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MAGNETO: Mapping the Earth's Magnetic Field at 300 km using COTS Sensors

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ABSTRACT

In the nearly two decades that CubeSats have been in significant use, over 800 have been launched, and many more are under construction. They have gained popularity in the industry and are often the choice for most first-time small-satellite missions. The University of Southern California's (USC) Space Engineering Research Center (SERC) has developed a 1.5U student-built science mission called Magneto. Magneto is USC's fourth CubeSat mission, and it has the goal of mapping the Earth's magnetic field in Low-Earth Orbit (LEO) using Commercial Off-The-Shelf (COTS) hardware, to determine the viability of using COTS sensors to decrease the mission cost by a hundred-fold from similar missions using dedicated science instruments, while offering similar levels of precision.

The spacecraft, built in partnership with Omega Engineering, will utilize COTS sensors provided by Omega to measure the Earth's magnetosphere. These will be deployed on carbon-fiber booms to minimize the spacecraft's effect on the magnetic field measurements throughout the mission.

To collect accurate magnetosphere measurements without the use of GPS or a star tracker, the team at SERC developed a novel method to acquire attitude updates using a single sun sensor. This new GNC methodology is able to obtain the spacecraft's attitude while operating under an unknown rotation rate. The spacecraft obtains its position from the USC ground-station by finding the time of closest approach using the Doppler effect. Combining this data over multiple passes and using statistical analysis, the spacecraft position can be determined to within a few kilometers.

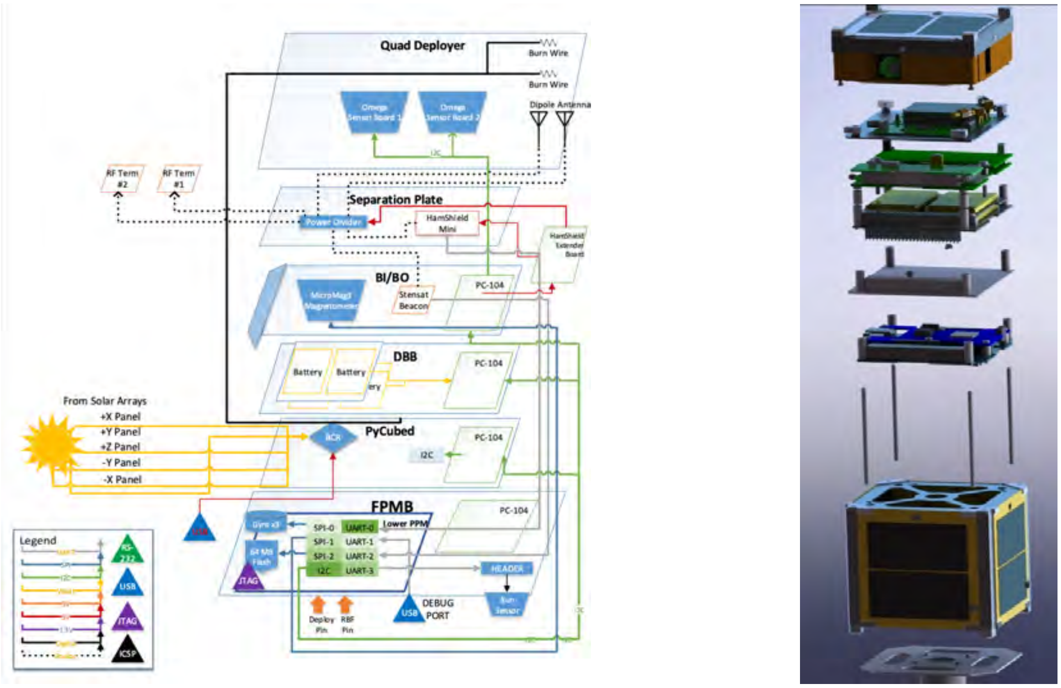
The Magneto spacecraft was scheduled on the manifest for the inaugural launch of the Firefly Alpha vehicle as part of Firefly's DREAM program, a STEM outreach effort to offer University and High School students a free launch opportunity to LEO. Due to the Covid-19 delays Magento's delivery was moved to alternative opportunities in Fall of 2020 or Spring of 2021. This paper will describe the design of the CubeSat, its unique mechanisms that enable compact stowage and deployment of antennas and magnetometers, and the novel GNC approach used to determine attitude and position throughout the orbit.

INTRODUCTION

The Magneto spacecraft is a 1.5U CubeSat, with a primary mission objective to use low cost COTS sensors to measure Earth's Magnetic Field in LEO and compare results to the previously published ESA Swarm satellite's data. By comparing data produced by a much more expensive mission, this mission has the potential to show smaller and cheaper doesn't necessarily mean inaccurate; thus encouraging and enabling other student-group space projects. In addition, insight on the performance of COTS sensors in space may also allow the commercial non-space industry to become more accessible, as it is often limited due to manufacturing and hardware costs.

Other mission goals are focused on testing techniques that may also help to further reduce the cost of a space mission. These techniques include using an ephemeris, a sun sensor, and gyros to estimate attitude while in orbit and updating ephemerides through time of closest approach (TCA) accesses from the global amateur radio community. The first could prove to reduce production costs by reducing the number of sensors needed for attitude determination, as the technique focuses on altering an existing algorithm to function with the use of only a single sensor. While the latter has the potential to provide mission ops with sampling ability around the globe without having to pay for each scheduled pass with a private ground station provider.

As a university student-run project, having learned from the trials and errors from three previous CubeSat projects,[2–4] the USC SERC team understood the importance of investigating different approaches to CubeSat mission designs that could significantly reduce costs. Funding plays a major role in projects like these, and the Magneto project was only possible due to the alignment of a few unique events. With a launch opportunity under Firefly's DREAM program, a STEM outreach effort to offer University and High School students a free launch



(a) System block diagram of Spacecraft Bus

(b) CAD depicting layers that make up the stack.

Figure 1: A complete system overview of the spacecraft is included for completeness.

opportunity to LEO,[5] and a relationship with Omega Engineering, the Magneto project began as a class project in Fall 2019 with limited funding, a team primarily consisting of undergraduate students, and without access to a large facility to build a satellite. As other student groups are often faced with similar challenges, this paper will primarily focus on the different low-cost mission designs and techniques taken to minimize mission cost.

BRIEF SYSTEM OVERVIEW

For completeness, a brief overview of the entire spacecraft is included before focusing on the mission-specific low cost strategies that may help other university-based CubeSat projects. The bus, often referred to as "the stack" because of the way Cubesats are designed, consists of the following layers: a sun sensor, spacecraft chassis, motherboard, Pluggable Processor Modulator (PPM), PyCubed board, battery board, Bus In/Bus Out (BIBO) board, beacon board, separation plate, and quad antenna deployer. The system block diagram and CAD layout of the layers are found above in Figure 1.

The PyCubed board was initiated from an open source CubeSat framework designed by Stanford University that integrates multiple satellite subsystems into a single PCB board.[6] The Magneto team at SERC decided to utilize this board provided by Stanford, for the Electrical Power System (EPS) and modified it to go beyond its original capabilities, i.e charging circuitry and an extra voltage line. The BIBO board serves as a bus in bus out board for beacon headers and magnetometers and connects to the beacon board, which holds a Stensat beacon used to relay spacecraft health and status. Above the beacon board lies a separation plate which holds a Hamshield Mini Transceiver board, a low-cost transceiver that is to be used solely for an emergency shutdown uplink.[7] Lastly, at the very top of the stack sits the quad deployer with the spacecraft payload. The quad deployer antenna housing involved creativity and multiple iterations to remain low-cost during the design process. Design and testing of the quad deployer will now be discussed below.

QUAD APERTURE ANTENNA DESIGN

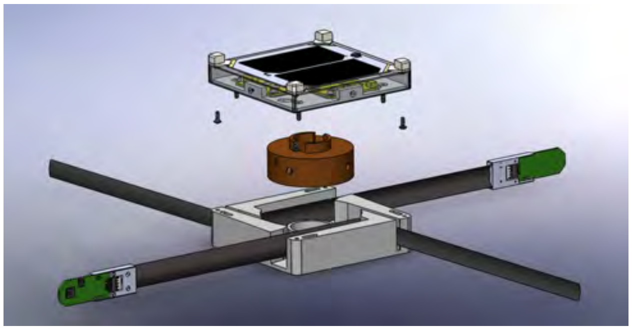


Figure 2: An exploded view of Quad aperture assembly.

Since two magnetometers are used to take readings of Earth's magnetic field while the satellite is in orbit, a quad aperture (see Figure 2) is designed to house and facilitate the deployment of two magnetometers, in addition to two UHF whip monopole antennas. The antenna housing is made out of Vespel to ensure electrical isolation of the antennas, and the magnetometer booms are made out of carbon fiber. Carbon fiber was selected as the optimal material for antennas because:

1. A nonmetallic material will not interfere with magnetometer readings.
2. Good shape memory will ensure its normal function in space.
3. High stiffness and tensile strength deem it qualified for space.

Apart from material selection, a good mechanical design is crucial in ensuring parts are protected and remain intact. The design of the antenna housing draws inspiration from Aneas, USC's 2nd CubeSat, and employs unique mechanisms that enable compact stowage during launch and the smooth deployment of antennas and (for the Magneto mission) magnetometers, once in orbit. The aperture is composed of an antenna housing, solar panels, burn boards, an antenna drum, two magnetometers, and a combination of two booms and two antennas that deploy. While in the launch vehicle, the booms and antennas are in a stowed position, with a nylon fishing line used to hold the drum in place and prevent rotating during launch. Two burn drivers are used to then cut the nylon lines (using nichrom wire) to release the booms and antennas once in orbit, as shown in Figure 3. This deployment utilizes the spring energy stored from the winding of the 4 separate thin booms/antennas during launch. Of the four deployables, two are metallic and function as the monopole antennae, while the other two are non-metallic carbon fiber booms (graciously supplied by Roccor Inc.) that extend the magnetometers away from any magnetic field interference created by the satellite's internal metallic components and structure.

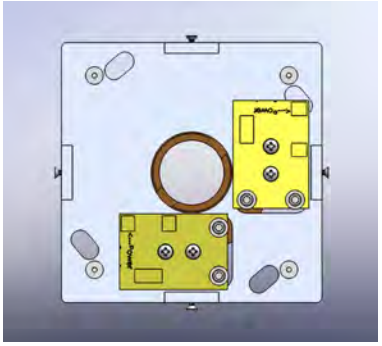


Figure 3: Implementation of two burn drivers.

A flat EP ribbon cable was selected for the magnetometer wiring harness to solidify the connection between the magnetometer and BIBO board and is connected via a DF11, double row, 1 mm pitch SMD connector. To enhance stability and structural integrity, while remaining lightweight and thin for magnetometer deployment, a mechanical connector was designed to enclose the SMD connector and fasten to the ROCCOR booms. 3D printing using a Dimension 1200es 3D printer at the USC SERC Fabrication Lab proved to be an efficient and low-cost method to manufacture and test the connector.

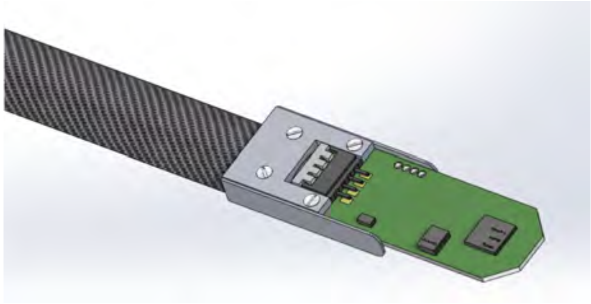


Figure 4: CAD of the magnetometer connector

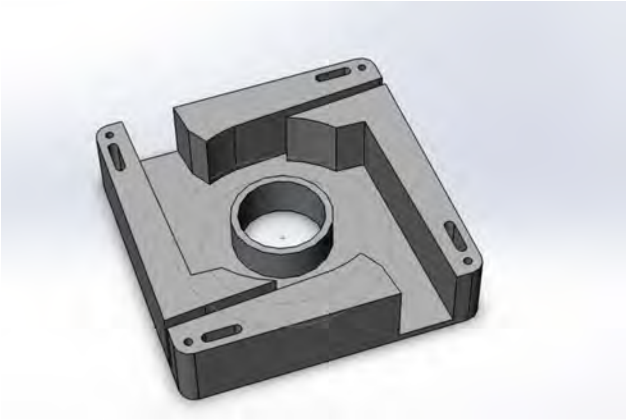


Figure 5: CAD of the modified antenna housing.

The inherited antenna housing design required some modifications in order to fit the 203 mm × 20 mm ROCCOR-supplied non-metallic carbon fiber tape booms, since the previous Aneas mission used the antenna housing to deploy antennas only. Similar to the magnetometer connector, adjustments to the antenna housing were also modeled in SolidWorks first and then prototyped. Prototypes were utilized for cost-efficiency and to allow for quick design iterations prior to manufacturing the final version using Vespel (Dupont Chemical), a man-made material qualified for space and easily machinable. After several iterations, the degree of openings on the four sides of the housing were modified from an initial 45 degrees to nearly 90 degrees, in order to allow for the natural extension of the booms/antennas. The protruding part on each of the four walls (see Figure 5) follows the shape of a circle, such that the stowed booms are aligned into a tight circular shape, mitigating the impacts of vibrations during launch. A total of five iterations, with updates between each iteration, were produced and assembled in order to confirm the smooth and repeatable deployment of magnetometers.

SINGLE SENSOR ATTITUDE DETERMINATION

One of the purposes of the low cost design and manufacturing of the quad antenna aperture was to minimize interference in the magnetic field data collected. This data however, is to be collected using a low-cost satellite without a control system and thus free to tumble. In order to accurately map Earth's magnetic field, the team determined the need for non-traditional methods for attitude determination, such as a method that involved the use of only a single sensor. For satellites in a low earth orbit (LEO), attitude determination is usually achieved by utilizing a sun sensor or star tracker with another orienting sensor such as a magnetometer. With a mission goal of mapping Earth's magnetic field, Magneto needed a different and low-cost technique to determine attitude without relying upon a magnetometer. Traditionally, attitude determination algorithms such as the triad method involve combining magnetometer measurements with a magnetic field model.[8]

The Magneto SERC team proposed modifying the traditional triad method algorithm to accommodate the use of a single sun sensor. The use of a single sensor for attitude determination is not a far-fetched idea, as it is often done for deep space missions which cannot utilize Earth-based measurements. However, many of these algorithms rely on expensive star trackers which prove challenging to a low-cost university based project and deemed finding an alternative necessary.

Before further discussing the modification that was made to the attitude determination algorithm, a brief review of the triad algorithm is included for completeness. The triad algorithm for attitude determination is based on constructing two triads of orthonormal unit vectors using the components of the body and inertial frames (See Figure 7).[8] It is assumed that one of the body/inertial vector pairs measured is correct/more accurate, i.e. the sun vector measurement is exact, and this measurement is used to construct the first base vector.

$$t_{1b} = s_b$$
$$t_{1i} = s_i$$

The second base vector is the unit vector that is constructed in the direction perpendicular to the two observations.

$$t_{2b} = \frac{s_b \times m_b}{|s_b \times m_b|}$$
$$t_{2i} = \frac{s_i \times m_i}{|s_i \times m_i|}$$

The third base vector is selected to complete the triad:

$$t_{3b} = t_{1b} \times t_{2b}$$
$$t_{3i} = t_{1i} \times t_{2i}$$

The three base vectors are combined to form the column vectors of the following two rotation matrices:

$$R^{bt} = [t_{1b} t_{2b} t_{3b}]$$
$$R^{it} = [t_{1i} t_{2i} t_{3i}]$$

The triad method is completed by combining these two matrices to form the attitude rotation matrix, R^{bi}:

$$R^{bi} = R^{bt} R^{ti} = [t_{1b} t_{2b} t_{3b}][t_{1i} t_{2i} t_{3i}]^T$$

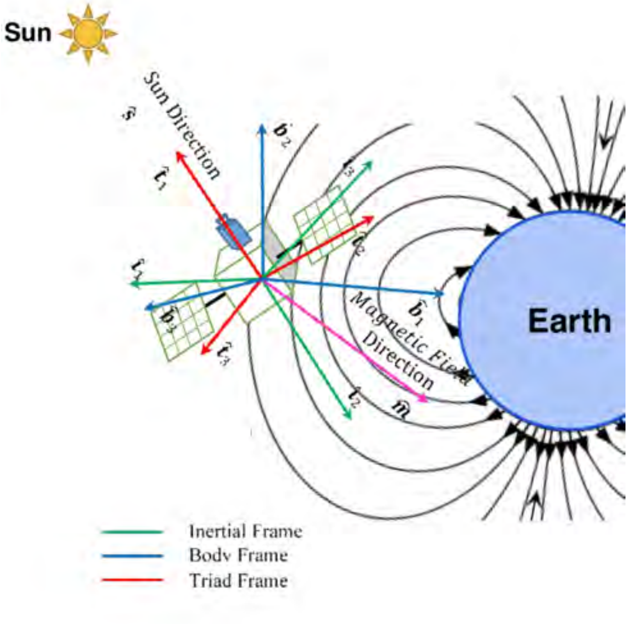


Figure 6: Diagram depicting traditional triad attitude determination technique with the use of a magnetometer and sun sensor.[9,10]

Spacecraft attitude, yaw, pitch, and roll can then be extracted from the attitude rotation matrix, and then transmitted down to Earth. As seen in the formulation above, the two measurements used in the triad method must also be known in the inertial frame. Typically, a sun and magnetic field model is included in the spacecraft's software, so that the measurements taken can be transformed to the inertial frame onboard, prior to performing the triad algorithm. This is the primary issue found with using a sun sensor and magnetometer for the Magneto mission.

Using spacecraft attitude combined with the COTS magnetometer measurements to map Earth's magnetic field is counter-intuitive if attitude is determined using a magnetic field model. Thus, the Magneto team proposed modifying the triad algorithm by using two sun sensor measurements (taken at different times) and combining with gyro measurements. The idea is that one can use the gyro measurements to transform a previous sun sensor measurement to the same reference frame of the current sun sensor measurement. Once the sun vector measurement from the previous sampling period is transformed to that of the most recent, using the spacecraft's known angular velocity at the time the earlier measurement was taken, the traditional triad algorithm is followed. The current sun vector measurement is used to form the first base vector, as it is known to be more accurate than the previous (transformed) sun vector measurement.

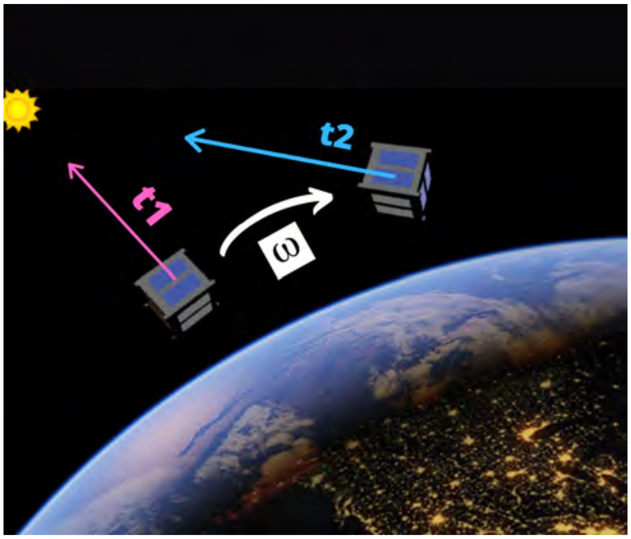


Figure 7: Diagram depicting CubeSat in orbit measuring the sun vector at two different instances, t1 and t2. Gyro readings, ω, are then used to transform the t1 measurement into the same frame as t2. Once this transformation is completed, the triad algorithm can be followed, taking the sun vector measurement taken at time t2 to be more accurate and using it to construct the first base vector.

The modified algorithm uses filtered gyro measurements and an additional algorithm that transforms the sun vector measurement taken in the body frame to the inertial frame using the current time. The errors associated with modifying the triad method have been considered and it should be noted that future testing of the methodology is still needed. Testing the algorithm with hardware-in-the-loop prior to launch is crucial in determining the effectiveness of the technique, as any error associated with attitude determination will propagate in the magnetic field map produced, and thus in determining the effectiveness of the use of COTS sensors for low-cost missions.

ORBITAL POSITION UPDATES USING THE AMATEUR RADIO COMMUNITY

In addition to the magnetometer data collected, and spacecraft attitude determined, orbital position is also required in order to successfully map Earth's magnetosphere. Typically orbital position can be obtained using GPS, however the Magneto mission was designed without one so that the project would be completely free of any export-controlled materials, and thus allow all students to participate in the design and testing of the CubeSat. Without GPS onboard, orbital position can still be determined by updating externally provided TLE data with the assistance of a global network of ground stations and the amateur radio community. In this way, the Magneto team can access data points from across the globe without the need of private ground station providers.

Turning to organizations like the Amatuer Radio Satellite Corporation (AMSAT), a non-profit educational organization, SatNOGS, an open source ground station network, and augmented with RBC Signals global network of individual-run ground stations, the Magneto team proposed crowd-sourcing the CubeSat's position as it was downlinked to these amateur ground stations across the globe, as well as to universities with their own dedicated ground stations involved in the DREAM program.

To accomplish this, each ground site is provided a decoder program to extract data from the hexadecimal encoding of the Stensat beacon signal. As the ground stations decode the data, they will log the Time of Closest Approach (TCA), calculated by the difference between the received bandwidth of the signal and the known, actual frequency transmitted (437.4 MHz), effectively using the doppler shift to correct the satellite's absolute frequency. As the time of closest approach between the spacecraft's orbit and each ground station is determined, the SERC is able to update the known ephemerides to greater accuracy. The unique latitude and longitude of each ground station are also known and associated with a time of closest approach for the spacecraft; the externally provided TLE sets are thus able to be adjusted as a whole, as the time of closest approach provides a method to up-

Figure 8: Map of global ground station network for crowd-sourcing downlinked CubeSat data.

date a single position that can be applied in turn to the orbit of the satellite. Feeding this data from these worldwide amateur radio users through a Kalman filter allows for a more accurate propagation of the ephemerides between orbital points.

In addition to receiving TCA information from these stations, the Magneto team can call on these amateur operators to record beacons from the CubeSat and relay those received magnetosphere measurements, along with attitude and position data, back to the team. This allows for collection of magnetosphere data in locations that would be otherwise inaccessible with only one primary ground station. Amateur ground station operators who express their ability to support the mission in this additional way, can use the decoder distributed to them to receive and interpret Magneto's beacon. Once the signal is decoded, that information can then be communicated back to the Magneto team via an allocated email server.

Expected coverage from the proposed network of amateur stations was simulated using MATLAB and Systems Tool Kit (STK).[7] Since the ground stations were not evenly distributed around the globe, and no ground stations exist over the large water areas, gaps existed in the expected knowledge of the magnetic field readings. Gaps are shown in the results of the initial simulation (See Figure 9), as example between plotted points over Africa depict lack of coverage due to minimal amateur radio users in this area. Inherent to Magneto's mission to map the geomagnetic field is the requirement to collect and downlink data with as extensive coverage as possible. The team realized the original beacon scheme, which was hard-coded to transmit a beacon every minute with current magnetometer data, needed to be modified to include a collection of historical data points.

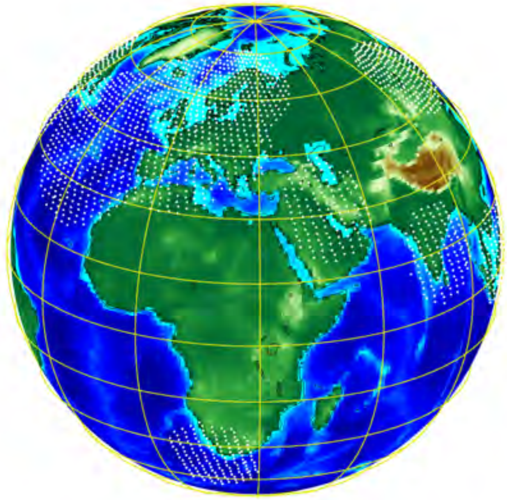


Figure 9: Simulated global coverage of instantaneous magnetometer readings crowd-sourced from amateur ground stations (over a period of 1 month).

Modified Beacon Scheme & Resulting Estimated Coverage

This CubeSat, as so many others before it, was faced with the challenge of limited flash storage and a low onboard power budget, which translates to limited downlink capability. The team sought to downlink a magnetometer reading from the moment the beacon was sent, as well as health and status readings from onboard sensors and electronics, and a small collection of historical magnetometer readings that would be stored, transmitted, and overwritten at set intervals. Because each beacon was very limited in the number of bytes it could transmit at one time, it was necessary to divide the total information into three separate independent beacons, sent at 60 second intervals (two for the magnetometer data, and one for spacecraft health and status). One full collection of data would then be contained in one full rotation of three independent beacons, set to continuously update and transmit on a loop.

Due to the limited data length of the beacon (120 bytes), only 7 historical magnetometer readings to be included in this 3 beacon rotation system, with a beacon being sent at the start of every minute, completing a full cycle every 3 minutes.[7] Through these stored readings, magnetosphere measurements will be obtained for locations around the globe that are not within range of a ground station to immediately downlink to. By storing even a small number of readings over each pass, global coverage is significantly increased. Simulated results of global coverage with 7 historical data points using the modified beacon scheme are found in Figure 10, with each point on the plot showing a successfully downlinked data point. Although it is recognized that limitations still exist using this method (e.g. gaps in the consolidated map of the magnetosphere exist due to the large distance between existing amateur ground sites over some continents), it is expected to obtain a global survey of the geomagnetic field at a significant reduction in cost to that generated by ESA Swarm satellites.

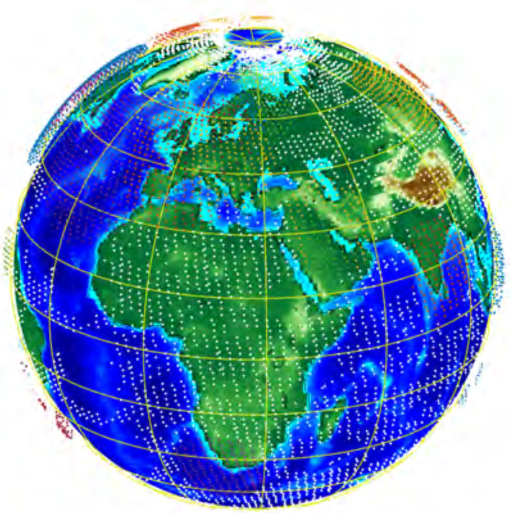


Figure 10: Simulated global coverage with amateur ground stations and stored magnetometer data (over a period of 1 month).

LOW COST INTEGRATION & TESTING

The general approach to integration and testing (I&T) for Magneto was an iterative development process. In order to keep I&T low-cost, the team was required to create a collection of test procedures before conducting any test, addressing the specific functionalities necessary to be tested, and to note down any risks or necessary deviations in test reports afterward. Considering that the team consisted mostly of undergraduate engineering students, this approach mitigates any decision making that may risk the ground and flight hardware, which would induce extra costs for the overall mission. Iterative integration and testing allowed the team to uncover both software and hardware compatibility issues and adopt different solutions in order to cut down the overall cost of the mission. Below, we discuss only a couple examples of low-cost integration and testing methods used in order to give the reader some ideas on how to be cost-effective in this iterative process.

Quad Antenna Housing Testing

The quad antenna housing was quickly prototyped out of wax blocks using a CNC mill to uncover its relevant design flaws. With this approach, creating prototypes quickly and cheaply accommodated frequent testing of the interactions between mechanisms, such as the drum antenna deployer and quad housing. The quad antenna housing mock-ups were fabricated out of wax models over 3D printing, as CNC milling could effectively complete the job with a shorter lead time without sacrificing details and quality. Testing the quad aperture was also made low-cost by using dummy-antennae booms created from scrap tape measures. As the tape of COTS tape measures comes pre-fabricated with a cross section ideal for coiled storage, its use in low-cost testing was intuitive. Multiple design iterations were tested using a single tape measure purchased for less than $10. In addition to the low-cost dummy antennae boom, low-cost dummy magnetometers were also created using FDM 3D printing and designed to the size and weight specifications of the actual Omega magnetometers to be used during the mission.

Far-Field Beacon Testing using Mobile Testing Unit

In order to perform far-field radio testing of flight components on a low budget, a Mobile Radio Test Unit (MRTU) was developed. The MRTU enabled full link testing of the entire CubeSat communications system without needing to purchase a second transceiver solely for testing purposes. The MRTU consists of a rechargeable battery, a set of DC-DC power converters to provide multiple voltage rails for internal components, an ODroid XU-4 microprocessor to control the radio transceiver using UART communications, and a sealed “clean enclosure” with grommeted connectors that can be removed to facilitate transceiver installation in the cleanroom. It also contains a wide array of internal sensors for easy field diagnostics. The MRTU was housed inside a strong Pelican case for ease of transport.[11]

Given that the USC ground station is located at USC’s main campus in downtown LA, the furthest line-of-sight

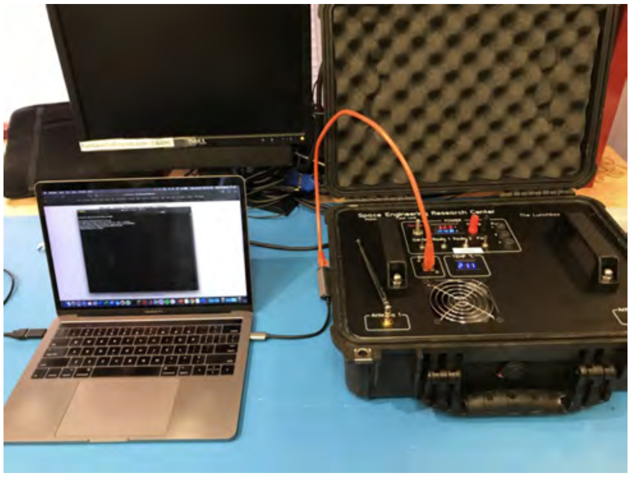


Figure 11: Mobile Radio Test Unit (MRTU) nicknamed "The Lunchbox", next to a laptop sending commands to the unit.[11]

vantage point with road access was determined to be Griffith Observatory, overlooking most of the LA basin. At a straight-line distance of about 11.5 km (7.15 mi), this allowed for full verification of telemetry from the CubeSat's health and status beacon to verify that all transmitted data can be received by the command and control station at the frequencies far-field RF distance. Since the transmission was in the amateur band, an amateur radio technician license was used to legally transmit the signal. The successful reception of all health and status beacons, using a custom receiver built using GNU Radio, validated that the communications system will close the link from orbit.

Figure 13: Beacon data received at USC command station using custom GNU Radio receiver.[11]

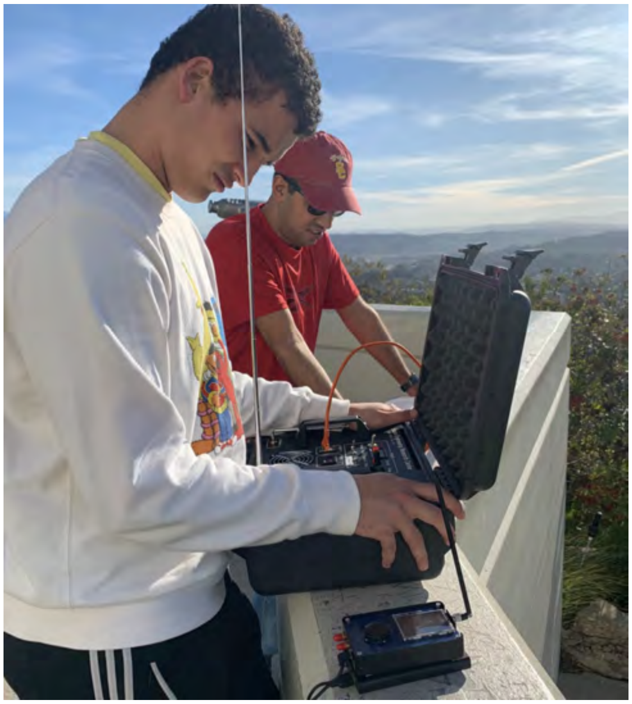


Figure 12: Transmitting the Health & Status beacon from Griffith Observatory to USC.[11]

CONCLUDING REMARKS

As a university-based CubeSat project, the Magneto mission designed and implemented a few low-cost strategies and techniques during development. Using wax and 3D printing materials in order to manufacture prototypes may help others meet required deadlines and timelines all while remaining low-cost. The single sun sensor and gyros attitude determination algorithm may be helpful when a magnetometer or other Earth-based sensor is not affordable and spacecraft attitude is needed. Use of the amateur radio community is quite common and can be extremely useful for other university-based projects as it can also be used as a teaching tool, while providing a mission with greater data coverage. Other integration and testing methods can also be implemented to reduce cost and risks involved with a student team.[2] The team shares a few of these ideas in hope to help other teams in their development on a low-cost CubeSat mission.

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