 51.6387 201.0952 0006480 22.9331 337.1948 15.54365198 27497
```

First of all, the above TLE of RAAVANA–1 was downloaded as a text file. To Extract the necessary Keplerian Elements, the TLE file was read using the Common TLE format. Then those extracted six elements were given as the inputs for the further coding procedure. Then the Epoch and the Greenwich sidereal time (θ_G) were calculated. Then Two frame transformations were done in order to calculate the inputs for WMM using the following equations.

Perifocal frame equation-

$$\begin{bmatrix} X_{perifocal} \\ Y_{perifocal} \\ Z_{perifocal} \end{bmatrix} = \frac{a(1-e^2)}{1+e\ \cos\upsilon} \begin{bmatrix} \cos\upsilon \\ \sin\upsilon \\ 0 \end{bmatrix}$$

where,
a - Semi major axis of the orbit

First from Perifocal to ECI was performed to determine the eccentric (e) and true anomaly (v) using the equation below.

$$\begin{bmatrix} X_{ECI} \\ Y_{ECI} \\ Z_{ECI} \end{bmatrix} = \begin{bmatrix} \cos\Omega & -\sin\Omega & 0 \\ \sin\Omega & \cos\Omega & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{bmatrix} \begin{bmatrix} \cos\omega & -\sin\omega & 0 \\ \sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{perifocal} \\ Y_{perifocal} \\ Z_{perifocal} \end{bmatrix}$$

where,
Ω - Right Ascension of Ascending Node; ω - argument of perigee; i - Orbital Inclination

Then from ECI to ECEF frame transformation was done as follows.

$$\begin{bmatrix} X_{ECEF} \\ Y_{ECEF} \\ Z_{ECEF} \end{bmatrix} = \begin{bmatrix} \cos\theta_G & -\sin\theta_G & 0 \\ \sin\theta_G & \cos\theta_G & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_{ECI} \\ Y_{ECI} \\ Z_{ECI} \end{bmatrix}$$

Then an algorithm was created to evaluate the three inputs (LLA) which express the position of the satellite at any point of the orbit using the ECEF coordinate system. Finally, the LLA coordinates were set into the WMM as inputs and derive the orbital magnetic fields experienced in one period of the orbit.

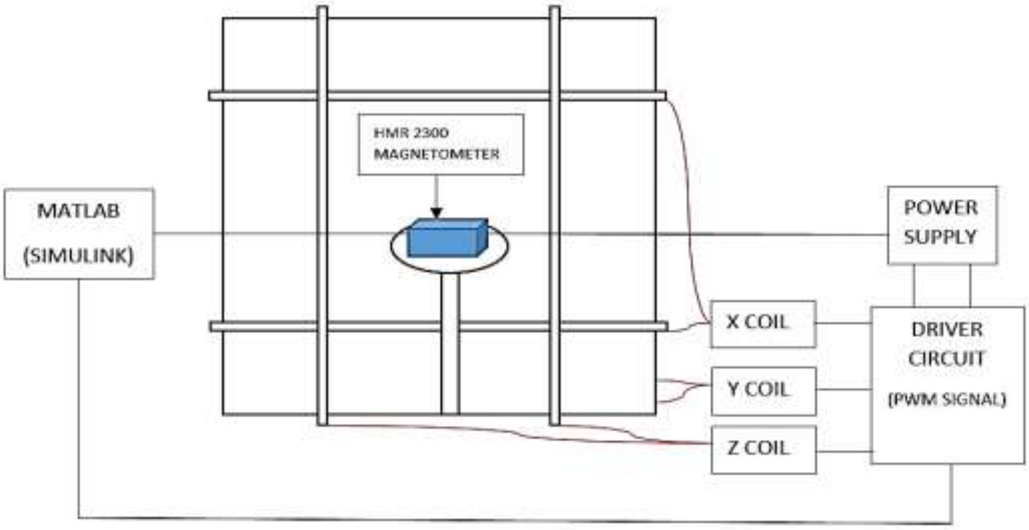


Figure 3. *The fully-equipped experimental setup.*

All the hardware was connected like the above experimental setup. Here only one coil was focused. The driver circuit was connected with the cage and the magnetometer. Then the whole setup was connected to a power supply and a Cathode Ray Oscilloscope to supply the power to the cage and take the real-time readings of the centre of the cage using the Magnetometer. For the driver circuit, 12 V and 6 A were given. The selected coil was supplied with 10 V and 0.15 A of a current through the Arduino-based driver which can vary the provided current according to the pulse width of a rectangular pulse. By getting the PWM scale 0 to 255, the resulting magnetic field at the center of the coil was measured by magnetometer by increasing pulse width 5 by 5. The magnetic fields created by the coil were measured and plotted against the pulse widths. Using that, a relationship between the pulse width and the created magnetic field was obtained.

Emulation of the magnetic field inside the Helmholtz cage.

After deriving the relationship between the pulse width given to the current driver and the generated magnetic field, the pulse widths required to create the orbital magnetic field generated by the algorithm using the TLE data set were calculated. Next, those pulse widths were supplied to the current driver to generate the orbital magnetic field inside the Helmholtz cage. Finally, the generated magnetic field was measured and recorded. Then the graph of experimentally generated X-axis magnetic field was plotted throughout one period of the Nanosatellite. Finally, the experimental and theoretical graphs were compared.

Results and Discussion

This graph shows the real-time on-orbit x-axis magnetic field (B_x) of RAAVANA – 1 satellite for the chosen TLE over a period along the orbit. It was found that the X components of the EMF (B_x) of this orbit ranges from 1.014×10^4 to 3.228×10^4 nanotesla.

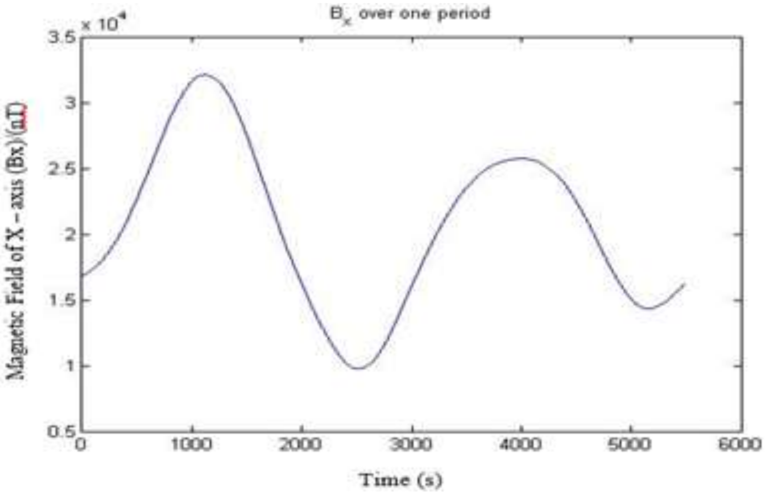


***Figure 4**. The graphs (theoretical) of the real-time on-orbit x-axis magnetic field (B_x).*

According to the experiment, variation of B_x with the increment of PWM value was observed to be linear as shown below.

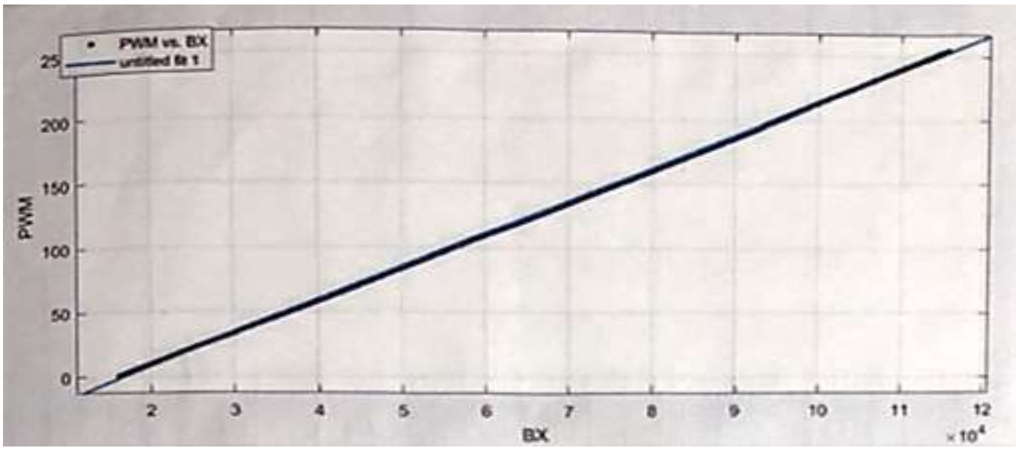
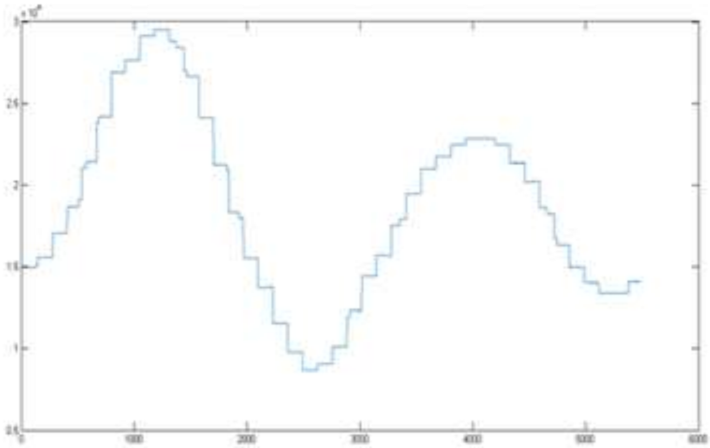


***Figure 5.** Characteristics Bx with the PWM of the X-axis coil pair of Helmholtz cage.*

So, the following linear relationship between PWM and B_x was obtained using the above graph.

$$\mathrm{PWM} = (0.0026)\mathrm{B_x} - 43.4330$$

Using this relationship, by giving the calculated B_x values using the implemented algorithm by reading the TLE, the pulse widths were obtained. Then the experimental graph was plotted for the B_x values given for the newly generated pulse width values using the above relationship for one period of the CubeSat. It was found that the X components of the EMF (B_x) of this orbit ranges from 0.901×10^4 to 2.958×10^4 nanotesla.



X axis => Time (s)

Y axis => Bx (nT)

Figure 6. *The experimental graph of x-axis magnetic field (B_x) for a period.*

Comparing the above theoretical and experimental graphs below, it is shown that the shapes of the graphs are similar and lie within an approximately simal range. The slight changes might have happened because of the magnetic field disturbances from the devices, equipment around due to lack of proper experimental facility of a cleanroom.

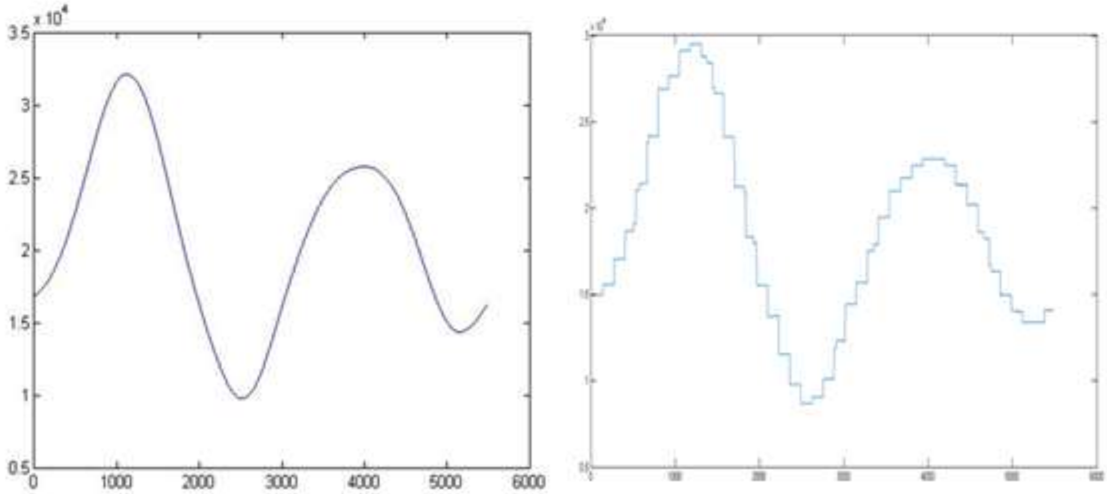


Figure 7. *The theoretical graph (left) and the experimental graph (Right).*

Conclusion

This research focuses on emulating the magnetic fields experienced by CubeSats in their orbits utilizing a Helmholtz cage for ground testing of the ADCS of Nanosatellites. By implementing the algorithms using MATLAB (2018b) to analyze the required magnetic fields inside the cage for one of the three coils is successful since the plot of the expected magnetic field variation and the experimentally implemented magnetic field variation of the selected coil (X–coil) were found to be fairly similar Since both ranges of the theoretical and experimental are from 1.014×10^4 to 3.228×10^4 nanotesla and from 0.901×10^4 to 2.968×10^4 nanotesla respectively. So, it concludes the relationship between the pulse width and the created magnetic field was obtained is linear and correct. Since the graphs of the orbit of the RAAVANA – 1 satellite are presenting accurate information, this method can be used to calculate the Longitude, the Latitude and the Altitude for any TLE of any CubeSats at any time. It was found that the total EMF of this orbit ranges from 2.103×10^4 to 4.419×10^4 nanotesla. The previous studies on EMF show it varies from the average of 2.5×10^4 to 6.5×10^4 nanotesla [3]. So, the resultant magnetic field is almost exactly within the limits. The slight changes might have occurred because of the devices, equipment around due to lack of proper experimental facility of a cleanroom. By calculating the magnetic field experienced by a CubeSat in the orbit using the implemented algorithm by reading a TLE dataset can be concluded as a suitable modelling method for the Helmholtz cage. Therefore, this whole process will be able to implement as an emulating the magnetic fields experienced by CubeSats in their orbits utilizing a Helmholtz cage for ground testing of the ADCS of Nanosatellites.

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