

Attitude-Independent Magnetometer Calibration with Time-Varying Bias

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Magnetometer background & motivation

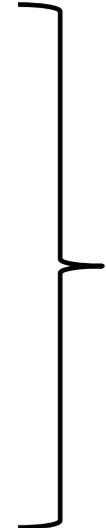
- Magnetometers are common sensors in low-Earth orbiting satellites
- Electronics create time-varying magnetic fields
- Typical methods to mitigate time-varying effects increase design time and cost
 - Booms
 - Design for magnetic cleanliness (for example, Ref. 1)

We are motivated by *improved attitude determination accuracy*, but our methods extend to all magnetometer applications:

- Attitude determination
- Scientific measurements
- Non-spacecraft applications

[1] M.H. Acuna, et al. Magnetic field cancellation techniques for the Mars Global Surveyor solar array. *Proceedings of the IEEE Photovoltaics Conference*, Washington, D.C., 1996

Magnetometer errors & causes

Error	Potential Causes		
Constant bias	Inherent to sensor, nearby ferromagnetic (hard iron) material	 <p data-bbox="1541 596 1875 815">Methods have been developed to estimate these parameters [2,3]</p>	
Scale factor	Different sensitivities in each axis, nearby soft iron materials		
Non-orthogonality	Manufacturing, thermal stress, mechanical stress		
Time-varying bias	Nearby current-carrying wires	<p data-bbox="1479 1043 1904 1142">New method includes time-varying bias</p>	

[2] Roberto Alonso and Malcolm D. Shuster. Complete linear attitude-independent magnetometer calibration. *Journal of the Astronautical Sciences*, 50(4):477 – 490, 2003.

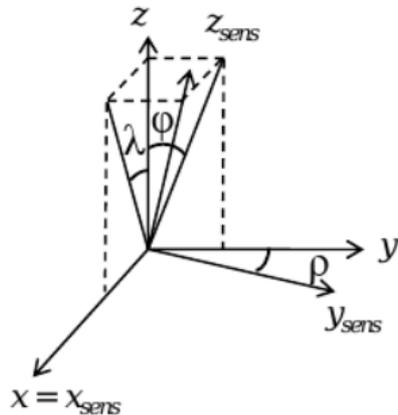
[3] C.C. Foster and G.H. Elkaim. Extension of a two- step calibration methodology to include nonorthogonal sensor axes. *IEEE Transactions on Aerospace and Electronic Systems*, 44(3):1070 – 8, July 2008.

Existing attitude-independent calibration method [3] (1 of 2)

1. Model each axis of the sensor

$$\left\{ \begin{array}{l} \tilde{B}_x = aB_x + x_0 \\ \tilde{B}_y = bB_y + y_0 \\ \tilde{B}_z = cB_z + z_0 \end{array} \right.$$

2. Include axis non-orthogonality



$$\left\{ \begin{array}{l} \tilde{B}_x = aB_x + x_0 \\ \tilde{B}_y = b(B_y \cos(\rho) + B_x \sin(\rho)) + y_0 \\ \tilde{B}_z = c(B_x \sin(\lambda) + B_y \sin(\phi) \cos(\lambda) + B_z \cos(\phi) \cos(\lambda)) + z_0 \end{array} \right.$$

[3] C.C. Foster and G.H. Elkaim. Extension of a two- step calibration methodology to include nonorthogonal sensor axes. *IEEE Transactions on Aerospace and Electronic Systems*, 44(3):1070 – 8, July 2008.

Existing attitude-independent calibration method [3] (2 of 2)

3. Use expected field *magnitude* to form a single equation

$$\left[\begin{array}{l} \tilde{B}_x = aB_x + x_0 \\ \tilde{B}_y = b(B_y \cos(\rho) + B_x \sin(\rho)) + y_0 \\ \tilde{B}_z = c(B_x \sin(\lambda) + B_y \sin(\phi) \cos(\lambda) + B_z \cos(\phi) \cos(\lambda)) + z_0 \end{array} \right. \longrightarrow \text{Solve for } \begin{array}{c} B_x \\ B_y \\ B_z \end{array} \longrightarrow \text{Constrain the magnitude:}$$

$$B^2 = B_x^2 + B_y^2 + B_z^2$$

The magnitude is assumed to be known (IGRF, other models)

4. With the magnitude constraint, minimization is used to estimate the constant bias, scale factors, and non-orthogonality

[3] C.C. Foster and G.H. Elkaim. Extension of a two- step calibration methodology to include nonorthogonal sensor axes. *IEEE Transactions on Aerospace and Electronic Systems*, 44(3):1070 – 8, July 2008.

Application of the calibration to RAX data

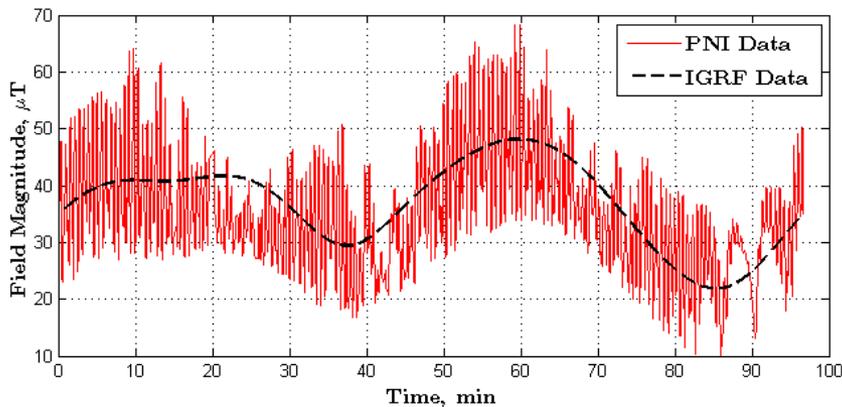
RAX [4] includes two 3-axis magnetometers

- PNI MicroMag3 (referred to as PNI)
- Analog Devices ADIS16405 (referred to as IMU)

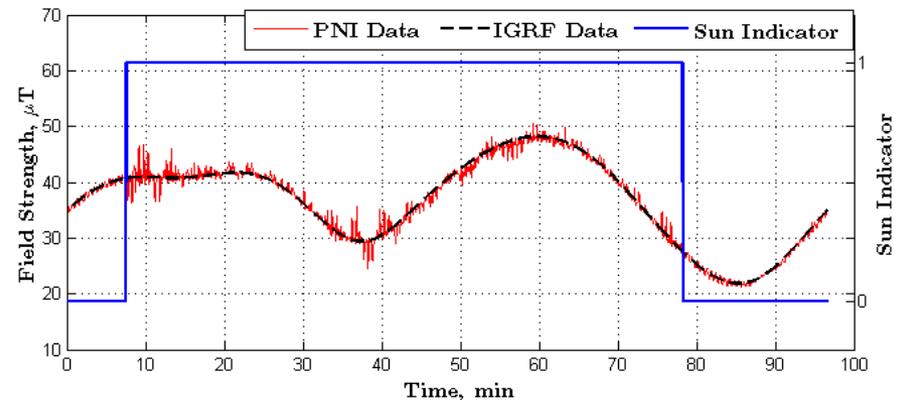
First modification for calibration: time-varying field magnitude requires a numerical algorithm to estimate the calibration parameters. We use non-linear least-squares.

[4] James Cutler, et al. The radio aurora explorer – a bistatic radar mission to measure space weather phenomenon. In *Proceedings of the 24th Annual Small Satellite Conference*, Logan, Utah, August 2010.

Application of the calibration to RAX data



**Measured field magnitude from one orbit
of raw 1 Hz data starting December 1, 2010
08:30:46 UTC**



Field magnitude after on-orbit calibration

This indicates that the solar panels are causing significant magnetometer bias

Extension of calibration to include time-varying bias

Include spacecraft current telemetry in the magnetometer model:

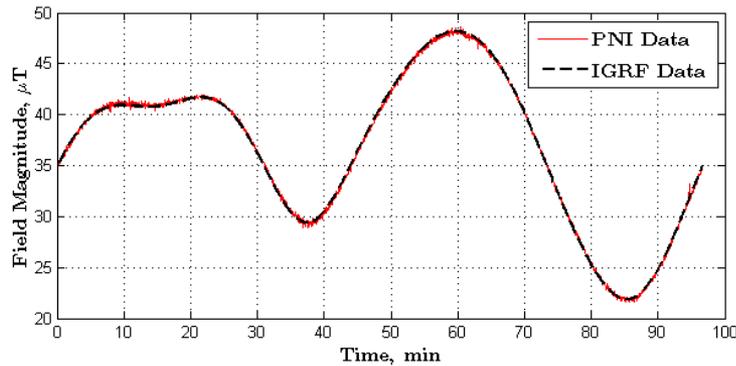
Map the current in the $+x$ panel to bias in the x -axis of the magnetometer

$$\left\{ \begin{array}{l} \tilde{B}_x = aB_x + x_0 + \underline{s_{x,+x}\tilde{I}_{+x} + s_{x,-x}\tilde{I}_{-x} + s_{x,+y}\tilde{I}_{+y} + s_{x,-y}\tilde{I}_{-y}} \\ \tilde{B}_y = b(B_y\cos(\rho) + B_x\sin(\rho)) + y_0 + \underline{s_{y,+x}\tilde{I}_{+x} + s_{y,-x}\tilde{I}_{-x} + s_{y,+y}\tilde{I}_{+y} + s_{y,-y}\tilde{I}_{-y}} \\ \tilde{B}_z = c(B_x\sin(\lambda) + B_y\sin(\phi)\cos(\lambda) + B_z\cos(\phi)\cos(\lambda)) + z_0 + \underline{s_{y,+x}\tilde{I}_{+x} + s_{y,-x}\tilde{I}_{-x} + s_{y,+y}\tilde{I}_{+y} + s_{y,-y}\tilde{I}_{-y}} \end{array} \right.$$

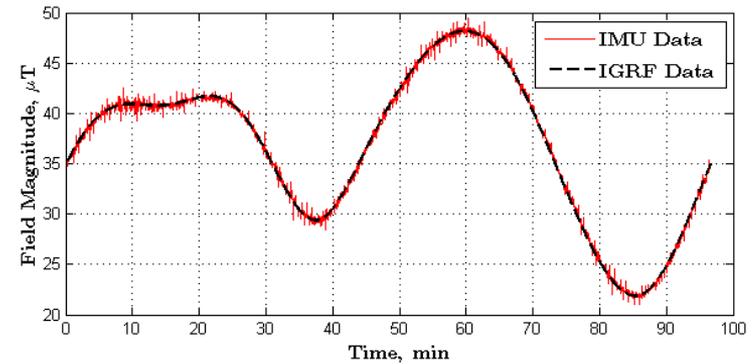
Estimate *constant* parameters to map *time-varying* telemetry to the resulting magnetometer bias

21 total parameters: 9 previous, 12 current bias coefficients

Results of calibration that includes solar panel currents

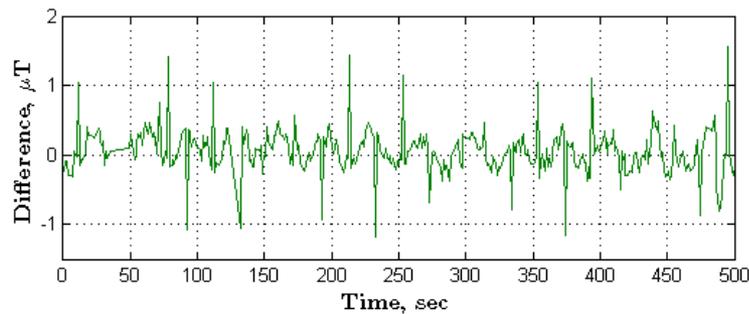


**Calibrated PNI Data. RMSE: 176 nT
(previously 903 nT)**

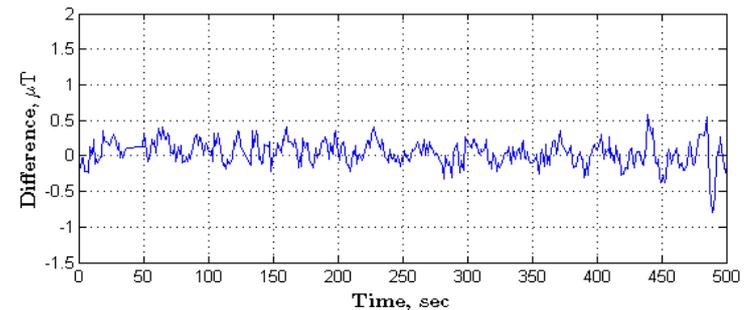


**Calibrated IMU Data. RMSE: 290 nT
(previously 2,017 nT)**

Zoom in in IMU error:



IMU error after inclusion of
additional current measurements:



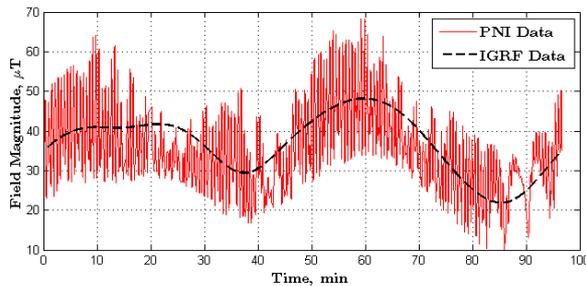
Resulting magnetometer accuracy

Sensor	RMSE after calibration		De-integrated sensor resolution/noise floor	Calibration improvement
	Existing method (constant parameters)	New method (time-varying bias)		
<i>Magnetic field accuracy (nT):</i>				
PNI	903	174	128 nT resolution	729 nT
IMU	2,017	225	111 nT noise floor	1,792 nT
<i>Corresponding angular accuracy* (°):</i>				
PNI	1.0-2.6	0.2-0.5	0.1-0.4	2.1°
IMU	2.3-5.8	0.3-0.6	0.1-0.3	5.2°

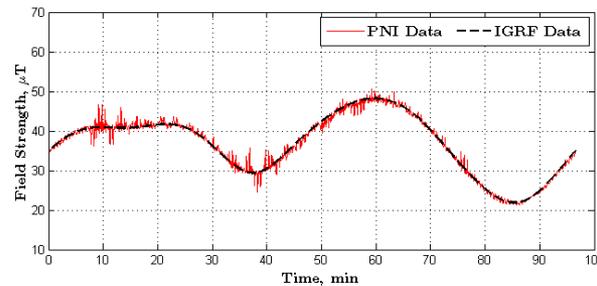
* Angular accuracy depends on the ambient field strength. Range given corresponds to 50 μ T - 20 μ T, respectively.

Summary

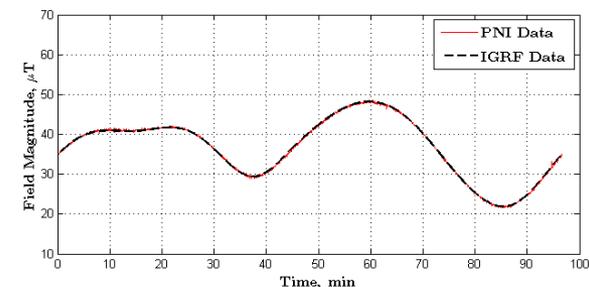
- Developed a method to mitigate time-varying bias due to on-board electronics
- Current measurements are included in the calibration
- Demonstrated the effectiveness with RAX data, but the algorithm is general and can be applied to any magnetometer application
 - After application to RAX, the angular uncertainty decreased from 5.8° to 0.6° , and is nearly that of the stand-alone sensors



Uncalibrated data



Existing calibration methods



New calibration with time-varying bias

Implications

- Magnetometers can be placed anywhere within a spacecraft
- Low-cost magnetometers can be used (pre-existing sensor errors are fine)
- Magnetic cleanliness requirements and/or booms are replaced by improved processing algorithms

Future work

- Continued development to increase accuracy

Goals:

- Integrated sensor accuracy reduced to stand-alone accuracy
 - Since-grade magnetic measurements from within a satellite
- Extension to real-time implementation (can currently perform batch calibration, then upload parameters for real-time correction)

Acknowledgements

This work is a subset of magnetometer calibration developed in collaboration with **Creare, Inc.** and funded by the **Air Force Research Laboratory** (SBIR contract number FA9453-10-C-0056)

RAX is funded by the **National Science Foundation** (grant ATM-0838054)

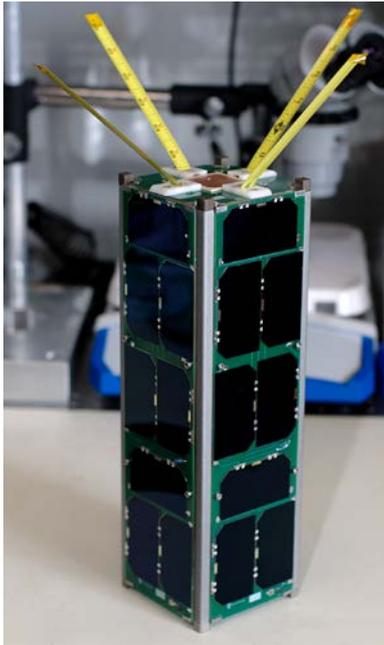
Thanks to the **RAX team** for support of this work

Questions?

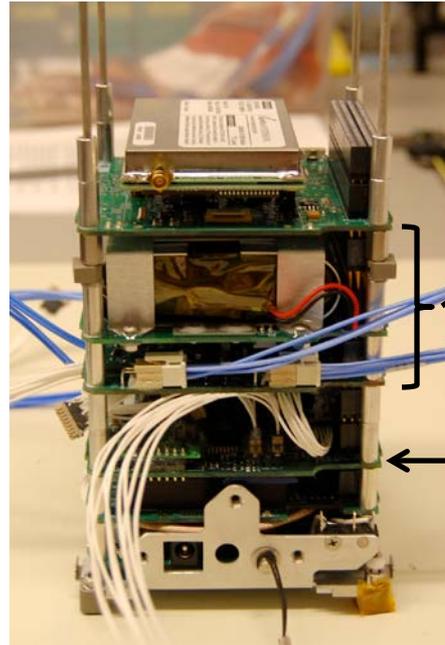
Email: jspringm@umich.edu

Extra Slides

Example application: RAX satellite



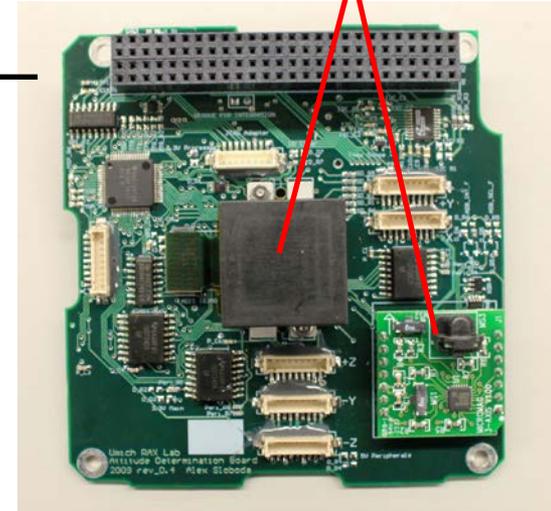
RAX [1]. 10 x 10 x
30 cm³, 2.8 kg.



Partial integration

Electrical Power System

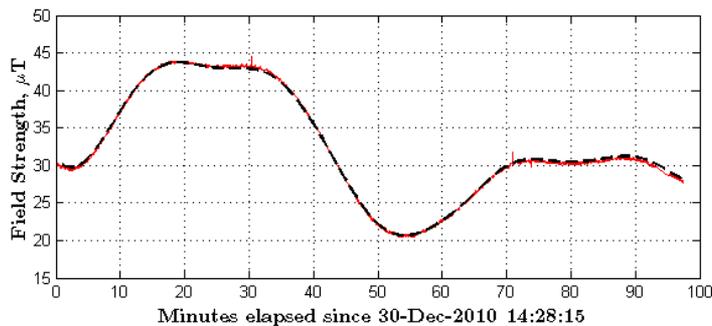
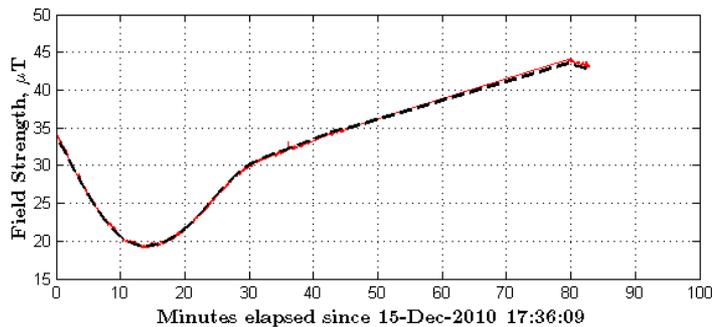
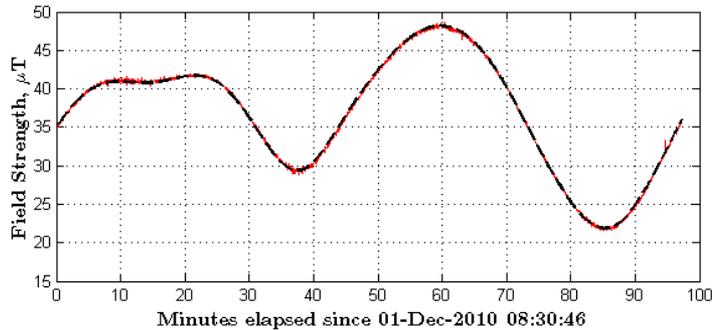
3-axis magnetometers



Attitude Determination
Board (ADB)

James Cutler, et al. The radio aurora explorer – a bistatic radar mission to measure space weather phenomenon. In *Proceedings of the 24th Annual Small Satellite Conference*, Logan, Utah, August 2010.

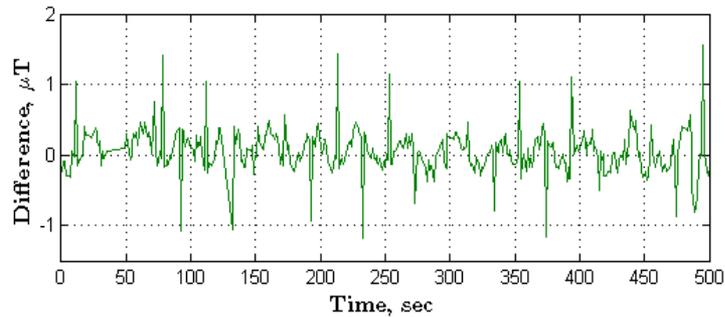
Calibration parameters are constant over time



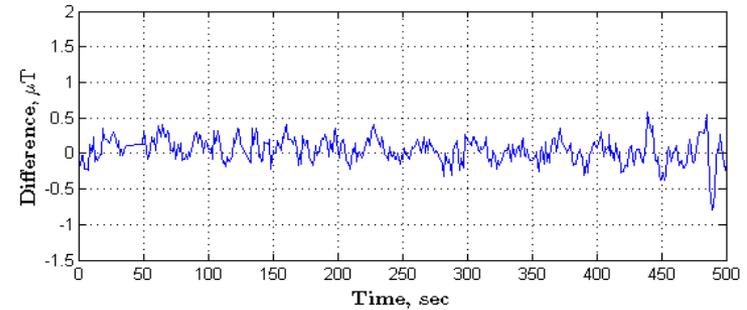
RMSE (nT) from set 1 calibration parameters applied to data sets 2 and 3

	PNI	IMU
Set 1 applied to Set 1	174	225
Set 1 applied to Set 2	220	212
Set 1 applied to Set 3	210	199

Extend calibration to include current draw from EPS



Previous error, RMSE: 290 nT



**Error after inclusion of current draw,
RMSE: 225 nT**