Photodiode Placement & Algorithms for CubeSat Attitude Determination

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Photodiodes are very common attitude sensors.

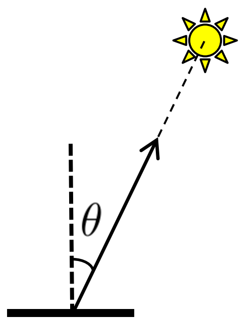
What are the design considerations?

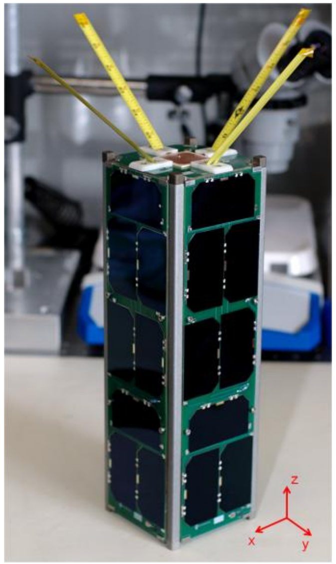
How can they be used more effectively?

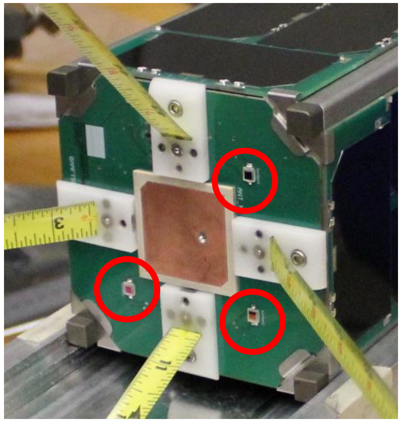
Photodiodes output current as a function of light intensity and angle to the light source

$$\tilde{I} = I_0 \cos(\theta) + \eta_i$$

$$\tilde{V} = V_0 \cos(\theta) + \eta_v$$

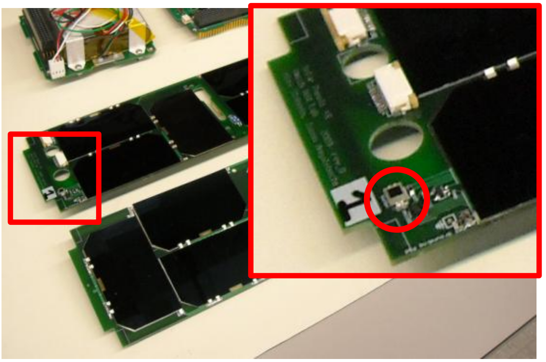






Use for coarse sun sensing.

A single photodiode provides 1D information – combine sensors for sun vector estimates.



Photodiodes on RAX-1

Typical photodiode configurations for estimating a sun vector

1. Perpendicular sensors – photodiodes mounted on each face of the CubeSat

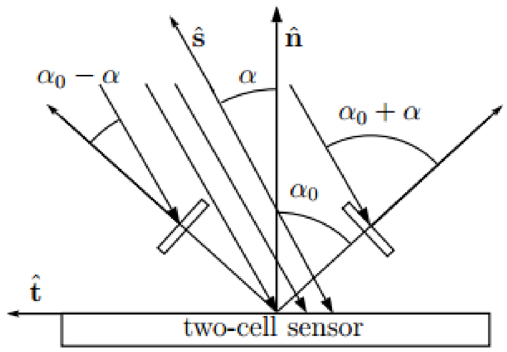
Single measurement:

$$\tilde{V} = V_0 \cos(\theta) + \eta_v$$

Vector from 3 sensors:

$$\tilde{\vec{s}} = \begin{bmatrix} \frac{\tilde{V}_i}{V_{0,i}} & \frac{\tilde{V}_j}{V_{0,j}} & \frac{\tilde{V}_k}{V_{0,k}} \end{bmatrix}^T$$

2. Two photodiodes combined to get sun vector component in single plane [1]



Closed-form equation for the sun components in the **n-t** plane with known angles α

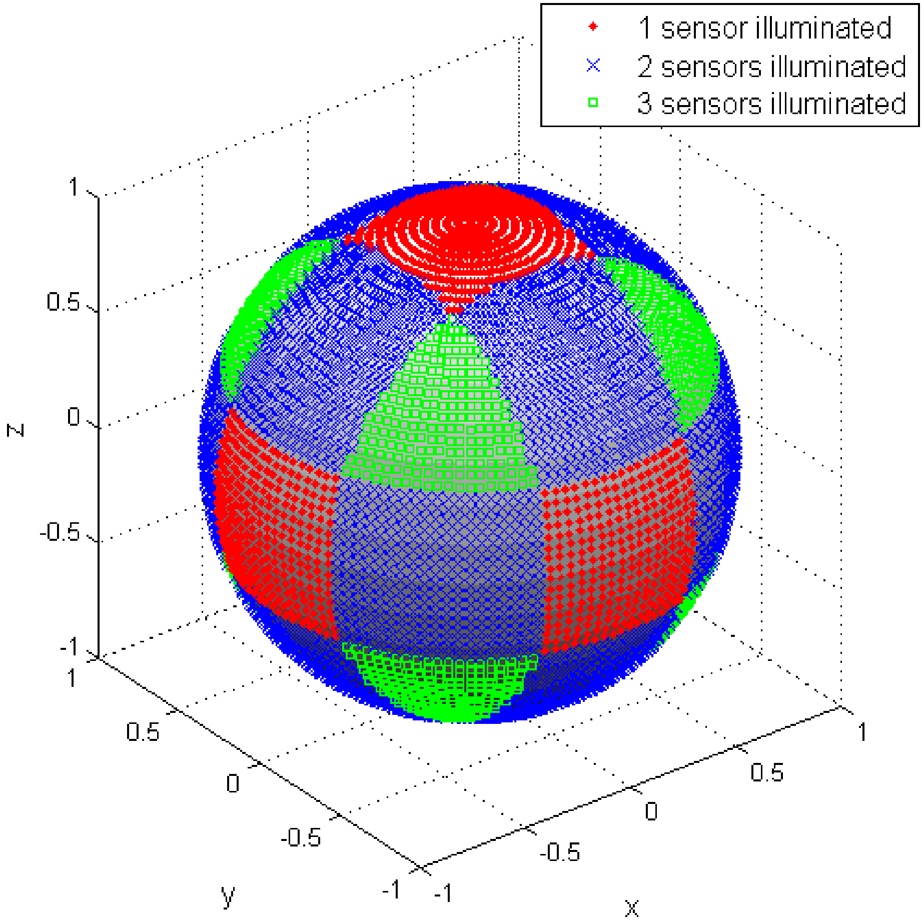
[1] Chris Hall. Chapter 4: Attitude Determination. Course notes. http://www.dept.aoe.vt.edu/~cdhall/courses/aoe4140/attde.pdf

Consider field-of-view constraints carefully

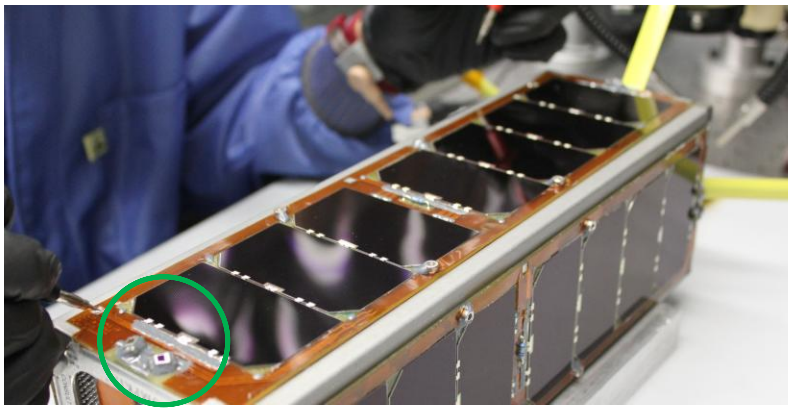
Number of photodiodes illuminated for 60° photodiodes mounted on each surface of the CubeSat (RAX-1 configuration):

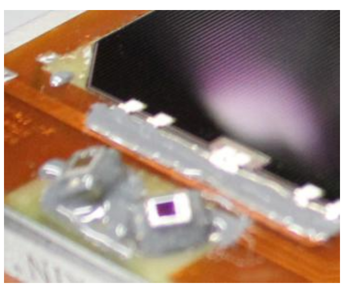
Complete sun vector available only for limited attitudes.

Is a full sun vector needed or 1-2 components ok?



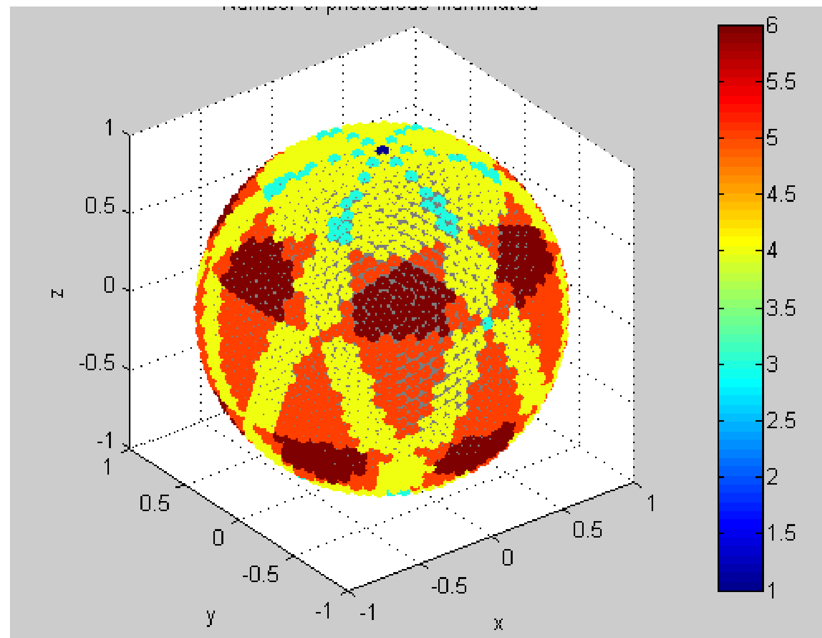
On RAX-2, photodiodes mounted at angles to improve coverage





3 angled photodiodes on the 10 x 30 cm faces, single direction on the 10 x 10 cm faces

Number of photodiodes illuminated over the attitude sphere



> 99.5% of attitude sphere covered by at least 3 phototiodes

Peak sensor output is key for sun vector estimation. How to measure?

Single measurement:

$$\tilde{V} = V_0 \cos(\theta) + \eta_v$$

Vector from 3 sensors:

$$\tilde{\vec{s}} = \left[\begin{array}{ccc} \frac{\tilde{V}_i}{V_{0,i}} & \frac{\tilde{V}_j}{V_{0,j}} & \frac{\tilde{V}_k}{V_{0,k}} \end{array} \right]^T$$

Ground-based testing? Spectrum and intensity must match orbit for accurate results.

On-orbit estimation?

Ground-based testing for rough gain validation. Use on-orbit data improve accuracy.

On-orbit, attitude-independent photodiode calibration

Goal: estimate maximum voltage of each sensor

$$\tilde{\vec{s}} = \begin{bmatrix} \frac{\tilde{V}_i}{V_{0,i}} & \frac{\tilde{V}_j}{V_{0,j}} & \frac{\tilde{V}_k}{V_{0,k}} \end{bmatrix}^T$$

Approach:

Attitude-independent calibration using the vector magnitude

$$\left(\frac{\tilde{V}_i}{V_{0,i}}\right)^2 + \left(\frac{\tilde{V}_j}{V_{0,j}}\right)^2 + \left(\frac{\tilde{V}_k}{V_{0,k}}\right)^2 = 1$$

Minimization problem to estimate the peak voltage output given the measurements. For estimate peak voltages only, can formulate as linear least-squares problem.

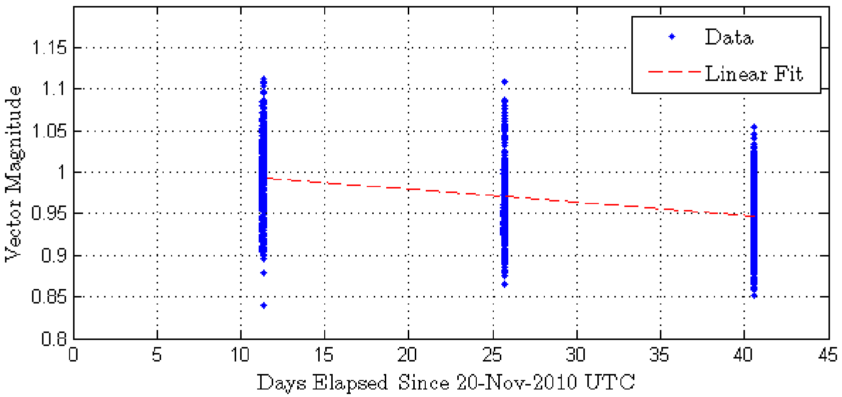
Application to RAX-1 data:

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

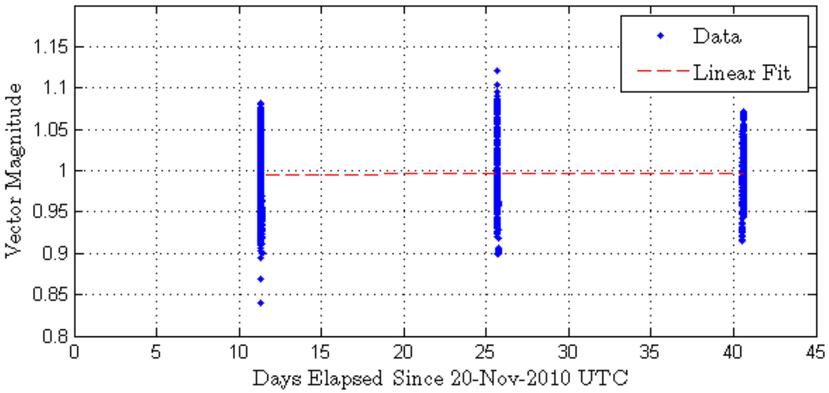
Accessible from http://exploration.engin.umich.edu.

Lesson learned: photodiode degradation on-orbit due to UV radiation (RAX-1 data)

Sun vector magnitude using pre-flight estimates of max voltages from 3 data sets over 2 months:

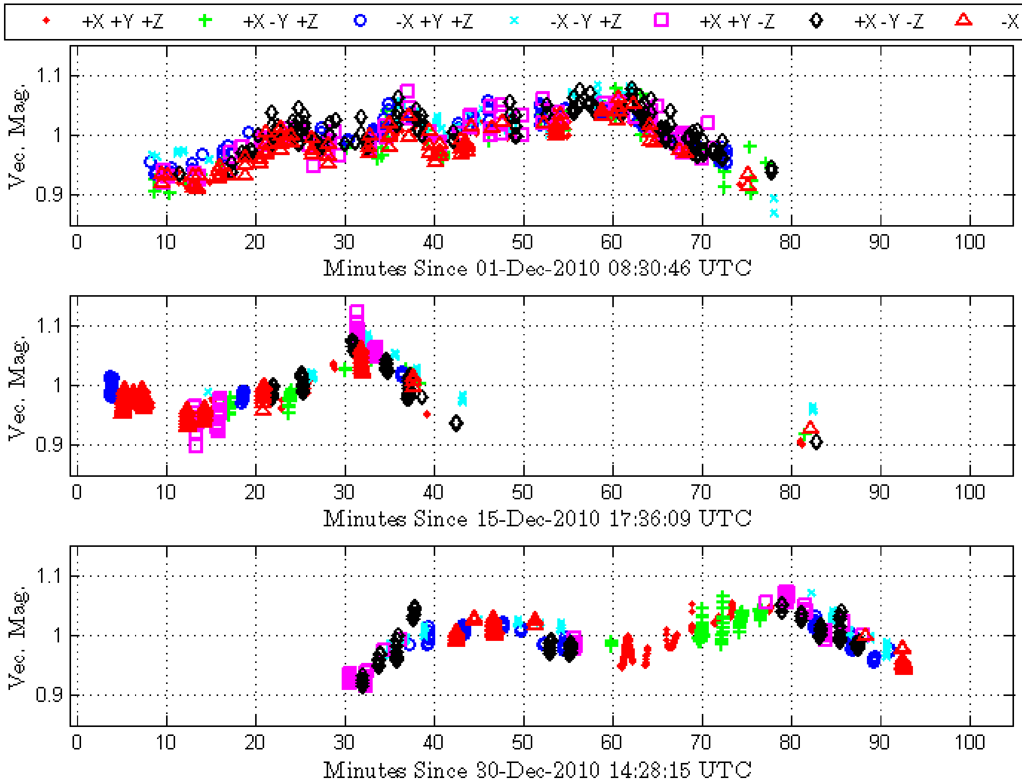


Vector magnitudes after calibration with on-orbit data:



Calibration used to compensate for degradation. Can also be used to estimate peak output of saturated sensors

Results for individual data sets



Mean: 0.9959
RMSE: 0.0411, ~2.5°

Mean: 0.9950
RMSE: 0.0449

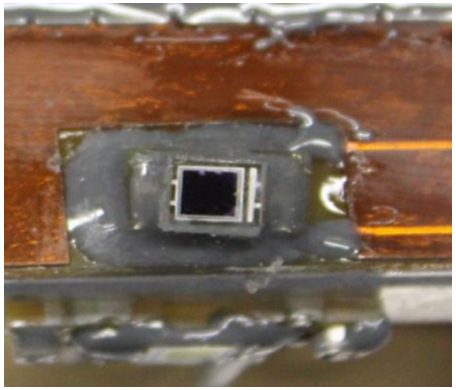
Mean: 0.9978
RMSE: 0.0296

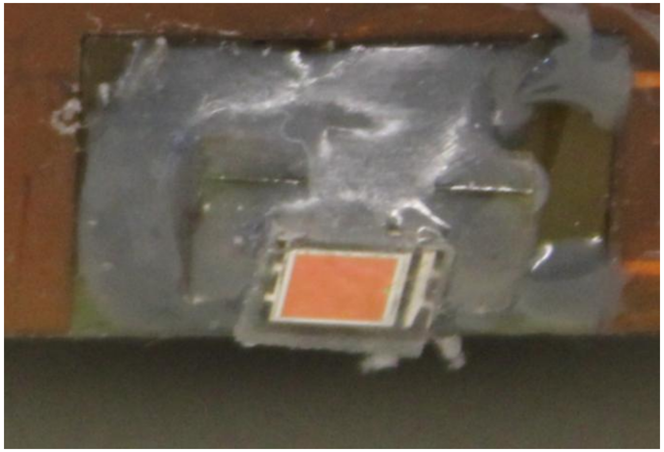
Future improvements: inclusion of temperature and angular mis-alignments

Changes for RAX-2 to prevent degradation

Coverglass added to photodiodes. Same type a used on solar cells.

RAX-1 and RAX-2 photodiodes are OSRAM SFH2430.

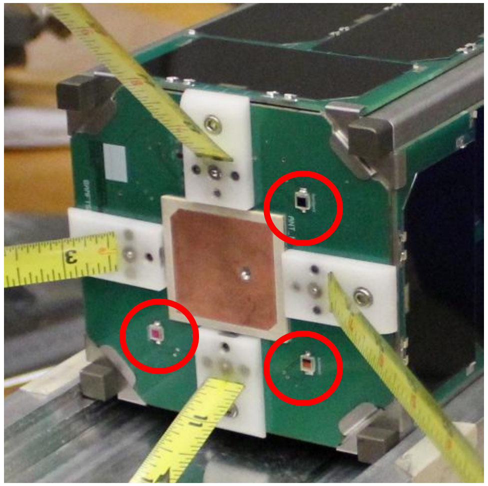


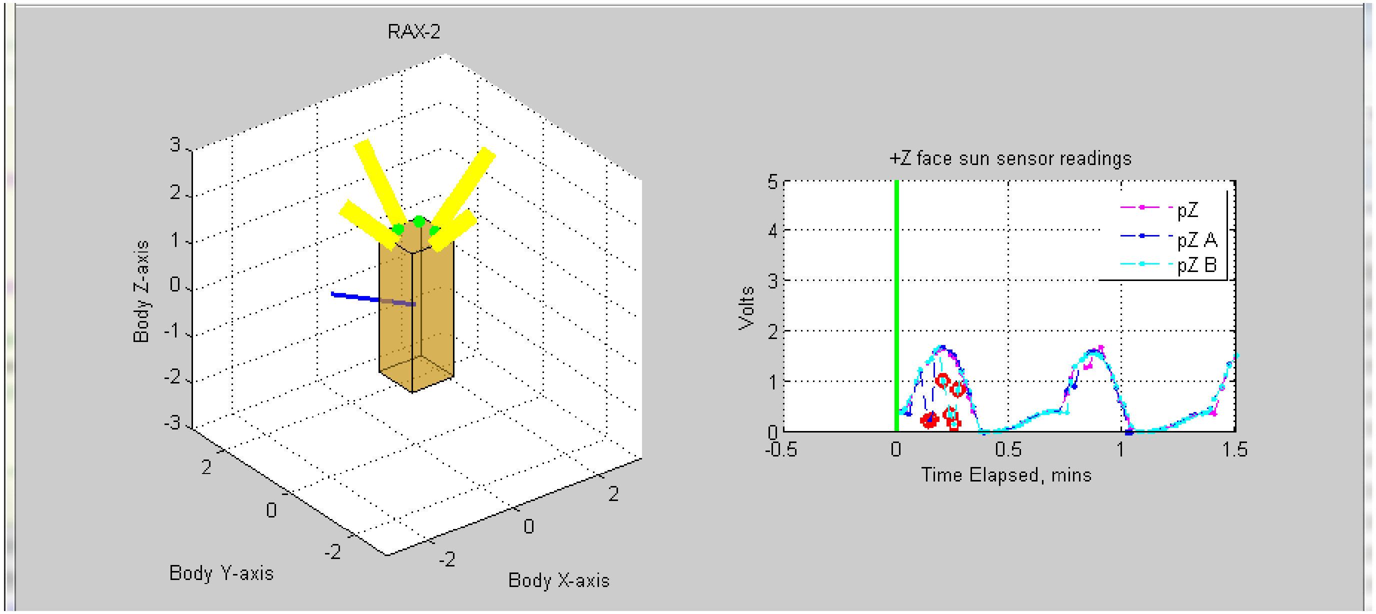


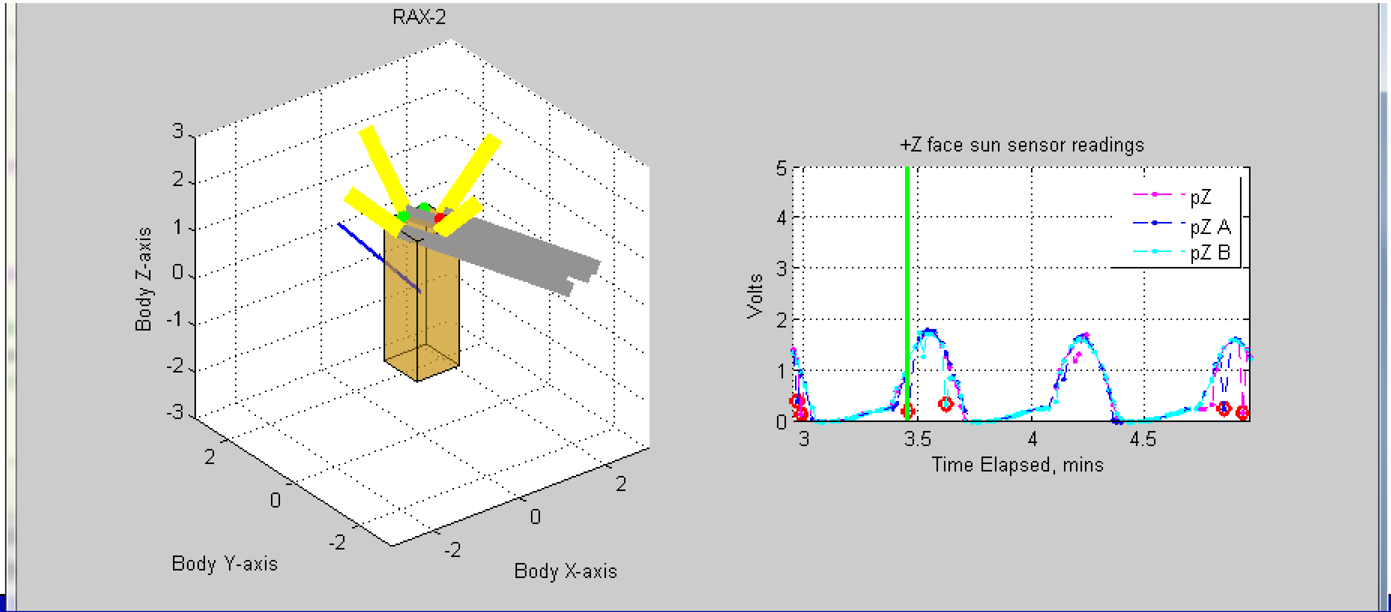
Uses beyond attitude determination…

- Single photodiode per solar panel is useful to easily verify solar panel performance

- Antenna deployment verification




RAX-2
Body Z-axis
Body Y-axis
Body X-axis
+Z face sun sensor readings
pZ
pZ A
pZ B
Volts
Time Elapsed, mins


RAX-2
Body Z-axis
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Body X-axis
+Z face sun sensor readings
pZ
pZ A
pZ B
Volts
Time Elapsed, mins

Summary

Photodiodes can be very beneficial. Key factors:

- Peak sensor output is the dominant calibration parameter
- Sensor normal directions and FOV

Is a full sun vector needed?

Can be useful beyond attitude determination, such as antenna deployment verification

RAX attitude determination subsystem design:

John C. Springmann, Alexander J. Sloboda, Andrew T. Klesh, Matthew W. Bennett, James W. Cutler, **The attitude determination system of the RAX satellite, Acta Astronautica**, Volume 75, June–July 2012, Pages 120-135.

Acknowledgements and questions

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