Multi-Point Measurements of the Aurora with a CubeSat Swarm

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ABSTRACT

Space weather research is data-starved and small satellites offer an opportunity to the community. Over the past few years, Boston University’s Center for Space Physics has been developing a 6U CubeSat that deploys a small swarm of magnetometers to measure the fine-scale structure of the Birkeland currents that create the Aurora. By using direct three-axis measurements, spatially distributed, we hope to probe the plasma currents and fuse the data with other data products from ground-based optical and radio measurements. Boston University’s broad expertise in space physics and engineering systems offers a strong platform to foster a close relationship between those communities and to tailor the development of experiments while closely integrating students from several research fields. Through the efforts of such students, the ANDESITE program was selected to fly by the Air Force University Nanosat Program, and has been awarded a launch opportunity through NASA’s Educational Launch of Nanosatellites (ELaNa) initiative for the summer of 2017. Our university continues to foster a small satellite program and has used the momentum of its success in UNP-8 to lead development of new missions. Here in this paper, we will discuss the mission and concept of operations of ANDESITE, and how it integrates into current research at Boston University, along with a description of the strengthening satellite program at the school.

INTRODUCTION

Over the past few years, Boston University has been developing the ANDESITE small satellite system to explore the electro-magnetic environment of the auroral regions, colloquially the northern and southern lights. ANDESITE was selected by the University Nanosat Program (UNP) as a finalist in 2015 and, later that year, awarded a launch through NASA’s ELaNa initiative to fly in the summer of 2017. The mission represents a step forward in small-scale spatial-temporal measurements that can be achieved with emerging ad hoc space networking capabilities along with small low-cost sensor developments. This is a path-finding mission aimed at demonstrating the potential of dense low-cost in situ sensor networks to provide the data-rich environment needed to advance space weather research. Boston University is well positioned to provide tight integration between the space physics community’s needs and engineering system implementations through its interdisciplinary Center for Space Physics, which conjoins the Astronomy and Astrophysics, Electrical and Computer Engineering, and Mechanical Engineering departments.

The design of our mission relies on deploying several small “sensor nodes” from a main spacecraft—a 6U “mule” designed to comply with CubeSat Canisterized Satellite Dispenser (CSD) standards. Each sensor node holds a magnetometer that will provide three-axis magnetic field measurements with roughly ten nanotesla accuracy. By distributing the sensor nodes spatially, the system measures relative variations of the field as it flies through the aurora. With Ampere's law

\[ \nabla \times (B_{Earth} + \delta B) = \mu_0 J \]  

(1)

from Maxwell's equations—seen in Equation 1 and pictorially in Figure 1—and a priori knowledge of Earth’s background magnetic \( B_{Earth} \), we can calculate and map the current densities, \( J \), due to energetic charged particles moving into and out of the atmosphere.

![Figure 1: Multi-point measurements of magnetic field variations in the auroral regions allows us to map out the invisible electric currents responsible for fine scale structures embedded within auroral arcs.](image)
To better understand the timeliness of ANDESITE, the next two sections demonstrate the need that led to the development of the concept.

**Auroral Science with Spacecraft**

The Earth’s aurora—commonly referred to as the Northern or Southern lights—is the manifestation of a current system that connects the ionosphere to the magnetosphere. This system was first discovered from a satellite-based magnetometer measurement in 1963 by A. J. Zmuda et al. [1] of the John Hopkins Applied Physics Laboratory (APL). The satellite observed a transverse magnetic field perturbation that can be explained through Ampere’s law as a current aligned with the main dipole field of the Earth [2] and named after Birkeland—who initially hypothesized such a current [3]. Since the measurement was only a time series from a single satellite the currents had to be modeled as an infinite sheet of finite thickness that crossed the trajectory of the spacecraft.

![Figure 2: High-resolution cameras reveal periodic fine-scale structure (order of 100 m) embedded within larger scale auroral arcs. The motions of these structures (red and yellow arrows) suggest the presence of dispersive hydrodynamic waves (Alfven waves).](image)

By the late 1990s and early 2000s APL had started to form what is now known as AMPERE. That mission uses precision magnetometer measurements from secondary payloads on the Iridium satellite constellation—more than 66 satellites in six distinct orbital planes. This network allows for a near real-time monitoring of the global current system, but is inherently limited in spatial resolution due to the orbital geometry chosen for the Iridium satellites [4]. When looking up at the aurora with ground based measurements such as that shown in Figure 2, instruments clearly show structures that occur on the order of 100s of meters [5,6]. While Utah State University recently launched a sounding rocket mission [7] with a goal to resolve the aurora, no satellite system has yet been able to spatially measure this structure scale directly with magnetometers.

**Formation Flight**

With the advent of the CubeSat standard, technologies for small satellites have emerged that make small swarms of sensors a possibility. Formation flight of closely spaced spacecraft has become less risky as the actual satellite cost and size has decreased. Many of these formation flight missions even have a scientific focus, but usually “multi-point” is limited to two or three spacecraft [8]. This is due to the cost and complexity involved in creating a fleet of spacecraft, each with full capabilities, and designing trajectories that keep them in some sort of useful configuration.

NASA’s Edison Demonstration of Smallsat Networks (EDSN) project was meant to demonstrate a peer-to-peer network of eight identical satellites—all with a space-weather sensor package [9]. This would have been one of the largest closely spaced formation of capable small satellites to date if the launch had not failed—nominally all the satellites would have stayed in a loose passively held configuration until they drifted apart. Each satellite could either directly communicate with the ground or transfer data along the network to the best available node for ground communication.

KickSat [10] represents another side of the spacecraft swarm engineering solution space, by deploying hundreds of ChipSats (effectively, printed circuit boards) as satellites and watching their aggregate behavior. Unfortunately, the main bus of the spacecraft system was unable to deploy the picosatellites due to an uplink failure.

The idea of an ad hoc network in space remains an intriguing engineering challenge and becomes even more useful when aiming at the design space between these previous cases—namely, the case where the sensor nodes are can be designed so small, low cost and simple, just satisfying the scientific needs of the mission, that they are unable to transfer their data individually to the ground. The design of ANDESITE is based on that idea—a mothership that contains all of the sub-satellites, deploys them on orbit, and serves as a central data hub for communication. To illustrate more clearly, the following sections overview the design and operational modes for ANDESITE in detail.

**ANDESITE**

The ANDESITE system consists of 8 identical sensor nodes, and a 6U “data mule.” All 9 satellites deploy in a single configuration called the aggregate satellite into a
500 km altitude near circular orbit at 85 degrees inclination. At this time, the aggregate satellite will enter de-tumbling mode—Figure 3-2. During this phase, the attitude control system on the 6U—designed around a three-axis magnetorquer arrangement—will activate and stabilize the craft using state knowledge garnered from six onboard sun sensors, gyros, and magnetometer. While nodes will be launched with pre-charged batteries, a slow rotation rate stabilized towards sun vector will ensure that the mule batteries are at full capacity before entering the next phase of the deployment. Once de-tumbling is finished the mule will stabilize with the bottom plate nadir pointing and eject a pair of sensor nodes. The sensor nodes begin startup sequences the moment they are launched from the mule via a mechanical switch. After initialization device discovery occurs and the self-organizing sensor network is consolidated.

In order to perform the science mission, the constellation must be in a near polar circular orbit. This geometry allows perpendicular passage through the Region 1 and Region 2 Birkeland current sheets around the polar regions of the Earth—to conserve power we will collect only during the southern hemisphere passes since we are launched during the winter of that region and the aurora will be most active at the pole pointing away from the sun—Figure 3-4.

Launched into low Earth orbit, the sensor nodes’ trajectory will naturally decay eventually terminating the mission after the objectives are complete. Based on the insertion altitude given by the launch system—500km—the nodes will reenter well before 25 years. Simulations have shown that this altitude also maintains a constellation of sensors that is within communication range of the mule for several weeks—setting the mission lifetime by the ability for the network to remain in that active distance.

**Mule**

The ANDESITE main bus—the 6U CubeSat known as the mule—houses eight (8) sensor nodes and electronics that manage the data network. Due to restricted transmission ranges of the sensor node radios, the mule will collect data from the dispersed node network and relay the information to the ground station through the GlobalStar satellite network as seen in Figure 3-7.

To spatially resolve the currents in the longitudinal direction, all eight sensor nodes will be launched symmetrically from the mule near the magnetic equator. This concept is schematically in Figure 3-3 and testing for deployment is shown in Figure 4. The change in velocity ($\Delta V$) gained from separation—around 3 m/s—will affect the inclination of the node orbits to give a desired separation of about 10 km between pairs near the science region of interest. This pattern will be periodic and the sensor node orbit trajectories will re-coalesce at the node of separation twice every orbit. To account for this, the difference in inclinations of the orbits will ensure crossings of the nodes occur out of phase—due to the differential $J_2$ gravitational perturbation each node of a pair experiences. With a slightly higher ballistic coefficient than the mule, each node pair will then also proceed to drift ahead along track—losing altitude due to drag and thus speeding up—and create a string that will roughly hold together as a formation of nodes and slowly recede from the mule.
The mule serves as the data link between nodes and a ground station. To communicate with individual sensor nodes, it uses a short-range radio (the RFM22B), setting up the mesh topology. The radio itself connects to the Command and Data Handling (C&DH) system via SPI, and is configured using a Linux C++ RFM22B library. Once the sensor nodes collect their required data, it will be transmitted to the mule with a self-consistent architecture, as all the nodes also use the RFM22B modules.

The C&DH software of the mule resides on a BeagleBone Black (BBB), a low cost, open source embedded development platform with 84 programmable I/O pins. Given that it is a full-fledged computing system—not just a simple microcontroller—using the Angstrom Linux distribution, the BBB sports extreme portability, capable of running almost any OS and ability to run/compile most languages.

The mule’s long-range communication protocol relies on the GlobalStar satellite network, a constellation of satellites used for communication with satellite phones to ground. To communicate with the network, the mule will have a Duplex radio, which connects to the BBB via UART connection, and allows for data dumping to be transmitted to the satellite network and then to the ground station via a web-based interface. The BBB will employ the use of data compression to reduce the amount of data being sent through the network, both lowering cost and increasing efficiency.

The power distribution on the mule will be operated by a CS-XUEPS2-60 Clyde Space electrical power system. The Clyde Space EPS connects to the solar panels via six independent Battery Charge Regulators (BCRs). The output of the six BCRs are then connected together and, via the switch network, supply charge to the battery, Power Conditioning Modules (PCMs) and Power Distribution Modules (PDMs). The battery linked to the Clyde Space EPS is a 6 cell Lithium-Polymer battery system also designed by Clyde Space. This battery has a 30 Wh capacity and will distribute regulated power through the 3.3 V, 5 V, and 12 V voltage buses to the AD&C, BBB, and interface boards inside the 2U avionics bay.

The 6U mule structure—seen in Figure 5—is composed of two regions: a launch bay that houses and deploys the sensor nodes, and an avionics bay enclosing all data-handling components. The size of the node bay dictates that it be located at one end of the mule, within a 4U space, with the remaining 2U space of the satellite composed of avionics equipment in a 14x22x10 cm compartment. This arrangement serendipitously allows the main 6U bus to benefit from aero-stabilization as the nodes are deployed.

The mule is clad in 3.2 mm and 2.3 mm thick sheet aluminum, supported by the walls of the sensor node bay as well as interlocking braces that enclose the avionics. The top plate and braces of the mule are made of AL 6061-T6. The bottom sheet of aluminum functions as a baseplate that supports the entire mule structure while inside the CSD through the tab-based interface. This baseplate is made of anodized AL 7075-T7—and will be the nadir pointing face once the aggregate stabilizes.

**Sensor Nodes**

The sensor nodes are approximately 1/4U—or about the size of a DVD case—and by requirement contain the instrumentation necessary to complete the scientific mission. This includes magnetometer circuitry, as well as the sensors necessary to determine position and orientation corresponding to each measurement—which when combined, represent the scientific data product transmitted back to the ground. Sensor nodes are simultaneously ejected out of the satellite in pairs to provide for the desired network formation, as well as to negate rotation that would be induced to the mule by the ejection of a single mass with a lever arm. All sensor nodes have an exterior dimension of...
approximately 17.5x10x1.75 cm with mass of 380 g—a CAD of the basic layout is seen in Figure 6.

![Figure 6: Exploded view of the sensor node.](image)

ANDESITE’s main feature is a mobile wireless network architecture intended for space and other harsh environments where nodes are allowed to move along three dimensions passively once they are deployed—and can communicate back to the main bus. Given the collaborative nature of satellite sensor nodes, the loss of multiple units would not be catastrophic for the mission because there are eight sensor nodes gathering data—nodes can hop data to any other node within the network until it reaches the mule.

Much of the network design for ANDESITE shares many of the characteristics of traditional sensor networks. However, there are a number of key differences between space networks and their terrestrial counterparts. For example, many of the popular protocols for static, ground-based wireless networks, namely IEEE 802.11 (Wi-Fi), cannot be directly used for space applications given the relatively large distances between sensor nodes and the mule, mobility of the network, time-synchronization, and the inherent three-dimensionality of the medium. Furthermore, many of these classical schemes may not account for the severe energy and computational limitations of a sensor node.

Each sensor node’s radio—an 435MHz RFM22B which is by design low-power and low-profile—can connect up to 16 km via a measuring tape dipole antenna that is attached to each picosatellite. While this range is insufficient for a sensor node to communicate with the ground, it is adequate for a multi-hop communication between a node and the mule.

To establish the network between the mule’s RFM22B and the eight other radios on the sensor nodes the RadioHead Arduino library is used extensively on the sensor node side. The RadioHead library has the functionality for routing between radios which creates a mesh network. A mesh network is important in the event that a certain sensor node is too far from the mule. As long as a sensor node is within range of another sensor node, it will be able to transmit data to it, and data will arrive to mule by hopping through this mesh network. The RFM22B radio on the mule interfaces with the BeagleBone Black through a Linux based C++ class—as mentioned before. This C++ Library will be used to transmit and receive data to and from the network created by the RadioHead library.

ANDESITE’s network is designed for hierarchical topologies, in which some nodes are designated as seeds and others as slaves. Furthermore, the RFM22B network allows sensor nodes which are not in range of the mule to transmit packets to their final destination through intermediate nodes via the mesh network. The RFM22B network is be operated by an 8-bit microcontroller with onboard flash housed within each of the sensor nodes.

Each sensor node also contains a set of standard avionics subsystems—which include Communications, GPS, EPS, gyroscope, along with the magnetometers used as the science payload. An off-the-shelf GPS—which has not been flown in space yet—was chosen to fit power and size restrictions since most space-qualified systems are too power hungry for the nodes. The custom designed node EPS has its own PIC16F1512 microcontroller to monitor the health of the battery as well as the charge process. Every node is able to determine its attitude through the use of a LSM9DS0 gyroscope and the magnetometer that is also used as the scientific instrument. The magnetometer onboard—i.e., the scientific instrument—is comprised of a 2-axis HMC1002 and a 1-axis HMC1001 Honeywell magnetometer. The magnetometers are oriented to sense 3 components of the magnetic field.

Table 1 describes the power consumption between the three different modes on the sensor nodes—a key concern for such small picosatellites. The sensor nodes are in science mode, when they enter the magnetic polar region. During this period, the nodes are not transmitting, as to minimize electromagnetic interference. During Low Power mode, only the essential subsystems are active to maintain orbital health, such as EPS and the C&DH. The sensor node is rarely consuming over 1W of energy during most of its lifetime.
The processing unit is based around the Atmel ATMega2560, a microcontroller with a wide array of peripherals (I2C, SPI, UART, and various ADC channels) and a built in USB transceiver. This is a simple, low power microcontroller capable of running robust real-time operating systems. The microcontroller communicates with the RFM22B radio via a SPI connection. Additionally, the board contains memory to buffer data during multi-hop transmissions. Though the central microcontroller commands the entire sensor node, there is an additional microcontroller for the EPS subsystem. The EPS microcontroller reports the status of the system to the central microcontroller. At any time, if power is disrupted or problems arise, the EPS microcontroller is able to interrupt the central microcontroller to protect the sensor node.

**Table 3: Summary of a Single Sensor Node Power Budget**

<table>
<thead>
<tr>
<th>System</th>
<th>Science Mode (W)</th>
<th>Data Transfer Mode (W)</th>
<th>Low Power Mode (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>0</td>
<td>0.2805</td>
<td>0.2805</td>
</tr>
<tr>
<td>ATMEGA2560</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>EPS</td>
<td>0.121</td>
<td>0.121</td>
<td>0.090</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SD Card</td>
<td>0.33</td>
<td>0.33</td>
<td>0</td>
</tr>
<tr>
<td>Gyroscope</td>
<td>0.02013</td>
<td>0.02013</td>
<td>0.02013</td>
</tr>
<tr>
<td>GPS</td>
<td>0.068</td>
<td>0.068</td>
<td>0</td>
</tr>
<tr>
<td>Total (with contingency)</td>
<td>0.742 W</td>
<td>1.013 W</td>
<td>0.539 W</td>
</tr>
</tbody>
</table>

Each sensor node will be powered by a 3.7 V, 10 Ah lithium polymer battery. This voltage will be converted to the 3.3 V, 5 V, and ±6 V used by all other on-board components. The EPS onboard all the sensor nodes shall a unique design built by the EPS subsystem. The custom EPS has an IC that regulates and monitors the lithium polymer batteries for charging and supply power to the other subsystems if there is excess power.

Over the course of an orbit the spacecraft will collect approximately 5 MB of data per polar pass. The data collected is stored on a 4 GB SD card within the node. After the sensor node exits the polar region, it begins to transfer the data in a multi-hop fashion. Each node has a unique address which is attached to each packet to know which node generated the packet. When a node receives a packet that begins with the common network message, it will read into the packet to see if it has already received it. If the node's address is not in the packet's viewing history, the node will check if the packet was sent to them. If not, the node will append its own address to the packet and rebroadcast the message. The message will continue to be rebroadcasted until it is received by the radio on the mule. By the time the network drifts away from the mule—about two weeks—each node will have nominally collected about 15 passes worth of scientific data each day or several hundred in all—far exceeding the capability of current sounding rocket experiments in terms of data volume.

**BU SMALL-SATELLITE PROGRAM**

This small satellite project represents a continuing effort by Boston University to foster educational opportunities to the student body. Our heritage begins with one of the first student built small satellites—TERRIERS [11]—launched in the late 1990’s, continuing onward to BUSat—a modular 27U design for shared a shared bus amongst standardized payloads and also a UNP contender—and now ANDESITE. We hope to solidify the connection with our expertise in the BU Center for Space Physics to create better space-based measurements of space plasma physics.

Along this vein, Boston University also leads the development of the Cusp Plasma Imaging Detector (CuPID) cubesat to be launched in 2019. The project is a collaboration between BU, NASA Goddard Space Flight Center, Johns Hopkins University, Merrimack College, and Drexel University.

CuPID is motivated by the goal to study meso- and macro-scale features of solar wind-magnetosphere coupling. The 6U spacecraft will address this goal by studying soft X-rays emitted from solar wind charge exchange in the magnetospheric cusps. The science payload includes a wide field-of-view (5x5 degrees) soft X-ray imager, the first of its kind to be launched into orbit.

Pending ANDESITE’s success, we have begun to move forward and develop a follow-on concept that creates an actively controlled swarm that can maintain its formation in a desired configuration for much longer. With our expertise in ground based all-sky imaging of the aurora along with probing with incoherent scatter radars we hope to lead the path towards data fusion techniques that include the multi-point in situ measurements provided by spacecraft.
CONCLUSION
With the development and launch of ANDESITE in the summer of 2017, Boston University will have developed its first satellite since TERRIERS and increased the number of spacecraft it has on orbit by an order of magnitude—the mule and sensor nodes total nine satellite buses. The momentum gained has already led to an increase of expertise and interest at the university, spawning several new projects in the pipeline.

The scientific mission of ANDESITE will also represent a new age of multi-point measurement capability for space science that will allow finer detailed investigations into the structure of the aurora with technology implications that affect many other areas of space plasma measurements. Effectively scaling down cost prohibitive experiment concepts, and opening up the opportunity for future multipoint measurements of the near-space plasma environment.

REFERENCES