# Design and Construction of an Inexpensive Magnetometer for the Study of Geomagnetic Variations and Solar Coronal Mass Ejections

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## 1. ABSTRACT

The primary goal of this research was to design and construct a low-cost magnetometer and enhance resilience against geomagnetic variations and solar coronal mass ejections (CMEs), aiming to match the accuracy of commercially available devices. It integrates the FG 3+ magnetic sensor, an ESP32 microcontroller, a NEO-6M GPS module, a Micro SD Card Module, and the power unit. The magnetometer was uniquely housed in a 114 cm long, 100 mm diameter PVC pipe.

To check the accuracy of the constructed magnetometer, measurements were taken throughout April 2024. A site in Kurunegala was selected for the measurements. The average magnetic field values of that location on April 12th are x-axis, (43749 ± 2) nT, y-axis, (-1538.59 ± 0.08) nT, and z-axis, (1195.63 ± 0.08) nT. The measured angles of declination and inclination are (-2.01 ± 0.01) degrees and (1.24 ± 0.01) degrees, respectively. The values closely matched those based on the latest World Magnetic Model (WMM) for Kurunegala.

## 2. INTRODUCTION

The Earth's magnetic field is produced by electric currents in the conductive iron alloys of its core, which are caused by convection currents caused by heat escaping from the core. This process is known as a Geodynamo [**Error! Reference source not found.**]. Paleomagnetic investigations on ancient rocks show that the Earth's magnetic field has existed for at least 3.45 billion years [**Error! Reference source not found.**].

Coronal mass ejections (CMEs) are tremendous eruptions of hot plasma and magnetic fields from the Sun's corona that are frequently connected with solar flares. Unlike the steady flow of solar wind, CMEs are transient occurrences that can release massive amounts of magnetized plasma into space. When directed at Earth, they can cause geomagnetic storms, increase aurora activity, and damage electrical grids and communication systems. Their frequency fluctuates over the solar cycle, peaking near solar maxima.

The construction of inexpensive, laboratory-grade magnetometers has both practical and scientific advantages. Geomagnetic studies have become accessible with the help of cost-effective instruments, which facilitate a variety of study and interest among learners in space science and geomagnetism. These magnetometers enable real-time monitoring of the Earth's magnetic field, providing important details about geomagnetic variations. They contribute to the studies of ionospheric disturbances that affect radio communication and GPS systems and the analysis of current magnetosphere systems and their effects on the Earth's magnetic environment. Furthermore, long-term monitoring helps in the detection of secular changes, geomagnetic reversals, and pole shifts, providing significant data for geophysics. Furthermore, identifying geomagnetically generated currents might help protect power grids and infrastructure from space weather disruptions.

This research was initiated to address the need for a practical, affordable tool to monitor the variations of the earth's magnetic field, resulting in the development of a low-cost magnetometer capable of delivering laboratory-grade performance. The instrument is constructed using innovative, yet affordable components that can measure the Earth's magnetic field with precision comparable to more expensive commercial devices. At the core of the magnetometer, the FG 3+ magnetic sensor is employed, noted for its high sensitivity and low noise levels, making it highly suitable for detecting subtle changes in magnetic fields. This sensor, along with an ESP32 microcontroller and a NEO-6M GPS module, is integrated into a robust system designed for real-time data acquisition and analysis.

A special feature of this magnetometer is the cost-effectiveness with which it was produced. Traditional magnetic field sensors, often prohibitively expensive, restrict their use to well-funded laboratories. In contrast, the components used in this project are both readily available and inexpensive, which significantly reduces the overall cost of the device without reducing its functionality. Moreover, the design of the magnetometer focuses on durability and ease of use. The device is enclosed in a custom-designed enclosure that protects its sensitive electronic components from environmental factors such as temperature fluctuations and electromagnetic interference, ensuring its reliable operation under various conditions.

## 3. INSTRUMENTATION AND METHODOLOGY

Design and construction focused on two main areas:

Electronic Circuitry: A sensitive and accurate system was designed to detect tiny magnetic field changes, using components considered for their sensitivity, stability, and cost-effectiveness. Housing: The magnetometer's housing was developed to shield electronics from external factors such as electromagnetic interference, moisture, and temperature changes, ensuring durability and ease of use.

Fluxgate magnetic sensors (FMS) use a ferromagnetic core driven to magnetic saturation by an alternating current to detect external magnetic fields with high sensitivity and precision. These sensors consist of primary and secondary wire coils around the core. An alternating current in the primary coil creates a magnetic field, driving the core to saturation. In the presence of an external magnetic field, saturation becomes asymmetric, enabling measurement of the field's direction and strength [6].

These sensors can be considered as the heart of the magnetometer which costs approximately 37.5 Euros each. The cost for this sensor is considerably low when compared with the sensors that have been used in the commercially available magnetometers. FG 3+ sensors emit a 5 V rectangular pulse whose Frequency is nonlinearly proportional to the field strength as the outputs. Two sensors were orthogonally oriented at the bottom of the Perspex sheet. Because to measure the Earth's magnetic field strength in terms of magnetic coordinates where the one sensor is aligned to the Horizontal component (H) of the magnetic field and the other sensor is pointed vertically downward (Z). Although the 5 V rectangular pulse whose Frequency is nonlinearly proportional to the field strength, but approximately linear for small fluctuations. It has been found that a change in 1 Hz translates approximately into a 1 nT difference in the magnetic field.

The magnetometer used the NEO-6M GPS module to calculate the magnetic field's North and East components via the declination angle (D), the angle between true north and magnetic north, with D being positive eastward. The GPS module provided data such as longitude, latitude, time, date, declination, and inclination angles, processed through the ESP32 microcontroller.

The ESP32, with its dual-core processor, efficiently managed tasks like GPS data processing, geomagnetic calculations, and SD card file operations. A Micro SD Card Module enabled real-time logging of sensor and GPS data, with timestamping, for later analysis on a computer.

A 5V, 2A phone charger connected by a 5m cable supplied power, and two lithium-ion batteries (7.4V combined) served as a backup. The voltage had been stabilized at 5V via a voltage regulator circuit (L7805 IC). Schottky diodes in a diode-OR circuit reduced loss by maintaining smooth switching between primary and backup power. For stable operation, each component had a common ground.

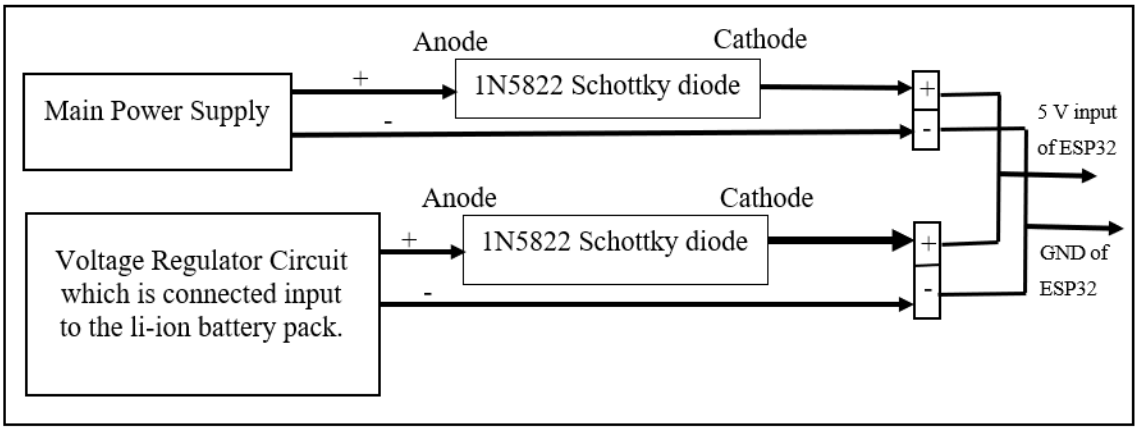

*Figure 1 - The block diagram for the power supply unit*

The magnetometer housing was built using a 114 cm long, 100 mm diameter PVC pipe, capped at both ends. The top cap was modified to be removable and replaced with a transparent Perspex sheet for GPS antenna visibility, while the bottom cap was sealed to prevent moisture entry. To minimize solar heating, the top section was painted white. The pipe was vertically buried at a site in Kurunegala, with 30 cm exposed above ground to stabilize the structure and ensure clear GPS reception.

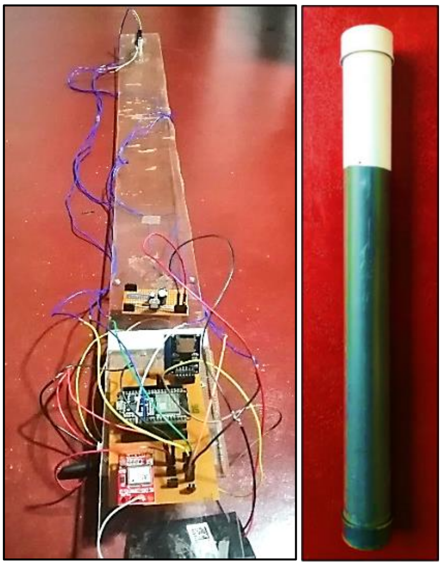

*Figure 2 - The internal and external structure of the magnetometer*

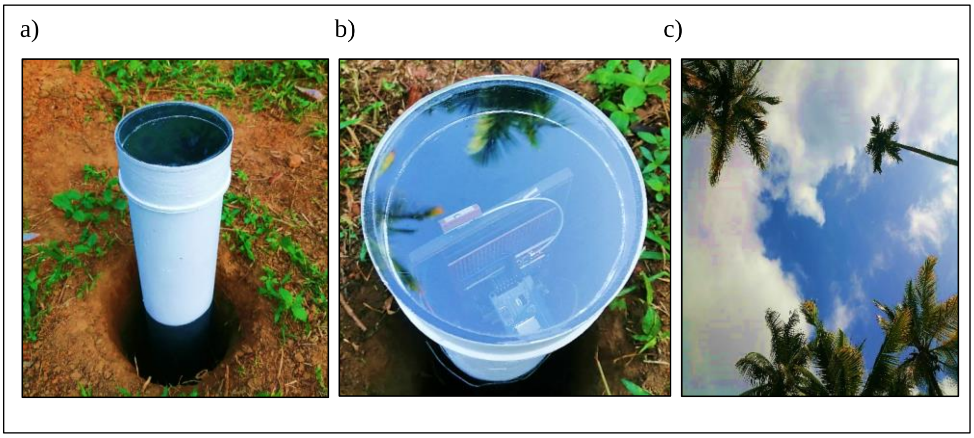

*Figure 3 - The housing of the Magnetometer Vertically buried (a), The view from the top of the Magnetometer (b), The sky view above the Magnetometer (c)*

## 4. RESULTS AND DISCUSSION

To check the accuracy of the constructed low-cost magnetometer, measurements were taken throughout April 2024, and the following shows the information that had been gathered on April 12, 2024.

The above graphs show the Magnetic field data gathered by the magnetometer from April 12, 2024 (Afternoon), in Kurunegala, Sri Lanka at a temperature of $32^0$C. A bulge appeared between 12:42 and 19:42 time, and the diurnal effect of the magnetic field was the cause of that pattern of the plot. The diurnal effect in the Earth's magnetic field is found by variations that are observed over a daily cycle. These variations are primarily caused by the interactions between the Earth's magnetic field and solar radiation, which affect the ionosphere.

The project aimed to create an affordable yet accurate magnetometer for measuring geomagnetic fields, making such tools accessible for educational and scientific use. To check the accuracy of the constructed low-cost magnetometer, measurements were taken throughout April 2024 and compared the measured values with international data. A site in Kurunegala was selected for measurements with a longitude of (80.251 ± 0.001) degrees and a latitude of (7.504 ± 0.001) degrees. It is found that the average values of the magnetic field measured in the said location on April 12, 2024, are: North component (X-axis) (43749 ± 2) nT, the East component (Y-axis) at (-1538.59 ± 0.08) nT, and the Vertical component (Z-axis) at (1195.63 ± 0.08) nT. The average horizontal and total magnetic field strengths are found to be (43775 ± 2) nT and (43793 ± 2) nT, respectively. The measured angles of declination (D) and inclination (I) are (-2.01 ± 0.01) degrees and (1.24 ± 0.01) degrees, respectively. These values indicated the angle between geographic north and magnetic north and the angle at which the magnetic field dips below the horizontal plane, respectively. The measured values closely matched those from the NOAA magnetic field calculator, based on the latest World Magnetic Model (WMM) or International Geomagnetic Reference Field (IGRF) for Kurunegala.

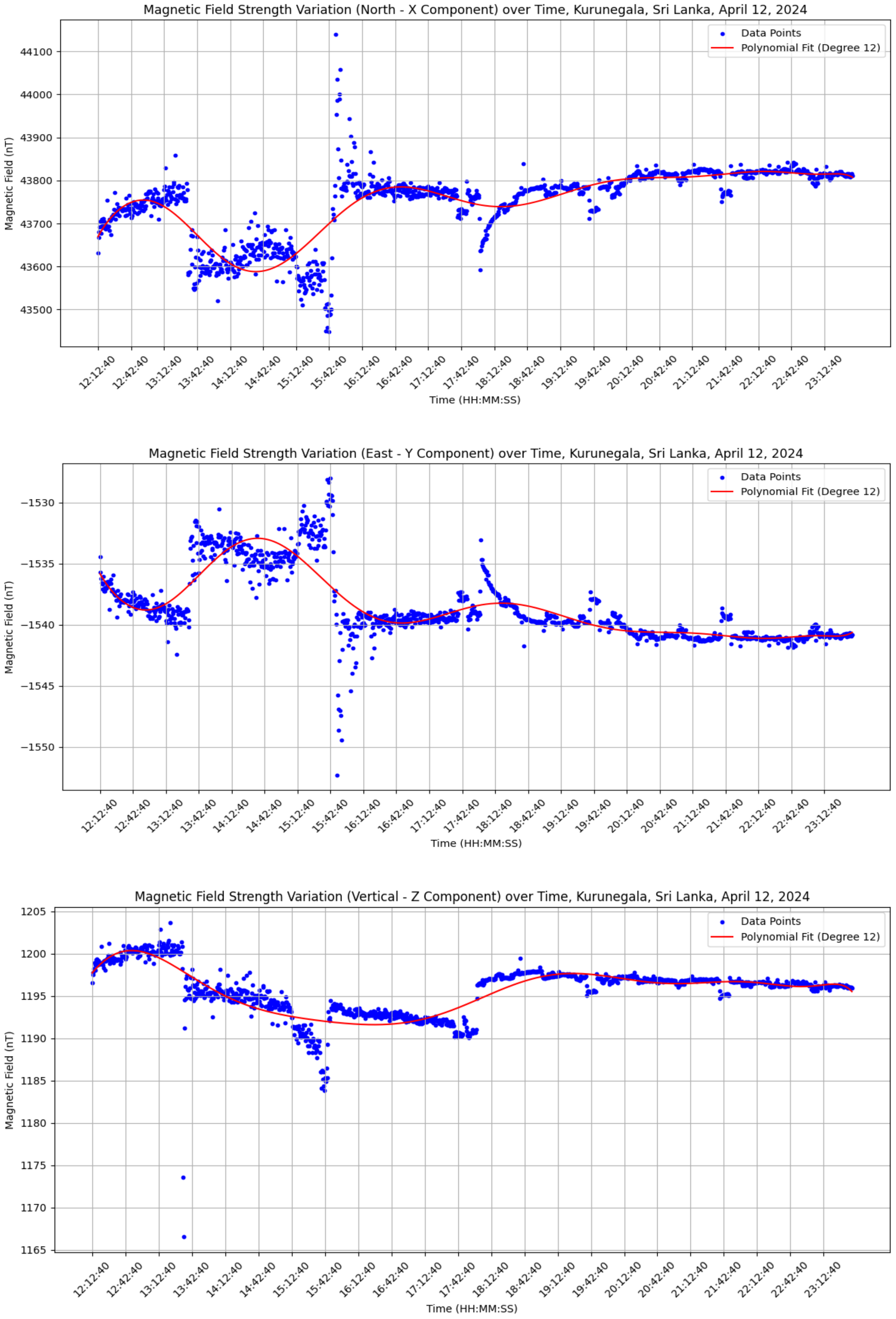

*Figure 4 - The X, Y, and Z Magnetic data gathered from the Magnetometer from April 12, 2024 (Afternoon), Kurunegala, Sri Lanka*

How to detect geomagnetic storms has reached an advanced level with the development of real-time monitoring systems, including ground-based magnetometers. These storms typically begin with a sudden commencement (SC), marked by a sharp increase in the horizontal component of the Earth's magnetic field due to the arrival of an interplanetary shock [0]. Following this, the main phase is characterized by a gradual decrease in magnetic field strength, caused by the intensification of the ring current [0]. The storm then transitions into the recovery phase, where the magnetic field slowly returns to its normal state. These phases can be detected using magnetometer readings by analyzing real-time variations in the Earth's magnetic field which is important for expecting and reducing the impacts of solar activities on technological systems.

## 5. CONCLUSION

A low-cost magnetometer was developed to provide accurate and accessible geomagnetic monitoring, using high-sensitivity components like the FG 3+ magnetic sensor, ESP32 microcontroller, and NEO-6M GPS module. During data collection in April 2024, it recorded average magnetic field values on April 12: North component (X-axis) (43749 ± 2) nT, the East component (Y-axis) at (-1538.59 ± 0.08) nT, and the Vertical component (Z-axis) at (1195.63 ± 0.08) nT, with horizontal and total field strengths of (43775 ± 2) nT and (43793 ± 2) nT respectively. The results aligned with the values of the NOAA magnetic field calculator, based on the latest World Magnetic Model (WMM) or International Geomagnetic Reference Field (IGRF) for Kurunegala, validating its accuracy despite minor power supply challenges. This innovation supports affordable geomagnetic studies and preparation for space weather.

## 6. REFERENCES

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