Design and Calibration Techniques for Improved Small Satellite Performance

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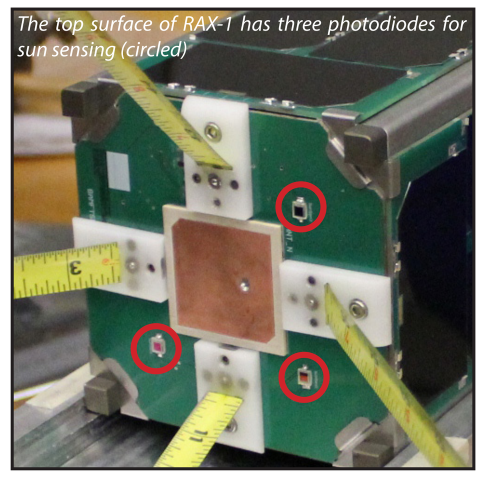
Introduction

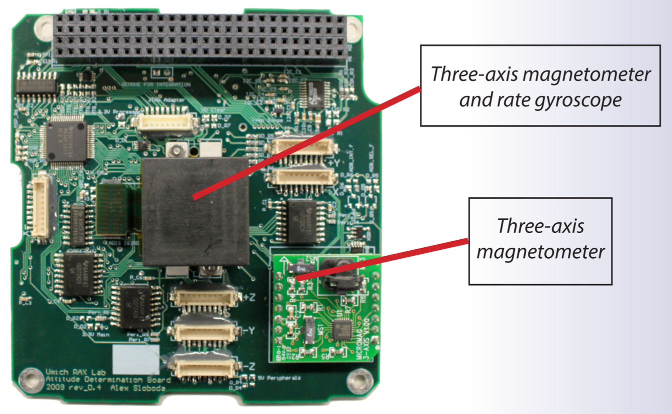
We are developing design techniques and sensor calibration algorithms that enable the rapid development of small spacecraft while maximizing the accuracy of low-cost sensors used within the spacecraft. The work presented here focuses on the attitude determination and control subsystem, but many of the principles can be extended to other subsystems as well. These methods have been applied to satellites developed by the Michigan Exploration Laboratory (MXL), and continue to be improved using lessons learned from their application in the design and operations of small spacecraft. Two specific methods are shown on this poster: magnetometer calibration, and sensor orientation optimization. These methods can be used to significantly improve the performance of small satellite attitude determination systems, such as the MXL-developed subsystem show below.

Small satellite attitude determination subsystem design and development

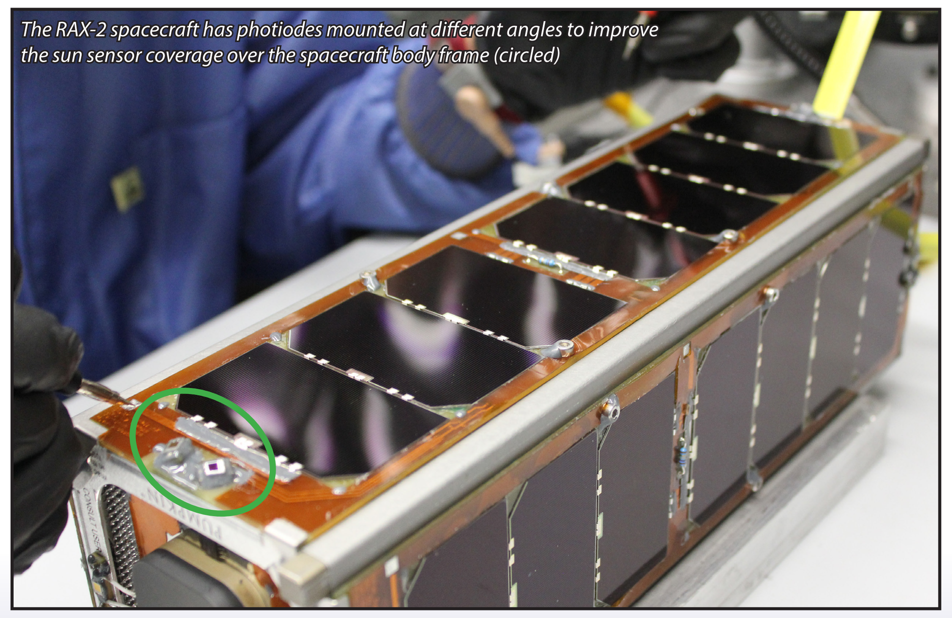
The Radio Aurora Explorer (RAX) satellites are 3U CubeSats developed by MXL to study space weather. A custom attitude determination system was developed for RAX, and it is currently being upgraded for the next generation of MXL spacecraft. This subsystem utilizes photodiodes for sun sensing, multiple three-axis magnetometers, and a three-axis rate gyroscope; all are off-the-shelf components. The subsystem has demonstrated accuracies of between 2° and 4° (1-σ) on the RAX-1 spacecraft.



The top surface of RAX-1 has three photodiodes for sun sensing (circled)



The RAX Attitude Determination Board

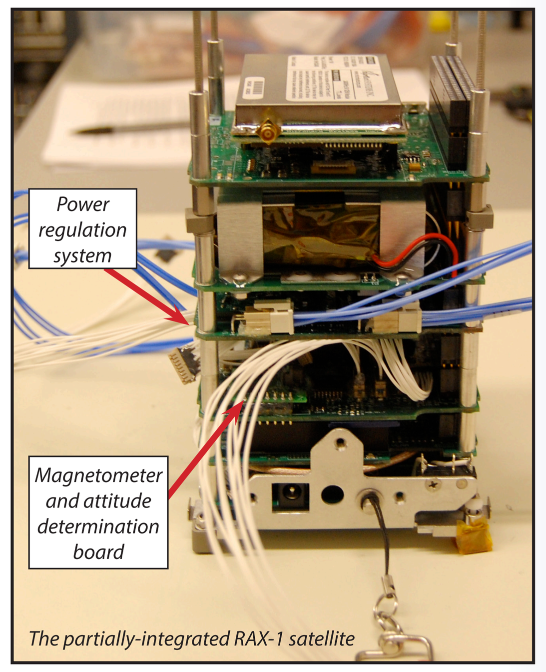


The RAX-2 spacecraft has photodiodes mounted at different angles to improve the sun sensor coverage over the spacecraft body frame (circled)

Magnetometer calibration: Removing satellite-induced magnetic fields

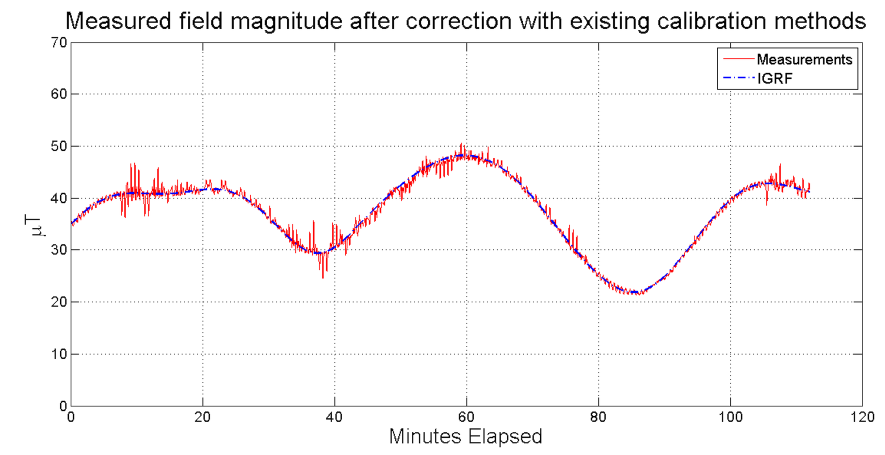
Magnetometers are a common sensor for attitude determination in low-Earth orbit because of their simplicity and low cost; however, their accuracy in measuring Earth's magnetic field can be severely degraded by the time-varying magnetic fields produced by on-board electronics. Traditionally, this error is mitigated by physically separating the magnetometer from the spacecraft with a boom or by design and manufacturing practices to minimize the magnetic field produced by onboard electronics. Both of these methods increase spacecraft development times and costs, rendering them potentially unsuitable for small spacecraft.

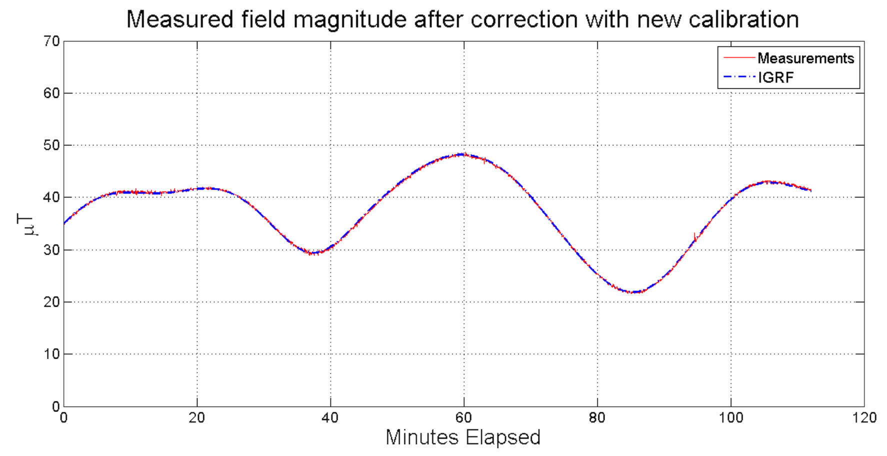
We have developed a method for on-orbit, attitude independent magnetometer calibration that mitigates the effect of nearby electronics. In application to the RAX-1 spacecraft, the technique reduced the magnetometer angular accuracy by an order of magnitude, and increased the accuracy of the measurements to the accuracy of the stand-alone sensor.



The partially-integrated RAX-1 satellite

The calibration method works by including measured currents in nearby electronics in the magnetometer measurement model. The current measurements are mapped to the corresponding magnetometer bias by parameters estimated in the calibration process. The calibration also includes bias, scaling, and axis non-orthogonality, and it is carried out using flight data without the need for attitude knowledge. RAX-1 data from before and after the calibration is shown in the plots. The accuracy of the measurements with the magnetometer embedded in the satellite has been improved to the accuracy of the stand-alone magnetometer.





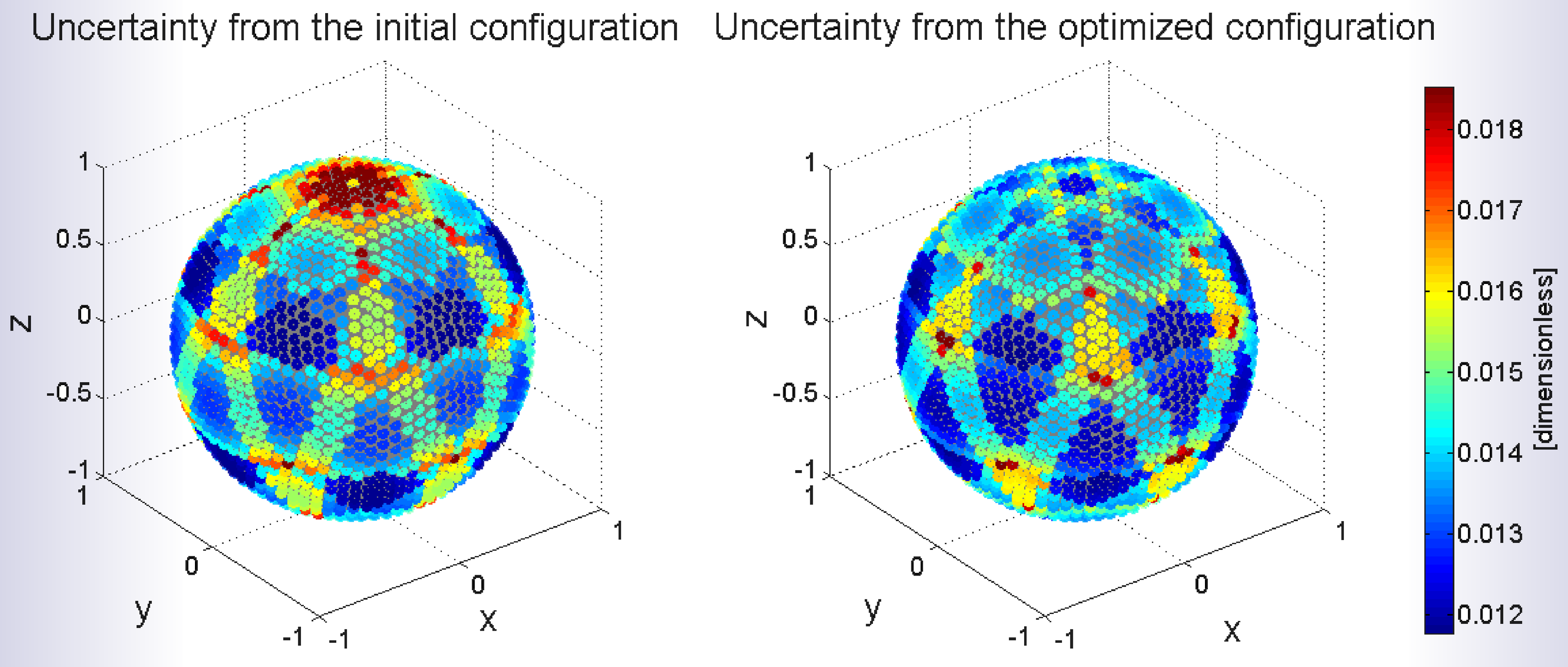
Above. The measured magnetic field magnitude plotted with the predicted (IGRF) field magnitude for 110 minutes of 1 Hz RAX-1 data.

Design methods for optimal configuration of directional sensors

Photodiodes are a common method of sun sensing on small spacecraft. Photodiodes produce a current as a function of the angle between their normal direction and the line-of-sight vector to the sun, and multiple photodiodes must be combined to obtain a unique sun vector measurement. The uncertainty (covariance) of this sun vector measurement depends on the performance of the individual photodiodes as well as the orientation of the photodiodes.

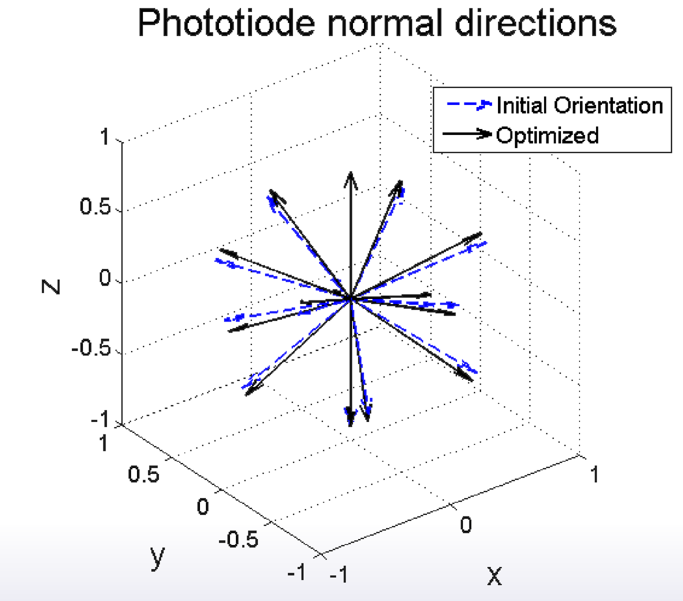
We have developed a formulation to find photodiode configurations that minimize the sun vector uncertainty. The method can be applied to find the optimal configuration for any expected attitude and orbit. It works by mapping the design parameters (photodiode mounting angles) to the resulting measurement uncertainties over every direction in the body-fixed frame, and these directions are subsequently used to form an objective function.

Beyond photodiodes, the method is generally applicable to directional sensors and instruments. For example, it could also be used to determine a body-fixed solar panel configuration to maximize power generation, or to find antenna orientations.



Above. *The points on the sphere represent directions in the body-fixed frame, and have an even resolution of 4 degrees. The directions are color-coded by the trace of the sun vector covariance matrix when the sun is in that direction. On the left is an initial configuration, and an optimized configuration is on the right. The photodiode configuration has been optimized to minimize the uncertainty over the spacecraft body frame.*

Right. *The initial and optimized photodiode configurations. The arrows show the photodiode normal directions*



References

J.C. Springmann, A.J. Sloboda, A.T. Klesh, M.W. Bennett, J.W. Cutler, The attitude determination system of the RAX satellite, Acta Astronautica, Volume 75, June–July 2012, Pages 120-135, ISSN 0094-5765, doi: 10.1016/j.actaastro.2012.02.001.

J.C. Springmann and J.W. Cutler, "Attitude-Independent Magnetometer Calibration with Time-Varying Bias," AIAA Journal of Guidance, Control, and Dynamics, Volume 35, Number 4, July–August 2012, pages 1080-1088, doi: 10.2514/1.56726.

J.C. Springmann, J.W. Cutler, "Initial Attitude Analysis of the RAX Satellite", Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, Girdwood, Alaska, August 2011.

Summary

We have developed calibration techniques that significantly improve the accuracy of low-cost attitude sensors used on small satellites. The sensor calibrations are performed on-orbit and do not require attitude knowledge. Since rigorous pre-flight calibration and high tolerance assembly are no longer required, this significantly decreases the development time and costs of satellites. We have also developed a method to optimize the orientation of directional sensors in the spacecraft body frame. This is used in the design phase of the spacecraft to maximize the performance of directional sensors or instruments, such as photodiodes, solar panels, or antennae.

These methods result in significant improvements in the accuracy of low cost sensors that are commonly used on small spacecraft, enabling more capable spacecraft. Future work includes extending these methods to enable completely new architectures, such as sensors that reconfigure themselves on-orbit to track optimal configurations.