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Low Cost Magneto-Sphere Measurement: Leveraging Fusion of Low Data Rate Downlink with Amateur Radio Community

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ABSTRACT

In the last 10-20 years, the simplified structure and low-cost attributes of CubeSats have given universities and other student groups the opportunity to build and launch their own small satellites. This was the case with the University of Southern California's 4th CubeSat, Magneto. Magneto's mission objective is to validate two magnetometers, provided in partnership by Omega Engineering, by attempting to map the Earth's magnetic field in a low Earth orbit (LEO).

This goal presented a multifaceted problem, characterized by the design challenges associated with building a low-cost CubeSat that can collect and downlink data from all over the globe. A balance had to be maintained, operating within onboard storage limitations and keeping power demands low, while still downlinking enough widespread data to make the mission meaningful. Amateur radio operators around the world were proposed to act as the CubeSat's distributed global ground station network, providing a means by which to receive downlinked data in locations out of range of Southern California. Additionally, a rotating onboard beacon scheme with stored data points further preserved magnetosphere measurements taken out of range of a ground station. Employing these resources and techniques, the Magneto team hopes to produce a map of the magnetosphere comparable to one produced by European Space Agency (ESA) satellites.

INTRODUCTION

The University of Southern California's Space Engineering Research Center (SERC) provides students of all skill levels, from high-schoolers to PhD candidates, the opportunity to work on a wide range of projects for applications in space.[1,2] Fall 2019 saw the commencement of work on a student-built 1.5U CubeSat called Magneto through an official course in the Department of Astronautical Engineering. This would be the 4th CubeSat developed out of USC's SERC.[3,4,5,6,7]

The Magneto Mission

The Magneto CubeSat was born of an opportunity provided by Firefly Aerospace, as a part of their Dedicated Research and Education Accelerator Mission (DREAM) program to host academic and educational payloads on the first launch of their new Alpha vehicle.[8] The CubeSat's payload came from a mutual research agreement with Omega Engineering; they provide the Magneto team with a technical science payload, and Omega gets the chance to send their sensors to space for testing. The sensors provided were two magnetometers – and thus was born the mission objective: to map the Earth's magnetic field in a circular low Earth orbit (LEO) at an altitude of 300 km, with an orbital inclination of 97° as defined by Firefly's projected launch parameters.

These two Omega magnetometers were designed to mount on two booms to be deployed out from the main body of the CubeSat. A third magnetometer, previously validated by SERC, will also ride on the CubeSat and provide data to downlink, serving as a check with the Omega magnetometer values. All collected data from these three magnetometers would then be further compared with documented magnetosphere data from ESA Swarm satellites. The intent here is to take note of how both data sets compare in terms of both magnetic field measurement accuracy, as well as density and coverage of collected data. The hope is to demonstrate that a similar level of resolution can be achieved by a significantly cheaper, student-built mission.

When it came to the goal of resolution, numerous data points collected over an extensive area of the globe became the primary interest. However, because of limitations to the CubeSat's low-cost design, Magneto's communications were limited to transmission of a fixed low data rate beacon at 437.4 MHz. This beacon would be received by the UHF Yagi antenna at USC's dedicated Ground Station, the CubeSat's primary ground station. Having a fixed beacon that transmits once every minute, and only a single ground station meant that the only data ultimately received by the team would be data measured and downlinked while within line of sight of the USC station. The team thus faced the challenge of finding methods by which to extend the coverage of downlinked data out beyond the range of USC. Before discussing these methods, the limitations that posed this challenge in the first place, will be more thoroughly discussed.

MOTIVATION

As a student-built project, the use of a fixed beacon came from the necessity to use very low-cost hardware and software that was available, which specifically came from previous USC CubeSat missions. However, the International Telecommunication Union (ITU) requires that a satellite be fitted with a device to facilitate cessation of radio emissions to avoid interference with other radio communications, if and when necessary.[9] Thus, the Magneto team installed, very late in the project, a HamShield Mini – a small tri-band transceiver board from Enhanced Radio Devices, with the exclusive purpose of receiving a kill switch command from USC's ground station to cut beacon transmission per ITU guidelines. Otherwise, no other uplink communications with the HamShield were planned to be supported by the CubeSat's previously validated telemetry flight code. Since the team will not have the ability to send commands to the satellite telling it to downlink as it passes over the USC station, a hard-coded beacon will instead be used to transmit packets of encoded data every minute. Limitations imposed by satellite memory and power budgets were necessary to consider and work around when designing Magneto's beacon.

Low Power Budget

Because Magneto only had small solar cells mounted on the chassis (body mount only), rather than deployable panels, battery cell recharge was sufficiently slow so as to restrict high power use items, such as the beacon, to limited operations. For Magneto's beacon, transmission rate was once per minute. This limitation significantly impacted the coverage possible under a standard real-time transmission schedule, driving the team to devise ways to maximize where and when the beacons could be heard, relative to the onboard magnetometer data being collected during an orbit. Thus, the storage of past data for future transmission was implemented onboard.

Limited Memory

The next challenge was memory; the single PIC24 microcontroller used by Magneto only provides 24 kilobytes of in-memory storage. In order to store sensor readings from a full orbit, Magneto needed to keep them in its larger on-board flash chip. This necessitated the creation of a dynamic, fixed-size data structure that could not only map out the data history in storage, but also quickly retrieve the correct data points from the flash chip at the time of beaconing. Details of this data storage structure will be discussed in further detail later in the paper.

Typically, a CubeSat with these constraints would be forced to adjust the scope of its mission to account for its ability to downlink only small amounts of data when in range of its primary ground station. Alternatively, a CubeSat team may have the option to turn to private ground station companies, who offer pay-per-pass services. In this case, passes may be scheduled at any number of a company's ground station locations, during which data from the satellite is collected and relayed back to the team. However, for a University class CubeSat team operating on a limited budget, this can quickly become expensive and is therefore not a feasible option in most cases. Rather than rely largely on private ground station companies, the Magneto team instead turned to a free – though in many ways, priceless – existing ground station network: the amateur radio community.

AMATUER RADIO COMMUNITY

Satellite ground stations range from simple to complex facilities for data reception, processing, storage, and distribution. At the most basic level, a ground station may consist of a receiver, an antenna, and a computer with a software-defined radio (SDR) program for signal processing and recording. A wide range of low-cost hardware and kits available online, along with numerous online resources, lend themselves to amateur radio enthusiasts around the world. In order to transmit, an Amateur Radio license must be obtained through the Federal Communications Commission (FCC).[10] However, anyone with the necessary hardware is able to receive and listen to satellite transmissions without a license, which is key to the amateur radio community's role in Magneto's mission.

Amateur radio organizations of particular interest to this mission include the Radio Amateur Satellite Corporation (AMSAT), an international, non-profit, educational organization, and SatNOGS, an open-source ground station network. Between these two organizations, there exist hundreds of amateur radio operators around the world that actively listen to and report successfully received satellite signals – including the beacons of CubeSats.

It is these amateur radio operators that the Magneto team is turning to in order to expand data reception to

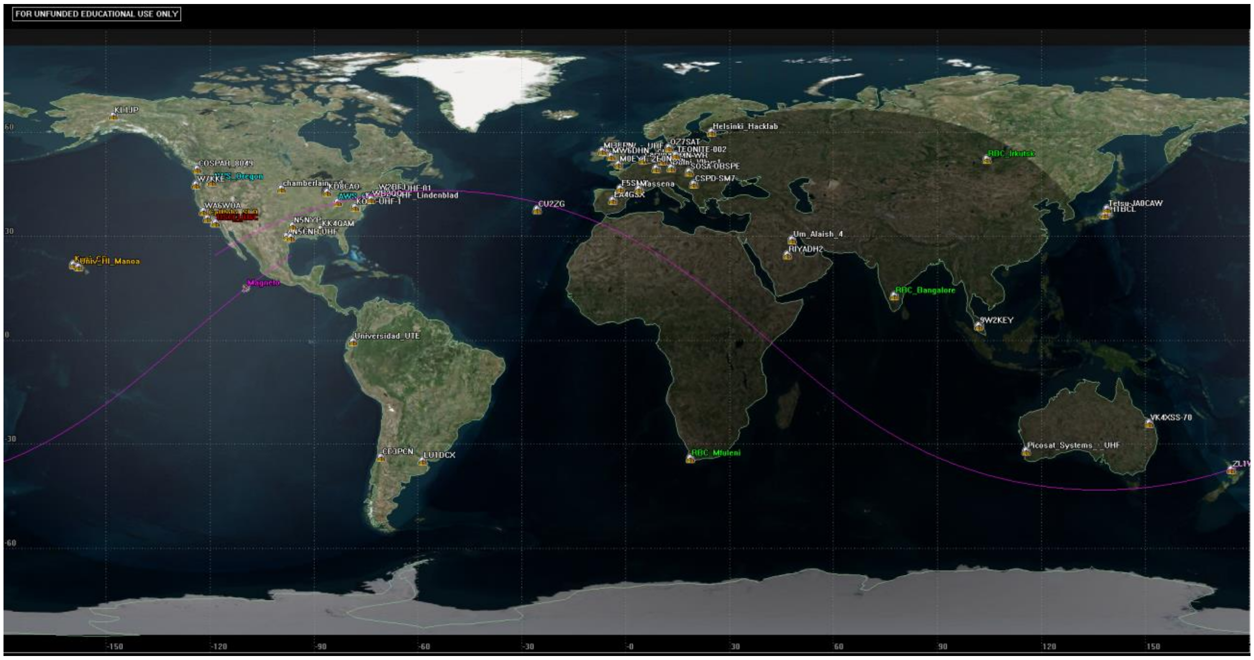

Figure 1: STK map of ground station locations and ground track of Magneto

locations outside of the USC ground station's line of sight. This effort to achieve maximum downlink coverage is crucial to the mission's overall objective to measure and downlink measurements of the magnetic field across the globe. To facilitate the communication of beacon data from amateur stations back to the Magneto team, a beacon decoder was created that could be sent out to the supporting station operators. The decoder would translate the received satellite beacon into readable data, which could thereafter be sent via email to USC's dedicated server. An email parser was created to receive the emails with data attached and read it into a database for later ease of access and analysis.

Compiling a Prospective Network of Ground Stations

The first step in building a network of amateur stations to support Magneto was to identify individual stations that were compatible with Magneto's communications – that is, stations set up to receive on the UHF band, (specifically, 437.4 MHz). This process was straightforward and simple, thanks to the user-friendly AMSAT and SatNOGS websites. These websites provide documentation of their members and users, including each user's location coordinates and recent activity (i.e. logs of recent satellite signal reception), making it easy to discern which stations are active vs inactive. Additional information available for stations on the SatNOGS network includes each station's unique call sign, type of antenna in use (and therefore frequency range it is equipped to receive in), and total number of observations with corresponding success rate.

Sifting through this available information, a spreadsheet was compiled, documenting call sign and coordinates for all recently active amateur stations capable of receiving at a frequency of 437.4 MHz. To begin building a visualization of Magneto in orbit relative to these selected ground stations, the compiled coordinates were migrated into a simulation scenario in AGI's Systems Tool Kit (STK), shown in Figure 1. All other expected supporting ground station coordinates were added to the scenario as well, including those of university partners California Polytechnic State University and the University of Hawaii in Manoa. From there, the team was able to further develop and visualize expected coverage.

SIMULATING EXPECTED COVERAGE

Investigating Current Access Coverage

To assess how well the mission objective was being met, the team needed a way to visualize and quantify the coverage achieved when relying on the supporting worldwide ground sites. This was done using MATLAB and STK.

STK is a simulation software commonly used for on-orbit satellite analysis. For coverage analysis purposes specific to Magneto, STK was used to produce position data for the satellite, as well as access periods between the satellite and each ground site. Position data consisted of 3D cartesian coordinates for the satellite in orbit, reported with corresponding time-stamps, at 1-second intervals. Access reports were also generated to provide the start and end times of each satellite pass over one of its proposed ground sites. Both sets of data were generated over the same month-long period.

These position coordinates and access times became the input to a MATLAB code written to organize and plot the data. Access start and end times for every pass over a ground station were used to filter through all position data, so that only coordinates that corresponded to a time that fell within a pass interval were kept. In other words, coordinates were kept only for times and positions when the satellite was within downlink range of a ground station. From there, coordinates that corresponded to the start of each minute were filtered out and kept. Recall, the CubeSat's beacon was set to transmit once per minute; at that point, each coordinate in MATLAB represented the location of the satellite at the time each beacon was sent.

To further simulate real on-orbit conditions, and in order to produce as realistic coverage predictions as possible, eclipse data was also generated in STK and brought into MATLAB. This eclipse data consisted of time intervals (specifically, interval start and end times) during which the satellite would be in the shadow of the Earth. Due to power budget constraints, the CubeSat would turn it's beacon off during eclipse; therefore, position coordinates were further filtered in MATLAB to throw out all coordinates that corresponded to a time predicted to be in eclipse.

At that point in the code, an array of coordinates existed that represented the predicted locations of the CubeSat in space, on its 300 km altitude, 97° inclined orbit path. More specifically, to reiterate, these coordinates represented the predicted location of the CubeSat when in range of a ground station, at the moment each beacon was sent, accounting for times the beacon would be turned off during eclipse. Each beacon contains a magnetometer measurement of the magnetic field taken at the moment the beacon is sent. Therefore, in the simulation output depicted in Figure 2, which shows these coordinates plotted over Earth, each white point represents a measurement taken of the magnetosphere at that location of the orbit in space.

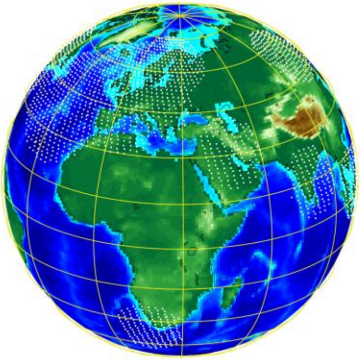

Figure 2: Simulated coverage when crowdsourcing magnetometer data from amateur stations, beaconing only real-time readings over a month-long period.

Figure 2 represents the best-case coverage obtained when using the previously compiled list of amateur ground stations and partner universities to collect and relay beacon data. Even with the amateur radio network, it was clear the team still fell quite short of the mission objective to map the global magnetic field. With the current approach of downlinking only magnetometer readings from the moment each beacon is sent, most of the magnetosphere was left apparently unmapped.

Now that the team had obtained simulations for scenarios utilizing external resources and support (i.e. the amateur radio community), it was time to investigate how the CubeSat's own systems could be maximized to extend coverage.

Design of Rotating Beacon Scheme

The next proposed solution to further extend coverage and fill in existing gaps between ground stations came in the form of a rotating beacon cycle with a fixed storage structure, as previously mentioned. To accommodate the downlink of all desired information, along with sets of stored data points to expand coverage, Magneto's downlink scheme was split into three separate beacons. One whole information set would be contained within that cycle of three beacons. The information outlined in Table 1 was the final set decided on, containing current magnetometer readings (label C), seven historical sets of readings (label H1, H2, etc.), and systems health and status information. Each data grouping in Table 1 contains additional labels where SM, OM1, OM2, and RPY stand for SERC Magnetometer, Omega Magnetometer 1, Omega Magnetometer 2, and Roll, Pitch, Yaw, respectively. This cycle of beacons will repeat indefinitely while Magneto is operational. The seven sets of historical readings became key in significantly improving Magneto’s expected data collection range.

Table 1: Beacon Breakdown

Beacon 1				Beacon 2				Beacon 3	
Contents		Bytes		Contents		Bytes		Contents	Bytes
Time		3		Time		3		Time	3
Header		8		Header		8		Header	8
C	SM	6	18	H4	SM	6	18	Health & Status	62
	OM1	6			OM1	6			
	RPY	6			RPY	6			
H1	SM	6	18	H5	SM	6	18		
	OM2	6			OM2	6			
	RPY	6			RPY	6			
H2	SM	6	18	H6	SM	6	18		
	OM1	6			OM1	6			
	RPY	6			RPY	6			
H3	SM	6	18	H7	SM	6	18		
	OM2	6			OM2	6			
	RPY	6			RPY	6			
TOTAL		83		TOTAL		83		TOTAL	73

Readings would be stored at set intervals, populating seven historical slots that would continuously be overwritten one at a time. While all other readings are beaconed in real time, magnetometer readings taken at defined intervals (ultimately decided to alternate between five and six minutes) are pushed to flash storage. Two distinct intervals were used to avoid the potential synchronization of data storage over the course of multiple orbits. The flash address of each set of data points is stored in a circular linked list in Magneto’s memory. Figure 3 provides a visualization of this circular data structure. Pointers maintain intervals of five and six minutes between historical datasets, which allows constant time access to the correct historical data being packetized for any given beacon. As each new set of sensor readings is taken, the sets of data identified by the data structure’s pointers at that time would be packetized with the current readings and beaconed. Then the current readings replace the oldest set of data in the structure, and all the historical data pointers rotate by one slot to mark the next set of data for beaconing. This data structure optimizes storage space and beacon packetization simultaneously.

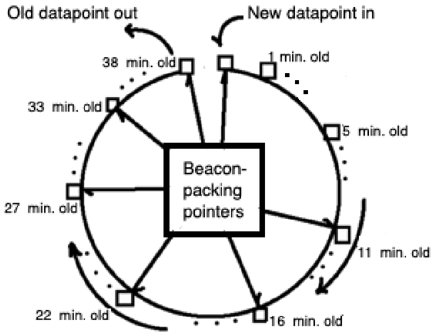

Figure 3: Fixed-interval data storage structure, for storage intervals of 5 and 6 minutes.

Simulating Coverage with Stored Beacons

Once an updated beacon design was decided upon, the MATLAB code was updated to produce a new coverage simulation that included stored data. Moreover, the code was then used to conduct a survey of storage interval combinations to study how various time intervals affected projected coverage.

It was a fairly simple process to create an array of coordinates that corresponded to the times defined by the storage intervals in the new beacon design. Variables were created to represent the minutes prior to a “current” magnetometer reading – the times at which data points would be pushed to flash memory for temporary storage. For example, if a proposed interval was a 5- and 6-minute combination, variables would be created to represent times of 5, 11, 16, 22, 27, 33, and 38 minutes (hence the labels on Figure 3). Each of these minute intervals was then subtracted from the start time of each ground station pass, to create an array of seven reference times. These reference times were used to identify the location coordinates that matched with the corresponding time in orbit. These coordinates, representing the location at which magnetometer readings were stored in flash memory, were then plotted to visualize how far expected coverage could be extended outwards from line-of-sight range from ground stations. Figure 4, especially when compared against Figure 2 for reference, clearly shows significant increase in projected coverage, leaving only relatively minor gaps when considering coverage of the whole globe.

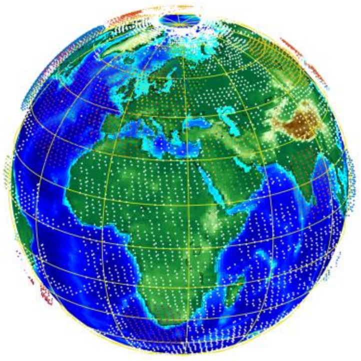

Figure 4: Simulated coverage when crowdsourcing data from amateur stations, beaconing real-time (colored) + stored readings (white) over a month-long period.

The remaining gaps in data points illustrate the absolute limits the CubeSat was constrained by in measurement and downlink of magnetosphere data. This was due to the scarcity of amateur stations located in Africa, as well as the unavoidable absence of stations in the Atlantic Ocean region, the effects of which are evident in Figure 4. To confirm that the mission was indeed achieving the best simulated coverage, a survey of storage interval combinations was performed to verify that the team used the optimal intervals for maximized coverage.

In order to study the effects interval combinations had on projected coverage, a quantifiable estimate of coverage had to be determined for each simulation. To accomplish this, first, the final collection of data coordinates (for both current, and stored measurements) were mapped onto a gridded sphere in MATLAB, as depicted in Figure 5. This sphere consisted of a 255x255 grid, a close approximation to the symbolic grid that would be created by lines of latitude and longitude on Earth.

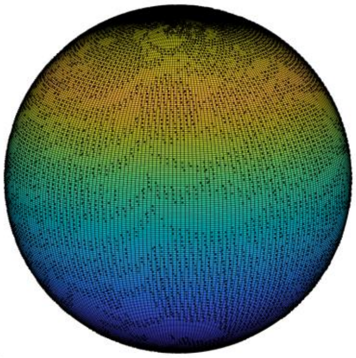

Figure 5: Data point coordinates mapped onto spherical grid for quantitative analysis.

This gridded sphere was then transformed into the 3D histogram depicted in Figure 6. This histogram represents the number of points (i.e. magnetometer measurements) present in each of the grid squares mapped onto the sphere in Figure 5. If there were no magnetometer measurements downlinked and received for a given location, then that location's grid square would remain empty. The number of empty grid squares could thus be determined using this 3D histogram. Once the number of empty grid squares was determined, a relative percent coverage could be obtained by comparing the number of occupied grid squares to the number of empty grid squares by the relation

$$\%Coverage = \left(1 - \frac{\#Squares_{empty}}{255 * 255}\right) * 100 \qquad (1)$$

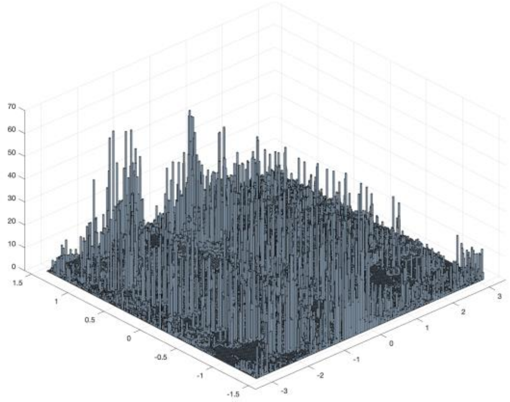

Figure 6: 3D histogram representing global density of measured magnetometer data points.

A value for expected percent coverage was documented for a range of storage intervals, with results as follow in Table 2. It appeared that the best coverage would result from smaller storage interval combinations. It was by this method that the 5/6-minute interval was determined to produce the best outcome, with a percentage slightly higher than other similar combinations, and approximately 7% overall better coverage than when only downlinking current readings.

The results obtained by this series of simulations informed the final design of the rotating beacon scheme to be coded into the CubeSat's flight software. It is recognized that assumptions and simplifications were made when developing the MATLAB code, but the team hoped that having these expected coverage projections would inform their efforts to design the communications system with intent. (as opposed to current + stored measurements).

Table 2: Coverage Achieved by Various Data Storage Schemes

Storage Interval	Added Coverage from Stored Sets (%)	Total Coverage (%)
No stored sets	-	13.62
1/1	1.34	14.96
12/15	3.70	17.32
9/12	4.08	17.70
2/3	4.63	18.25
7/10	5.23	18.85
5/11	5.74	19.36
3/7	6.28	19.90
5/8	6.32	19.94
5/7	6.46	20.08
4/6	6.87	20.49
5/6	6.92	20.54

COMPARISON TO SWARM SATELLITES

Once a final estimate of expected coverage was obtained, the team carried out a brief investigation to determine how Magneto's measurement resolution might compare against government missions with similar objectives. In particular, the European Space Agency's Swarm satellites would be used for reference and comparison.

The ESA's Swarm mission is a part of the broader Earth Explorer mission to better understand the planet we live on. The Swarm mission, still ongoing, began in 2013 with the launch of three identical 9.1 m long (including length of 4 m deployable boom) satellites, fitted with various sensors (including two types of magnetometers) to study Earth's magnetic and electrical field. Each of the three satellites, two from an altitude of 462 km and one from an altitude of 510 km, downlink data once per day to their primary ground station in Kiruna, Sweden.[11] The ESA states Swarm's mission objective as an effort to provide the "best-ever survey of the geomagnetic field."[12] This came at a cost of around $319,000,000 according to ESA officials.[13]

When comparing Swarm satellites against Magneto, the team focused on a few key factors including precision of magnetic field measurements, accuracy in position determination, and density of global data points (the factor this paper primarily focused on). Of these three factors, the precision of magnetic field measurements for each mission stacked up most closely to one another; magnetometers on the Swarm satellites report measurements with seven significant figures (± 0.01 nanotesla (nT)), while Magneto's magnetometers will report data with five significant figures (± 1 nT). Keeping in mind that the Earth's magnetic field ranges between roughly 25,000 and 65,000 nT, data reported from Magneto at five significant figures is more than adequate to characterize the magnetosphere. Greater disparities were present in the latter factors of satellite position accuracy and data density.

Accurate determination of satellite position in orbit is relevant to successfully mapping the magnetosphere due to the nature of data reporting; measurements of the magnetic field are taken at a specific location in space and downlinked with a timestamp. In order to determine what specific location each reading corresponds to, it is necessary to know the position the satellite was at in orbit when that reading was made. The most common method of tracking a satellite in orbit involves the use of two-line element (TLE) sets, maintained and updated by the North American Aerospace Defense Command (NORAD). However, the accuracy of TLEs can range from within 1 km to on the order of 100s of kms from the satellite's true position at a given time. To narrow in on true position, Swarm satellites use onboard sensors (e.g. GPS receivers) to determine position with approximated sub-kilometer accuracy. The Magneto team, by contrast, limited by a low-cost budget, expects to be able to determine satellite position to within approximately ± 12 km using a time of closest approach method for TLE updating.[14]

To make comparisons of collected data density, the ESA's VirES Swarm web interface was used to generate plots of Swarm magnetosphere data (available through the ESA's website). Figure 7 shows Swarm data collected by all three satellites over a month-long period. Analysis of these plots suggested the presence of only small holes in magnetosphere coverage ranging from 1-10 km.

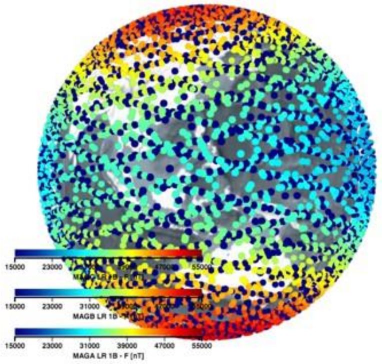

Figure 7: ESA Swarm satellite magnetometer data collected over one month. Colors indicate measure of magnetic field in nanoteslas.

MATLAB simulations for Magneto, previously described and also run over a month-long period, produced coverage estimations that exhibited large gaps ranging approximately from 500-2000 km in areas with no ground access. Figure 8 is included for clarity, omitting the underlying map of Earth. Smaller gaps that exist in-line with the CubeSat's orbit path are estimated to range from 1-180 km.

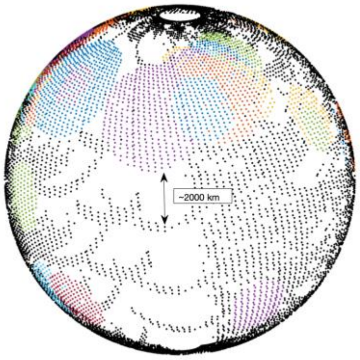

Figure 8: Largest existing gaps with amateur ground stations (colored) + stored data (black).

For reasons addressed in this paper, ability to achieve global downlink coverage was a significant challenge for Magneto. Based on the team's simulations, the CubeSat is expected to achieve notably less coverage than a mission on the scale of Swarm. However, when considered relative to that difference in scale, it becomes quite notable, instead, that a mission expected to be on the order of 0.01% the cost of the Swarm mission may achieve the level of coverage simulated herein.

CONCLUDING REMARKS

For a university team, development of the Magneto CubeSat presented the opportunity (dictated by necessity) to engineer creative solutions with the available resources. Magneto's communication capabilities started as a simple link between the satellite's singular beacon and sole ground station on USC's main campus. This communication link ultimately expanded to achieve simulated relay of data collected over every continent. Based on the simulations presented here, utilizing the amateur radio community to build a global network of ground stations may drastically increase a low-budget CubeSat's ability to collect widespread data and maximize satellite-to-ground contact. The optimization of beacon cycling within the CubeSat's flight code presented an additional low-cost method of preserving widespread data for successful subsequent downlink, all while working with the existing systems. One of the greatest takeaways from the challenges and efforts described herein should be the idea that being limited in budget does not necessarily mean being unable to pursue and accomplish meaningful scientific investigation of space.

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