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Using Cellphone Magnetometers for Science on CubeSats

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Abstract

This paper explores the feasibility of using a smartphone magnetometer for CubeSat space science applications. Although smartphone magnetometers are less precise than other low-cost magnetic sensors that have been used on CubeSats, the study demonstrates the detection of Field-Aligned Currents (FACs) and Auroral Electrojet (AEJ) and Equatorial Electrojet (EEJ) signatures with low-precision, low-cost smartphone magnetometers. It shows that low cost smartphone magnetometers, despite being significantly less sensitive than research quality sensors, can measure FACs and AEJ and EEJ signatures by using the newly developed signal processing method described herein.

1. Introduction

Modern cellular phones, i.e., smartphones, incorporate many types of sensors, including magnetometers that are used by many applications as a compass. The cost of sensors embedded in smartphones has dropped dramatically, as the number of phones produced each year is estimated to have increased to more than one billion smartphones sold in 2013 (Fingas, 2014). The magnetic sensors inside the Apple iPhone 5S and the Samsung Galaxy S4 are the Asahi Kasei AK8963 and the Yamaha YAS532, respectively, which are tri-axial hall effect sensors. This study uses the iPhone 5S and Samsung Galaxy S4 to represent popular smartphones and examine whether the level of sensitivity of the smartphone magnetometer is suitable for space science studies.

A 1U CubeSat is a small satellite that is cube-shaped with a side length of 10 cm and usually weighs no more than 1.33 kg ("CubeSat Design Specification Rev. 13"). CubeSats have significantly lowered the cost of satellites by often using commercial-off-the-shelf electronics and sensors. A NASA project, PhoneSat, explored the use of smartphones to control

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all of the critical functions of the satellite (such as to help determine attitude, store data, and use the camera to take images of the Earth) and has already flown the Nexus One smartphone in space (Talbert, 2013). PhoneSat 2.4 made use of the Nexus S smartphone magnetometer with a magnetorquer (Kramer, 2002) to help orient the satellite. Hence, smartphones in general, and smartphone magnetometers in particular, have been used as part of the attitude control system on CubeSats.

Satellites often use research quality magnetometers to help stabilize the satellite, determine orientation, or measure the magnetic field for scientific research. These magnetometers are sensitive and accurate, but much more expensive than a smartphone (Table 1).

It is anecdotally understood that research quality magnetometers are about $1,000 USD, but for space missions the price increases an order of magnitude because of the radiation tolerance feature. The added bonus is that smartphones come with a data acquisition unit, microprocessor, and storage device already integrated with a simple development platform. By launching smartphone-based CubeSats in a distributed constellation of small satellites, similar to the IRIDIUM-based Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) mission (Clausen et al., 2012), they can perform a science mission for lower cost and higher mission security. AMPERE uses the IRIDIUM communication satellites to measure high latitude auroral currents flowing through the Earth's upper atmosphere to monitor space weather. Smartphone-based CubeSats are much cheaper than CubeSats and larger satellites with research-grade magnetometers. At the same price, it is possible to launch multiple smartphone-based CubeSats, so that even if one fails, the others can perform the mission, ultimately increasing mission success probability. Moreover, the CubeSat constellations have the advantage of measuring in different locations simultaneously for mapping purposes.

Like AMPERE, which uses low-sensitivity magnetometers designed for attitude control, this study explores whether low-resolution smartphone magnetometers can be used to identify field-aligned currents and electrojet currents that flow in the Earth's ionosphere. The Field-Aligned Currents (FACs) and Auroral Electrojet (AEJ) and Equatorial Electrojet (EEJ) currents flow into and through the ionosphere and have latitudinal thicknesses between 700 km and 1000 km, and often give rise to magnetic perturbations observed on low-Earth orbit satellites on the order of 100 nT (for the EEJ) and many hundreds to more than 1000 nT (for the FAC and AEJ) (Alken and Maus, 2007; Slavin et al., 2008; Vennerstrom and Moretto, 2013; Gasperini and Forbes, 2014). The location and intensity of these current systems provide information about how energy is flowing and dissipating in the Earth's space environment and are often used as proxies for measuring the intensity of geomagnetic disturbances (Moretto et al., 2002).

This study demonstrates that the smartphone magnetometer is able to measure variations in the magnetic intensity of FACs, AEJ, and strong EEJ signals using signal post-processing techniques, by taking advantage of the known range of dimensions and expected magnetic bipolar magnetic signature that current sheets and electrojets possess. Though the signal processing technique described here is designed to pull current signatures from low-resolution commercial cellphone magnetometer data, the technique can be used to extract weak signals for research grade magnetometers as well.

Table 1. Performance Comparison of Magnetometers

	Price (USD)	**Intrinsic Noise Rating** $(\mathrm{nT}(\sqrt{Hz})^{-1}$
Typical Smartphone	< $1,000	100
Space-rated, Radiation-Hardened Research Magnetometer	~ $10,000	0.1 or less

2. Performance of Smartphone Magnetometers

The purpose of evaluating the sensitivity of smartphone sensors is to show that it is feasible to measure the changes expected when passing through field-aligned currents, AEJ or strong EEJ. A typical signal varies up to 300 nT peak to peak over a degree in latitude (Alken and Maus, 2007; Slavin et al., 2008; Vennerstrom and Moretto, 2013; Gasperini and Forbes, 2014).

The manufacturer's specifications on the magnetic sensor used in the iPhone 5S (Asahi Kasei Microdevices Corporation, 2010) claims a measurement range of ± 1200 μT and a resolution of 300 nT LSB^{-1}. Detecting the EEJ field change of 300 nT with a sensor that only has a resolution of 300 nT LSB^{-1} requires taking additional measures. Therefore, this study proposes a method for detecting magnetic current signatures based on digital signal processing and knowing the expected duration and shape of the magnetic perturbations due to current sheets and jets.

As a first step, the analysis evaluated the smartphones sensitivity and accuracy similarly to what has been done for other commercial magnetometers (Matandirotya et al., 2013). For both devices, recording was for ten minutes at a sampling rate of 10 Hz. The data are then transferred to a PC for further processing. The mean value, standard deviation (σ), and power spectrum density (PSD) were calculated. Figure 1 shows the setup used for testing the noise density inside a three-layer magnetic shield can which practically blocks the external magnetic field and thereby enables the measurement of the phone's intrinsic noise. Table 2 shows the calculated σ of the different magnetic sensors in different phones.

The Earth's magnetic field in Ann Arbor, MI, USA is about 54,050 nT (National Oceanic and Atmospheric Administration National Geophysical Data Center: Magnetic Field Calculators). Both sensors' measurements are in the range of about ± 3,500 nT relative to the nominal field. Since the focus is on using the magnetometers as variometers, this is an acceptable accuracy. In the future, it might be improved by first calibrating the sensors.

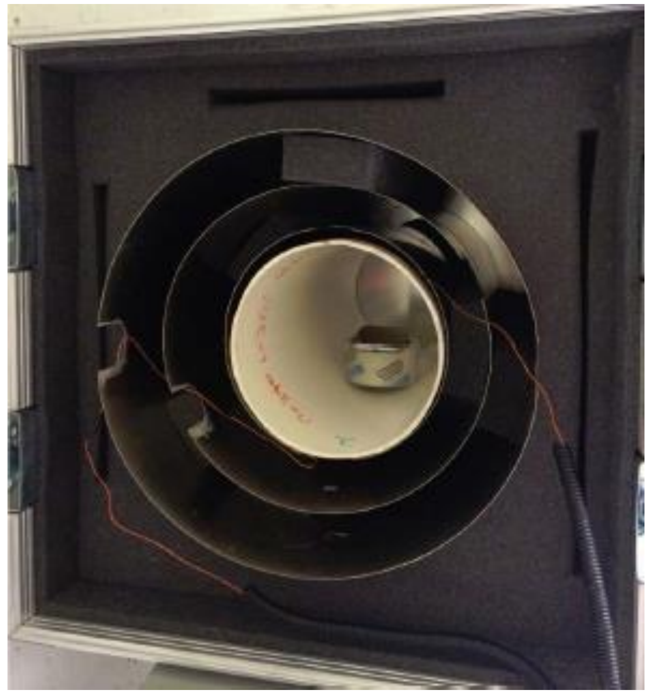

Figure 1. Galaxy S4 running the Sensor Dump app inside of a three-layer magnetic shield.

Table 2. Comparison of the σ Between Magnetic Sensors

(nT)	**Galaxy S4 (YAS532)**	**iPhone 5S (AK8963)**	**Galaxy S4 (AK8963)**
σ	350	380	320

Figure 2 shows the noise density, which is above 1,000 nT $(\sqrt{Hz})^{-1}$ within the relevant bandwidth. The measurements were carried out inside the magnetic shield which allows the measured magnetic field to represent the sensor's intrinsic noise. As expected, the intrinsic noise follows the trend of about $1/f$ (Slawomir, 2011). The calculation of the signals period, shown later, is 91–130 seconds. The corresponding bandwidth is at least 0.01 Hz. To achieve fine resolution and be able to filter out interferences while avoiding aliasing, the bandwidth should be about 1 Hz.

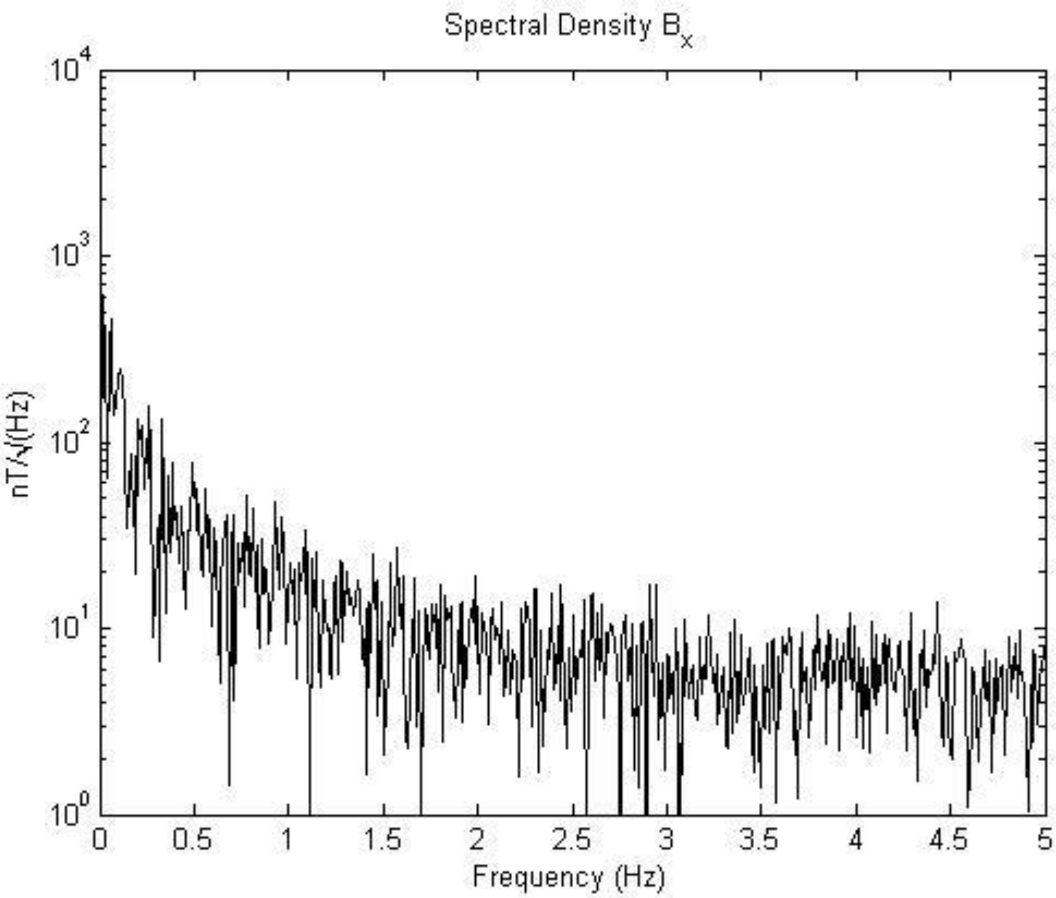

Figure 2. PSD of the x-axis of the iPhone 5S measured inside the magnetic shield.

3. Signal Processing Method and Results

The current study proposes the following method to extract the signal out of the noise. Figure 3 shows the proposed method comprising of bias removal, low pass filtering, decimation, and applying match filtering.

First, the bias was removed, since the only interest is in changes in the magnetic field. Next, averaging was applied, comprising low pass filtering (while avoiding aliasing and decimation). Afterwards, a matched filter was employed, to correlate the measured signal with a reference signal that resembles the

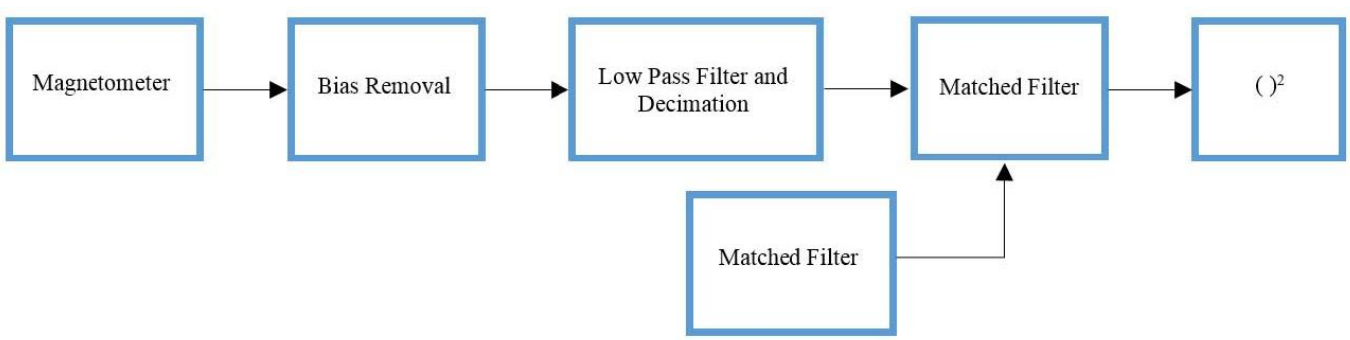

Figure 3. Block diagram of simulating the EEJ environment and process of noise reduction.

expected EEJ signal. Figure 4 shows the reference signal used in the simulation. The inspiration for the shape of the reference signal is anomaly expected when passing through the current sheet seen in Figure 5. The matched filter enables detecting signals with similar patterns to the reference signal while suppressing all other signals. Finally, a threshold was used for making the decision of whether an EEJ signal has been

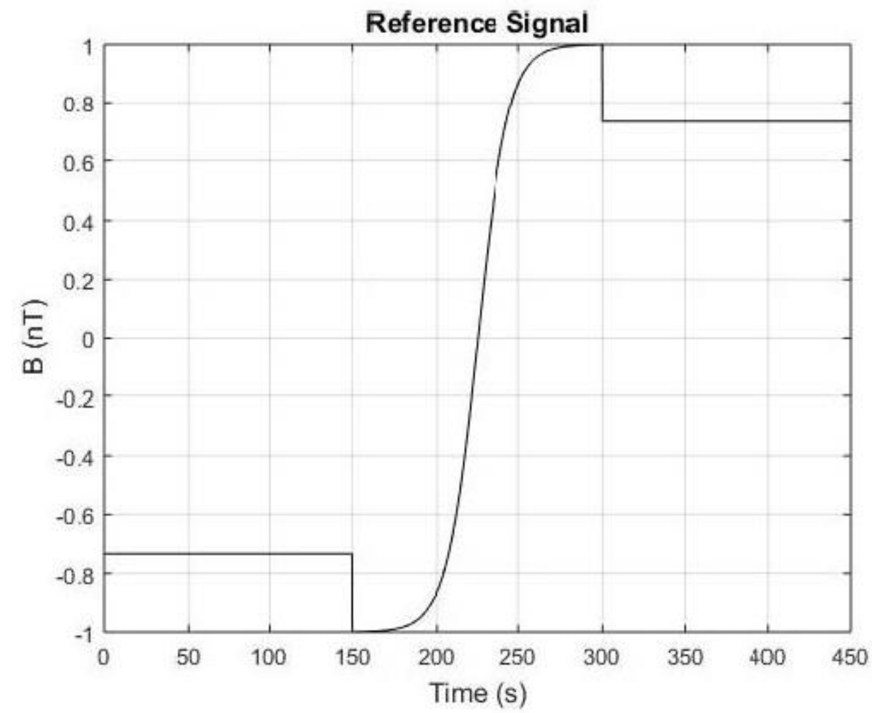

Figure 4. Normalized, reference signal for matched filtering step.

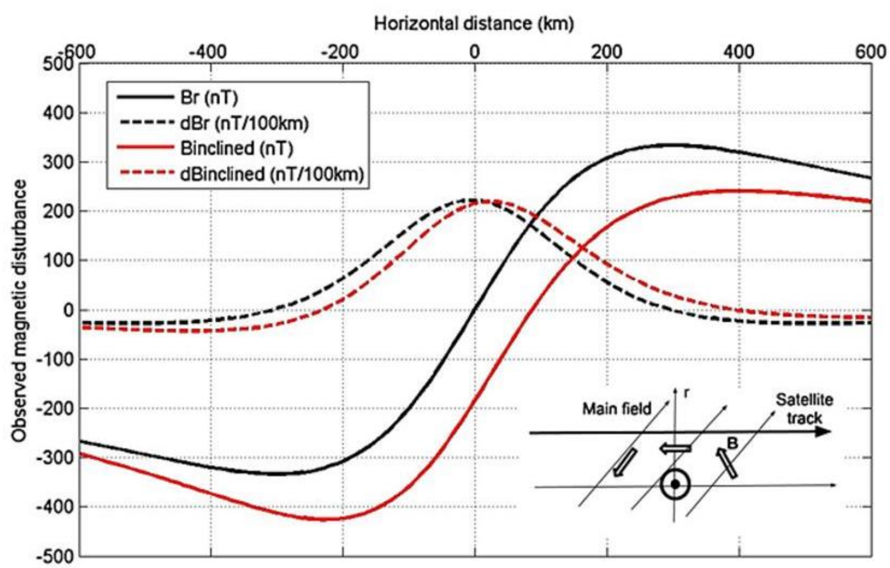

Figure 5. The magnetic perturbations and spatial derivatives in vertical (radial, black line) and inclined (radial, red line) components of a satellite crossing an infinite line current of 1MA at a height of 300 km. The satellite track and field geometry are shown in the bottom right corner (from Vennerstrom and Moretto, 2013).

detected. In tests, the signal-to-noise ratio (SNR) was around 0.3 using a smartphone satellite without signal processing. The improved SNR at the output, approximately 3, enables one to empirically choose an adequate threshold for detection. However, determining an optimal threshold is a subject for future investigation.

Given the conditions and a typical sample of noise, the study simulated the iPhone acquiring data while flying through the current sheet seen in Figure 5. Assuming a CubeSat in low Earth orbit (LEO) traveling at a velocity of 7.7 km s^{-1} and knowing that the thickness of the EEJ/FAC/AEJ is between 700 km–1000 km (Alken and Maus, 2007; Slavin et al., 2008; Vennerstrom and Moretto, 2013), the relevant period is 91 s to 130 s. The corresponding frequency bandwidth is 7.7 mHz through 11 mHz. Figure 5 (from Vennerstrom and Moretto, 2013) shows what the magnetic signature would look like for a satellite at 300 km orbital altitude.

The sensor tests show that the smartphone's magnetometer noise is higher than the expected environmental noise in orbit. Therefore, the magnetic noise acquired in the shield can be used to simulate the expected noise in orbit. The next step was to add the noise measured from the magnetometers while inside the magnetic shield to the simulated signal. For future reference, this signal is referred to as the simulated measurement. The EEJ with zero noise is shown in Figure 6a. Figure 6b shows a simulated signal of an EEJ using a smartphone quality magnetometer, while Figure 6c is the smartphone simulated measurement after applying decimation. As seen in Figure 6b, the EEJ signature is practically hidden inside the noise. Figure 6c depicts the previously hidden signal after smoothing and decimation, which clearly improves the visibility of the ambient field.

This study averaged the data by oversampling (using a faster data acquisition frequency) and then averaging a number of samples to one data point. This is repeated through the whole data set. Obtaining a larger number of samples should better represent the EEJ signal while providing enough points to prevent losing resolution.

Figure 6d is the output of the algorithm. The large peak seen shows detection of the simulated EEJ anomaly. With a suitable threshold, this data could return a binary response (Yes/No) and time stamp for mapping purposes. The reference signal is mimicking the solid black and red curves in Figure 5. The measured signal is the readings from the smartphone magnetometer (Figure 6b). The final step was to square the new signal to accentuate the peaks during the transition period through the EEJ. The detection is seen around 1500 s.

This study models the AEJ/EEJ/FAC signature depicted in Figure 5 by a reference function as depicted in Figure 4. However, tests show that even different functions, e.g., hyperbolic tangents and certain step functions, for the matched filtering produce similar results.

To further evaluate the robustness of the algorithm, it was important to verify that the reference signal period could be different than the simulated measurement period.

As previously mentioned, the time it takes to pass through the whole EEJ ranges from about 91 s to 130 s. For this reason, sine waves with periods of 90 s and 130 s were also tested while keeping the reference signal period of 120 s. The detection is apparent and of similar SNR.

When varying the period of the simulated signal between 50 s and 300 s, the detection output is bounded to within 10% of 150 (ambiguous units). Around 150 is peak, see Figure 6, when the reference signal period and simulated signal period are matched (both values at 120 s). In both cases, the detection peak around the 120 second timestamp is still more than double the amplitude of any other random peaks that appear from the noise of the phone. For routine current identification, a Monte Carlo approach should be used examining the time series and convolving the data with sine waves of varying duration across regions where bipolar signatures are observed. Since the strongest EEJ intensity is often significantly weaker than the AEJ, this analysis demonstrates that with signal processing, a smartphone magnetometer could be used to map the location of global current systems by

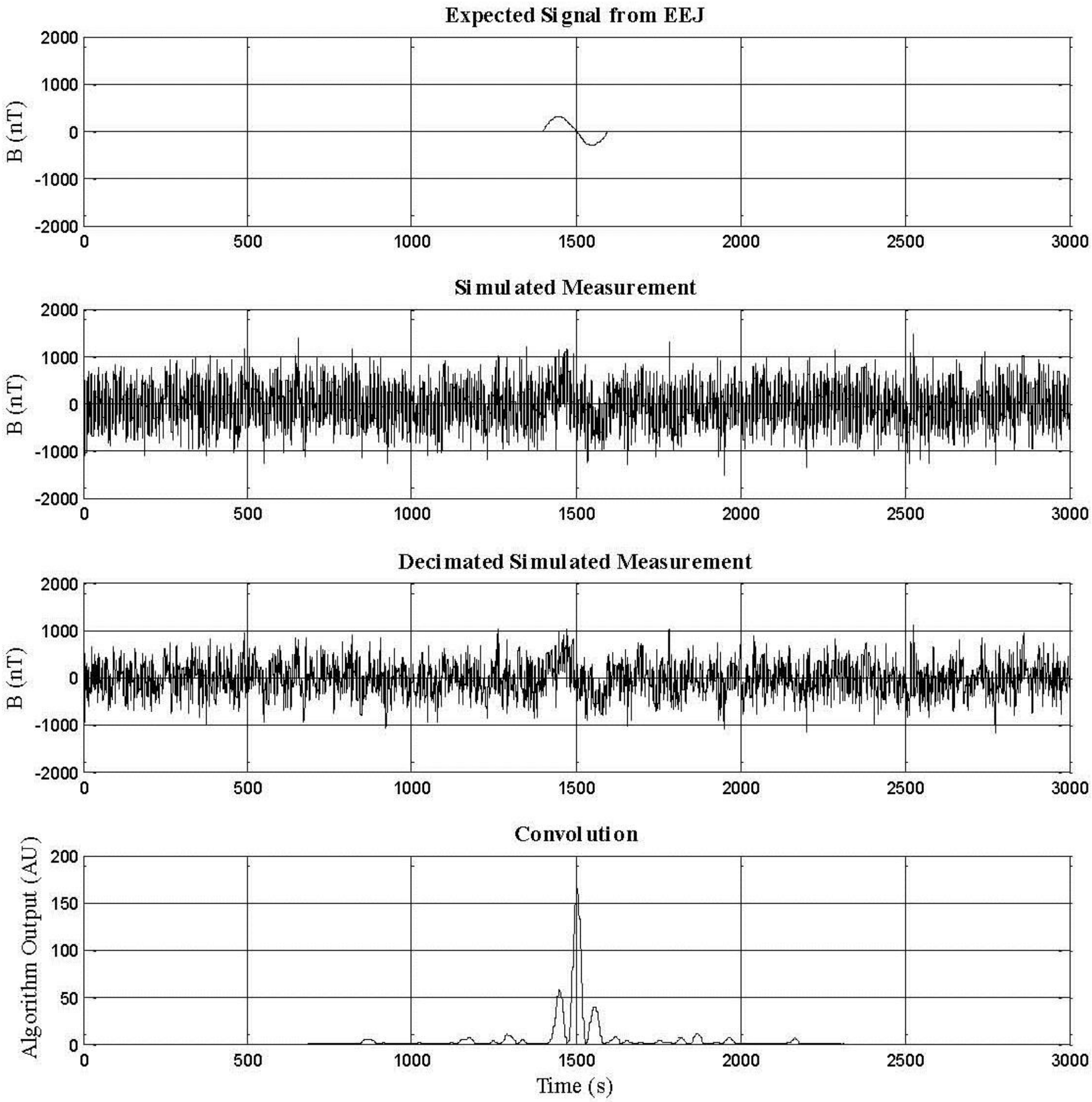

Figure 6. The top plot shows the signal we are attempting to detect. The next plot simulates the magnetic measurements of a CubeSat equipped with an iPhone 5S passing through an EEJ. The third plot shows the applied averaging and filtering. The bottom plot is the output of convolving the reference signal and third plot together.

taking advantage of the approximate shape of the current signature and range of expected current crossing durations.

4. Further Investigation

Despite the smartphone sensor's rather poor sensitivity compared to most advanced magnetometers used on other missions, the current study demonstrated that with signal processing, smartphones are able to measure FAC, AEJ, and strong EEJ with an SNR of about 3. Magnetometer calibration and smartphone noise mitigation will potentially allow the use of smartphones for many other applications involving detection of even lower magnetic signals. Development of a robust and computationally efficient search algorithm would also make routine identification and mapping of current systems possible using CubeSat based magnetometer data, even with low-resolution magnetometers.

5. Conclusions

Using a smartphone magnetometer on a CubeSat provides a low-cost navigational and science instrument capable of detecting the Earth's global current systems. The Smartphone sensors used in the iPhone 5S and Galaxy S4 have σ around 300 nT. Given the expected variations in magnetic field intensity for passing through FAC, AEJ, and strong EEJ, applying signal processing is required to detect the field signature of typical current intensities.

Acknowledgments

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