Enabling low-cost, high accuracy magnetic field measurements on Small Sats for space weather missions

Odile Clavier, Theodore Beach, Brynmor Davis, Ariane Chepko
Creare Inc.
16 Great Hollow Rd, P.O. Box 71, Hanover, NH 03755; 603-643-3800
ohc@creare.com

James Cutler
University of Michigan
1320 Beal Avenue, Ann Arbor, MI 48109; 734-647-8223
jwcutler@umich.edu

ABSTRACT

Magnetic field measurements play an important role in space weather and engineering applications of Earth-orbiting satellites, such as attitude determination, momentum management, and scientific instrument pointing. Unless built specifically for high accuracy magnetic measurements (an expensive process), satellites usually come with significant magnetic sources of errors that severely degrade the accuracy with which the Earth's field can be measured. This study presents innovative algorithms that enable high quality magnetic field measurements on smaller spacecraft without booms and using "standard" buses. We present results obtained on laboratory and space data from low-cost magnetometers on the Radio Aurora Explorer CubeSat launched in November 2010 to demonstrate how these algorithms can tremendously improve measurement accuracy on a spacecraft that includes instrumentation with significant variable magnetic signatures. The algorithms rely on both ground-based calibration procedures and on-orbit compensation using multiple magnetometers. When used with high accuracy magnetometers such as fluxgate space sensors, it will enable high accuracy magnetometry with nano-Tesla resolution in low-Earth orbit.

INTRODUCTION

Space weather observations enable the reliable and accurate prediction of conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere. These conditions can influence the performance and reliability of space-borne assets and ground-based technological systems both of which are extremely important to defense and civilian applications. Space-based magnetometers quantify the magnetic field surrounding the Earth and thereby represent one of the primary modes of observation of space weather. However, space-based magnetometry is complicated by the presence of disturbing magnetic fields on the spacecraft carrying the magnetometer itself. To ensure these sources do not interfere with the measurement, the approach has been to move the magnetometer far from the main payload as the field contributions decrease with increasing distance. This is usually accomplished with the deployment of a boom.

The objective of the research presented here is to provide an alternative solution that enables the placement of one or several magnetometers on a spacecraft and correct for magnetic disturbances from the spacecraft. While this approach may not replace the boom for extremely accurate and low level measurements, it promises to be a sufficient solution for most Earth-centered space weather missions, as well as spacecraft control applications at a much lower cost of integration. The objective is therefore to reduce the magnetic contributions of the spacecraft to a level close to the resolution of the magnetometer. Furthermore, with the advent of low-cost microsatellites designed for scientific missions, it is desirable to develop a magnetometer system that can easily install on any satellite and still provide very accurate scientific measurements of the magnetosphere.

LOCUST CONSTRAINT ALGORITHM

Description of Algorithm

The locus constraint algorithm uses a nonlinear two-step estimator to calibrate the magnetometer in the ambient field of the spacecraft. This approach has been presented in several published articles; see for example Gebre-Egziabher et al.[1] and Elkaim et al[2]. This estimator is an algorithm that relies on two specific premises: (1) when measuring an ambient constant magnetic field, the measurements of an error-free sensor sensitive only to the constant magnetic field will lay on a perfect sphere when the sensor is rotated through various angles in all three spatial directions; and (2) when measuring an ambient constant magnetic field, the measurements of a real magnetic sensor which is sensitive to all magnetic fields present and which may include inherent errors will lay on a distorted ellipsoid.

The first premise is well known and used for measuring heading. For example, measuring the x- and y-components of a perfect vector magnetometer in a location far from any other magnetic sources, and rotating that sensor in a flat plane yields a perfect compass rose. The second premise makes sense once the sources of error on the measurements of the Earth's magnetic field are analyzed. These include both errors due to the sensor itself and errors in the measurement of a constant field caused by the presence of other magnetic field disturbances. These errors and their mathematical representations are described below.

Null Shift Errors. These errors appear on each axis and shift the measurement by a constant offset. They are sensor errors and can be expressed as a constant offset on the overall measurement $\vec{B}^b_{ns}$.

Scale Factor Errors. These errors are representative of varying sensitivities across each axis. The scale factor error is a multiplicative error on the measurement and is expressed as a 3×3 matrix C_{sf}.

Misalignment Errors. These errors stem from non-orthogonality between the three sensing axes. This results in one axis producing a non-zero measurement even when the sensor is aligned with a field that is perpendicular to that axis. The misalignment error is expressed as a multiplicative error on the measurement as a 3×3 matrix C_O.

Hard Iron Errors. The hard iron errors are constant magnetic fields that occur due to the presence of magnetic fields near the sensor. These fields are extremely difficult to avoid on a spacecraft in which other instrumentation exists. The hard iron errors are represented as an offset on the measured field, which is a vector $\delta\vec{B}^b_{hf}$.

Soft Iron Errors. The soft iron errors are caused by materials which generate their own field when exposed to an external field, so that it is no longer a constant bias, but it depends on the orientation of the sensor, as well as the magnitude of the field. The soft iron errors can be represented as a multiplicative error which is a 3×3 matrix C_{si}.

The first three sources of error can be identified independently for each sensor through a calibration process in a magnetically clean environment where the local Earth field is well behaved. These errors are combined into one measurement equation:

$$\hat{\vec{B}}^b = C_O C_{sf} \vec{B}^b + \vec{B}^b_{ns} \tag{1}$$

where $\hat{\vec{B}}^b$ is the measured field and $\vec{B}^b$ is the ambient field. The b superscript refers to the body frame.

Sensor Calibration Algorithm. We combine this equation with the assumption that the components of the ambient field all fall on a sphere as follows:

$$\left|\vec{B}^b\right|^2 = {B^b_x}^2 + {B^b_y}^2 + {B^b_z}^2 \tag{2}$$

Substituting this expression into the square of the above expression for $\hat{\vec{B}}^b$ results in a shifted distorted ellipse on the measurement axes as follows:

$$\begin{aligned} &A{\hat{\vec{B}}_x}{}^{b\,2} + B\hat{\vec{B}}_x{}^b\hat{\vec{B}}_y{}^b + C\hat{\vec{B}}_x{}^b\hat{\vec{B}}_z{}^b + D{\hat{\vec{B}}_y}{}^{b\,2} + E\hat{\vec{B}}_y{}^b\hat{\vec{B}}_z{}^b \\ &+ F{\hat{\vec{B}}_z}{}^{b\,2} + G\hat{\vec{B}}_x{}^b + H\hat{\vec{B}}_y{}^b + I\hat{\vec{B}}_z{}^b + J = 0 \end{aligned} \tag{3}$$

where *A*, *B*, *C*, *D*, *E*, *F*, *G*, *H*, *I*, and *J* are functions of the misalignment errors, the offsets, and the scale factor errors. This equation is linear with respect to the parameters *A*, *B*, *C*, *D*, *E*, *F*, *G*, *H*, *I*, and *J* so that these unknowns can be solved using a batch least square estimation. Once these parameters are solved, the values of the scale factors and offsets can be determined. The details of this algorithm have been published in Elkaim[2] and Gebre-Egziabher[3].

Hard and Soft Iron Compensation. If we assume that C_o, C_{sf}, and $\vec{B}^b_{ns}$ are already known, then the same approach can be used to correct for the presence of soft and hard iron on the spacecraft. In this case, the measurement equation is now:

$$\hat{\vec{B}}^b = C_o C_{sf} C_{si}\left(\vec{B}^b + \delta\vec{B}^b_{hf}\right) + \vec{B}^b_{ns} \tag{4}$$

where the unknowns are C_{si} and $\delta\vec{B}^b_{hf}$. By rotating the entire spacecraft in the Earth's field, the locus of measurements is mapped to an ellipsoid to identify the offsets and scale factors. The resulting calibration parameters consist of three constant offsets (x_0, y_0, and z_0), three scale factors (s_x, s_y, and s_z), and three angles

(ϕ, ρ, and λ) which are applied in a rotation cosine matrix to correct for axis misalignment and soft iron errors.

Application to the Radio Aurora Explorer CubeSat

To test out the feasibility of these algorithms for space weather applications, the Radio Aurora Explorer (RAX) CubeSat mission was chosen as a test-bed. RAX is the first CubeSat funded by the National Science Foundation (NSF) Small Satellite Program. The project is a collaborative research of SRI International and the University of Michigan. The mission is a ground-to-space bistatic radar experiment wherein a ground-based incoherent scatter radar and a space-based radar receiver form a bistatic radar (Cutler[4]). The RAX satellite instrumentation includes two three-axis magnetometers. This configuration lends itself very well as a test-bed for the locus constraint algorithm on the ground and in space. It is also an ideal platform for the development of algorithms that can also correct for time-varying magnetic contributions in space. Figure 1 shows the approximate location of the various magnetic sensors for reference. Table 1 describes the manufacturers and sensitivity of each magnetometer. The three-axis PNI magnetometer has a noise floor of approximately 128 nT and the magnetometer included in the IMU has a noise floor of approximately 125 nT.

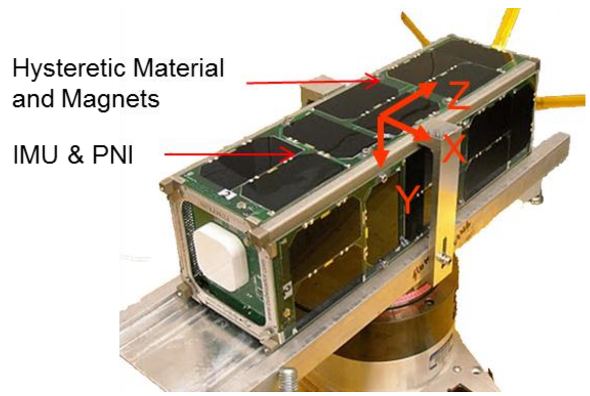

Figure 1: Magnetometer Locations on RAX CubeSat

Table 1: Magnetometers on RAX

Sensor Name	Manufacturer	Model	Noise Floor
PNI	PNI Sensor Corporation	PNI MicroMag3	128 nT
IMU	Analog Devices	ADIS 16405	125 nT

Tests with the RAX CubeSat flight unit were conducted in five different power states (see Table 2). One of the goals was to determine the effect of different subsystem operations on the calibration parameters produced by the locus constraint algorithm. To simplify CubeSat calibration, a pitch-roll fixture was built using strictly non-magnetic materials (see Figure 2). Using this fixture, each magnetometer on the spacecraft can be placed very close to the center of rotation (by sliding the spacecraft along its cradle) and field measurements can be made over the spherical locus. Keeping the magnetometer close to the center of rotation ensures that the effects of the local magnetic gradients are minimized. The test fixture was set-up on a sheet of plywood outside, where local magnetic gradients reached about 30 nT/m, as measured using a MEDA hand-held fluxgate magnetometer (Model FVM 400, Macintyre Electronic Design Associates, Inc., Dulles, VA). The Earth's magnetic activity was monitored during calibration and was stable during the test time with no detectable disturbances. The RAX CubeSat includes significant magnetic contributions which are both of the soft and hard iron type such as the steel antenna, the magnets and hysteretic magnetic material used for passive attitude control, and the power system. All these contributions must be compensated for during orbit measurements.

Table 2: Modes Tested During Calibration

Mode	Description
Baseline	No spacecraft on the apparatus
Standby	Spacecraft is mounted and in standby mode
GPS only	Standby mode with GPS also on
Operational	All subsystems (no solar panels or telemetry)
Payload	Operational mode, but with GPS off

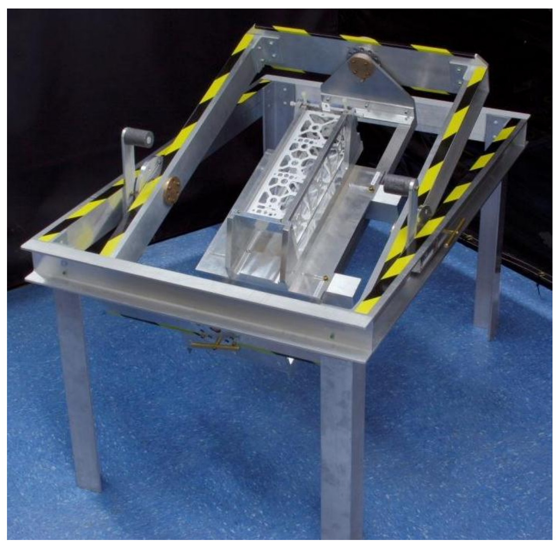

Figure 2: Pitch-Roll Apparatus to Perform Ground-Based Calibration of CubeSat

In the baseline test, only the fluxgate magnetometer was mounted on the calibration apparatus. The locus constraint algorithm extracted the measured magnetic field with a standard deviation of 7 nT using the MEDA magnetometer. The noise range for the magnetometer system was 3 nT, so the baseline fit was close to the limits of the instrument and reflected magnetic variations of the environment (tests were performed in Ann Arbor, MI, located at a magnetic corrected latitude of 52°N where magnetic activity would be expected to be significant enough to create such variations over the period of the measurements).

The locus constraint algorithm was applied to the PNI data for each of the four RAX power configurations. In each case, the residuals of the corrected magnetic field magnitude exhibited a standard deviation on the order of 80 nT which is within the noise limits of the sensor indicating that the calibration parameters can compensate for all the static sources of error present on the spacecraft, within the limits of the sensor. An example is shown in Figure 3 below for the operational case.

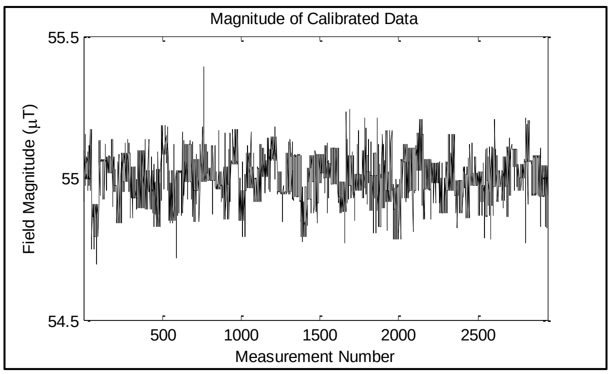

Figure 3: Corrected Field Magnitude from PNI Sensor for Operational Case

The resulting calibration parameters determined for each test are compared below in Table 3. The calibration parameters for the Standby power mode are significantly different from the rest of the modes, but the variations are much smaller between the other power modes. They are, however, significant. For example, a 0.4% change in scale factor in one axis can result in a field difference of up 2000 nT if the field is concentrated along that axis. This is significantly larger than the noise floor of the sensor. The conclusion here is that each change in power mode and current circulation within the spacecraft is likely to affect the calibration parameters. Since most of the operational modes are known ahead of time, their effect can be quantified ahead of time.

RAX ON-ORBIT CALIBRATION

RAX was launched on November 19, 2010, out of Kodiak, AK, aboard a Minotaur IV (STP-26) to a 650-km orbit at 72° of inclination. Due to a solar cell malfunction, only three orbits of data over the month of December 2010 have been obtained and analyzed so far.

Table 3: PNI Calibration Parameters for Four of the Five States Investigated

Parameter	Standby	GPS	Ops.	Payload
x_0 (nT)	-2,150	-1,710	-1,870	-1,750
y_0 (nT)	3,990	7,530	7,640	7,530
z_0 (nT)	-14,810	-9,630	-9,730	-9,660
s_x	1.104	0.881	0.883	0.880
s_y	1.001	0.903	0.905	0.902
s_z	1.001	1.131	1.134	1.131
ϕ (deg.)	-5.4	-4.0	-4.0	-4.1
ρ (deg.)	-1.6	-1.0	-1.1	-1.0
λ (deg.)	3.3	5.0	5.2	5.2

The first set of data was obtained while the spacecraft was still tumbling often on December 1, 2010. The second set was obtained on December 15 and the third set was obtained on December 30, at which point the spacecraft orientation with respect to the Earth's field was much more stable. The advantage of capturing magnetometer data during the early tumbling phase is that the tumbling is random enough to cover the full spherical locus of measurements, providing an excellent opportunity to use the locus constraint calibration technique.

Methodology

The RAX magnetometer data was used to perform a modified version of the calibration for a time-varying external field using the sensor model of Equation (1) that incorporates scaling factors, offsets, and misalignments. The locus-constraint method cannot be applied to estimate the model parameters directly, because the field magnitude is known to vary significantly over the measurement duration. As an alternative, Simulated Annealing (SA), a stochastic optimization technique, yields the model parameters that minimize the difference between the predicted field magnitude and the RAX-measured magnitude after calibration.

The predicted field magnitude is derived from the satellite position and a magnetic field model. GPS position data were not available for RAX during this collection period. Therefore, the Two-Line Element (TLE) generated by the U.S. satellite tracking network was used to propagate the satellite orbits. Figure 4 shows the satellite orbital position and field magnitude computed using the WMM2010 model. The

December 1, 2010, data collection period was quiet in terms of geomagnetic activity per the Space Weather Prediction Center. Therefore, the modeled field magnitude during this period is expected to be a reasonable prediction of the magnetic field environment encountered by the RAX satellite, at least within the sensor noise levels.

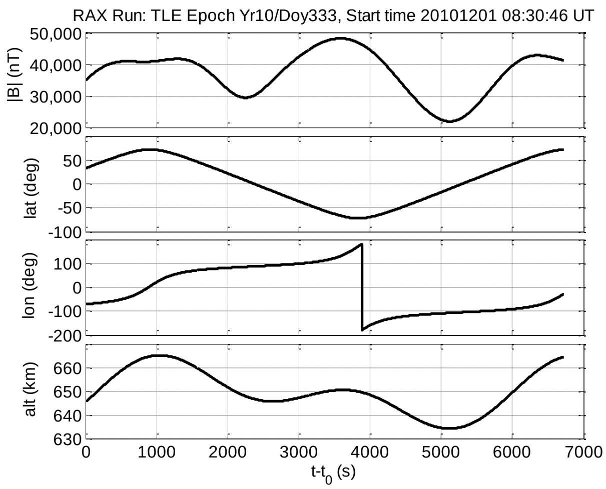

Figure 4: RAX Orbit and Magnetic Field

Results

After applying the calibration parameters derived using the SA method, the residuals show a standard deviation of about 970 nT Room Mean Square (RMS). This is a factor of ten worse than was achieved during ground calibration. When comparing the error residuals with the current in the solar panels, it appears that the largest contributor to this error is the magnetic field created by the current loops in the panels.

Solar Panel Current Compensation

The contribution of the solar panel currents was computed by the RAX team and results are reported in Springmann[5]. This added correction yields considerably better results. By modeling the magnetic field as a linear function of the currents in each panel, Springmann[5] was able to greatly improve the measurement accuracy. Additional compensation for battery currents during telemetry also improved the final parameters to an RMS error of 210 nT for the PNI magnetometer and 200 nT for the IMU magnetometer. Table 4 provides a comparison of the calibration parameters between the ground-based calibration, the SA method with on-orbit data, and the current-corrected calibration results.

The on-orbit current compensation demonstrates the feasibility of using a combination of the locus constraint algorithm with corrections for time-varying effects to greatly improve the accuracy of the measurements.

Table 4: Parameter Comparison

Parameter	Ground (Ops)	Orbit	Current Correction
x_0 (nT)	-1,870	-660	-660
y_0 (nT)	7,630	10,100	-9,940
z_0 (nT)	-9,730	-7,170	-7,670
s_x	0.883	0.902	0.890
s_y	0.905	0.891	0.910
s_z	1.134	1.135	1.131
ϕ (deg.)	-4.0	-2.7	-4.0
ρ (deg.)	-1.1	-1.3	-1.0
λ (deg.)	5.2	4.8	5.0

In addition, as Springmann[5] demonstrates, the calibration remains stable over time, providing the opportunity to measure the Earth's field with an accuracy of about 200 nT. This is the equivalent of an attitude error of about 0.2°, a significant result for CubeSat control applications.

MULTIPLE MAGNETOMETER SOLUTION

The locus constraint magnetometer calibration technique is a robust technique to correct for on-board magnetic disturbances due to spacecraft materials, and static time invariant sources; indeed, this technique provides correction factors for even fairly large contributions such as those coming from the magnets and hysteretic materials on board the spacecraft, allowing for performance close to the magnetometer's own noise floor. Contributions which are not time invariant must be dealt with in other ways. Also, while the RAX study provided a unique opportunity to test the algorithms with an orbiting spacecraft, the sensors used on this spacecraft have a noise floor that is large enough to mask many of the more subtle sources of error. To achieve an accuracy approaching 2 to 5 nT, as would be necessary for space weather applications, additional information is likely needed.

One approach is to use multiple magnetometers to separate contributions from the spacecraft and earth field variations. In general, contributions from the spacecraft can be known ahead of time through ground testing with all subsystems onboard. However, these may change during launch as was observed with the RAX spacecraft. Ideally, a ground-based calibration phase provides information on the relative contributions for each operating mode, and especially the relationship between the calibration parameters and the currents on the spacecraft.

Two techniques are currently being investigated in a hardware simulation. The first computes the magnitude difference of each axis component, as well as the average for any pair of magnetometers. If the difference varies differently from the average, from one instant to the next, then there is a contribution due to the spacecraft. The second takes all three components into account. For each component of a magnetometer, the change in value from one instant to the next is computed. For a pair of magnetometers, the change for each of the three axes is plotted for one magnetometer against the other. If all three points (one for each axis) lie on a straight line with a slope of one, then the variation from one instant to the next is due to a variation in the Earth's field. Using a stochastic model, a prediction can be obtained at any measurement point in time. An example is shown in Figure 5. The two techniques can be used together to reduce the uncertainty.

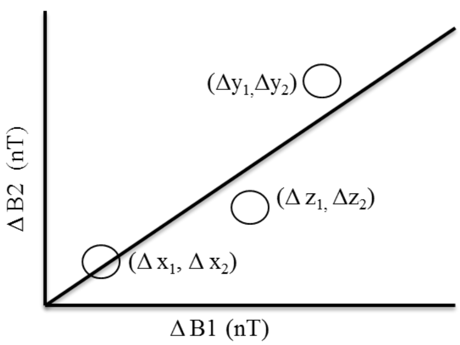

Figure 5: One of Two Techniques to Detect Variations Due to the Earth's Field

To test these techniques, several magnetometers have been purchased and set up in an apparatus that includes a small current-driven coil and a magnet. The magnetometers are three-axis fluxgate sensors (Model TFM 100G3, Billingsley Aerospace & Defense, Germantown, MD). The current coil is a small coil with a current controller that can generate currents between +1 A and -1 A. The coil has a diameter of 11.5 mm and is made with 29-AWG wire wound several times. This coil generates a field of about 200 nT about 5 cm away with 200 mA of current. This coil is enough to generate perturbations on par with those expected from currents flowing throughout the spacecraft. The magnet is used to generate known background magnetic field variations. The three magnetometers can be placed at repeated locations using a plastic board with predrilled holes. These concepts are currently under development as part of an SBIR Phase II project for the Air Force Research Laboratory.

CONCLUSIONS

The research presented here has shown how the locus constraint algorithm can be used for on-orbit calibration of magnetometers mounted on a CubeSat. The calibration technique can compensate for magnetic sources that are significant relative to the magnetometer noise floor such as magnets and hysteresis materials. Knowledge of current through solar panels or in circuit loops near the magnetometers greatly increases the accuracy of the resulting calibration through a simple linear model, to a level that would allow orientation knowledge to within 0.2°. Ongoing research is currently focused on using multiple magnetometers to improve detection and compensation of time-varying disturbances on-orbit, and to increase Earth field measurement accuracy to the level needed for space weather measurements.

Acknowledgments

The authors gratefully acknowledge the support of the Air Force Research Laboratory, especially Dr. E. Zesta and Dr. D. Ober, through SBIR Contract FA9453-10-C-0056. The Radio Aurora Explorer mission is funded by the National Science Foundation.

References

1. Gebre-Egziabher, D., G. H. Elkaim, J. D. Powell and B.W. Parkinson, "Calibration of Strapdown Magnetometers in the Magnetic Field Domain," Journal of Aerospace Engineering, Vol. 19, No. 2, pp. 6--16, 2006.
2. Elkaim, G. and C. Foster, "Extension of a Nonlinear, Two-Step Calibration Methodology to Include Non Orthogonal Sensor Axes," IEEE Transactions on Aerospace Electronic Systems, Vol. 44, No. 3, July 2008.
3. Gebre-Egziabher, D., and G. Elkaim, "MAV Attitude Determination from Observations of Earth's Magnetic and Gravity Field Vectors," IEEE Journal of Aerospace Electronic Systems, Vol. 44, No. 3, July 2008.
4. Cutler, J., M. Bennett, A. Klesh, H. Bahcivan, and R. Doe, "The Radio Aurora Explorer – A Bistatic Radar Mission to Measure Space Weather Phenomenon," Proceedings of the 24th Annual AIAA/USU Conference on Small Satellites, SSC10-II-4, Logan, UT, 2010.
5. Springmann, J., Proceedings of the 25th Annual AIAA/USU Conference on Small Satellites, Logan, UT, 2011, to be published.