Infrared Earth Horizon Sensors for CubeSat Attitude Determination

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Outline

- Background and objectives
- Nadir vector estimation using Earth Horizon Sensors (EHS)
- Model improvements
- System simulation and results
- Sensitivity to mounting errors
- Conclusions and future work

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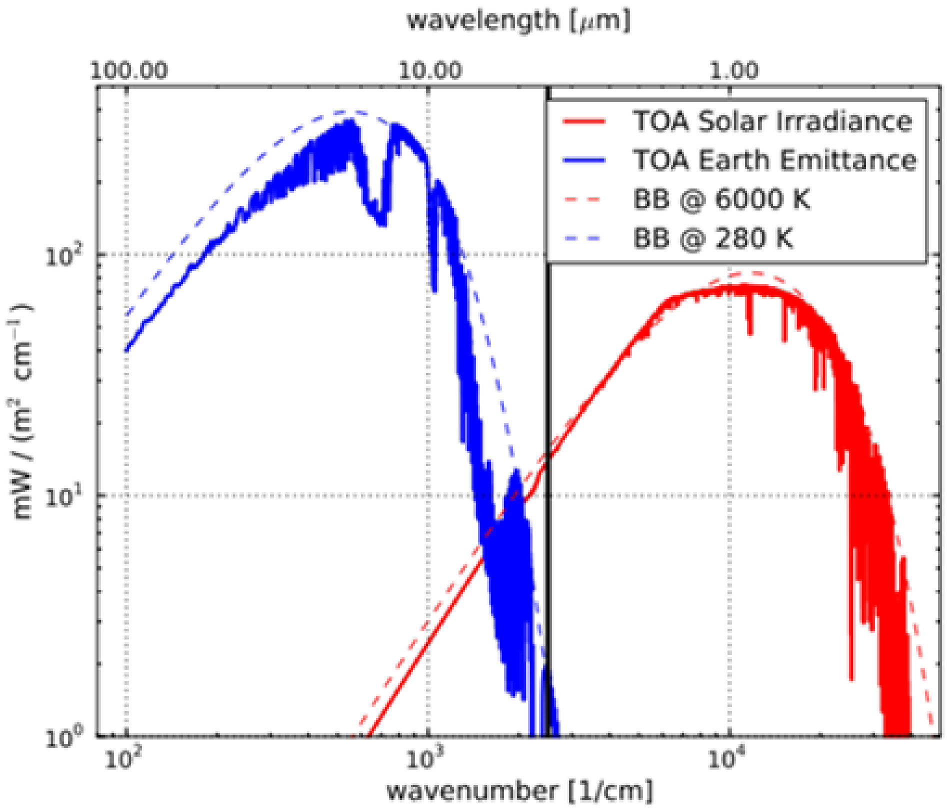
Earth Infrared (IR) Emission

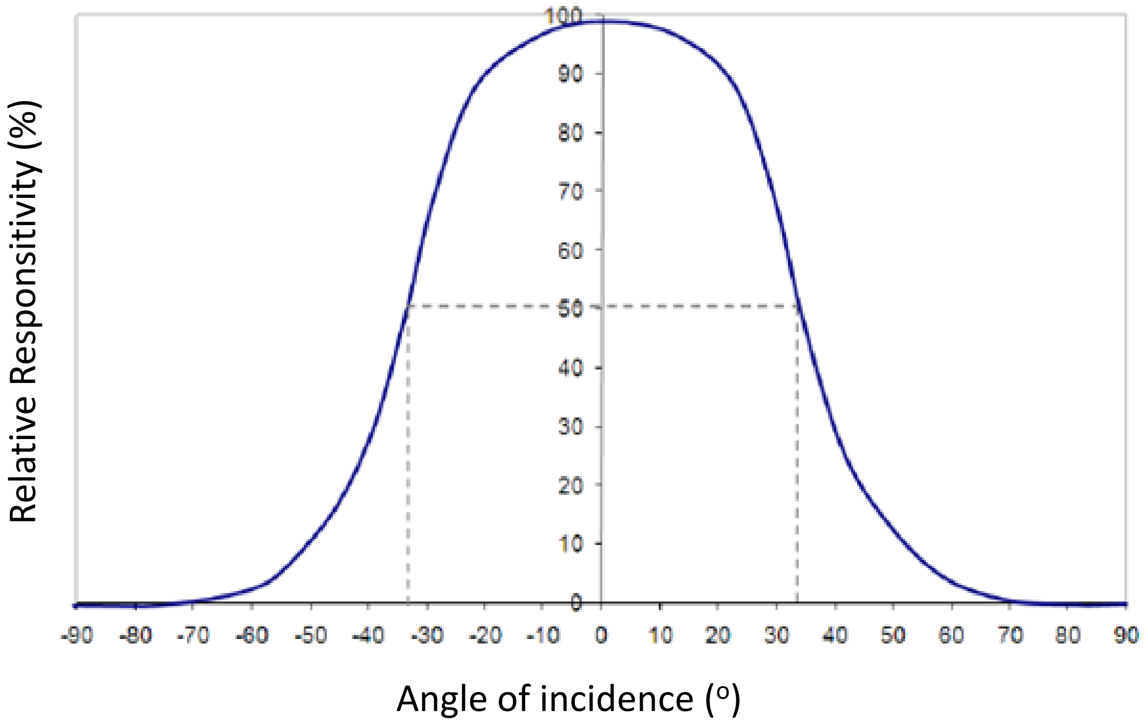


The solar irradiance and the Earth's spectral emittance
(for a clear sky standard atmosphere)

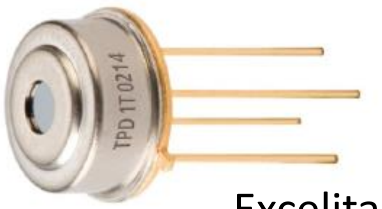
Merrelli, A. The Atmospheric Information Content of Earth's Far Infrared. University of Wisconsin-Madison. November, 2012.
http://www.aos.wisc.edu/uwaosjournal/Volume19/Aronne_Merrelli_PhD_Thesis.pdf

- Earth absorbs the Sun's radiation and re-radiates in the infrared range
- "Long-wave" considered > 4 µm (wavenumber of 2500 cm^{-1})
- Earth's emission is a strong long-wave IR signal
- For satellites in LEO at 500km, IR radiation from the Sun is insignificant due to the small solid angle subtended by the Sun in comparison to Earth
  - Sun solid angle: ~ 7×10^{-5} sr
  - Earth solid angle: ~ 4 sr

Thermopile Detectors



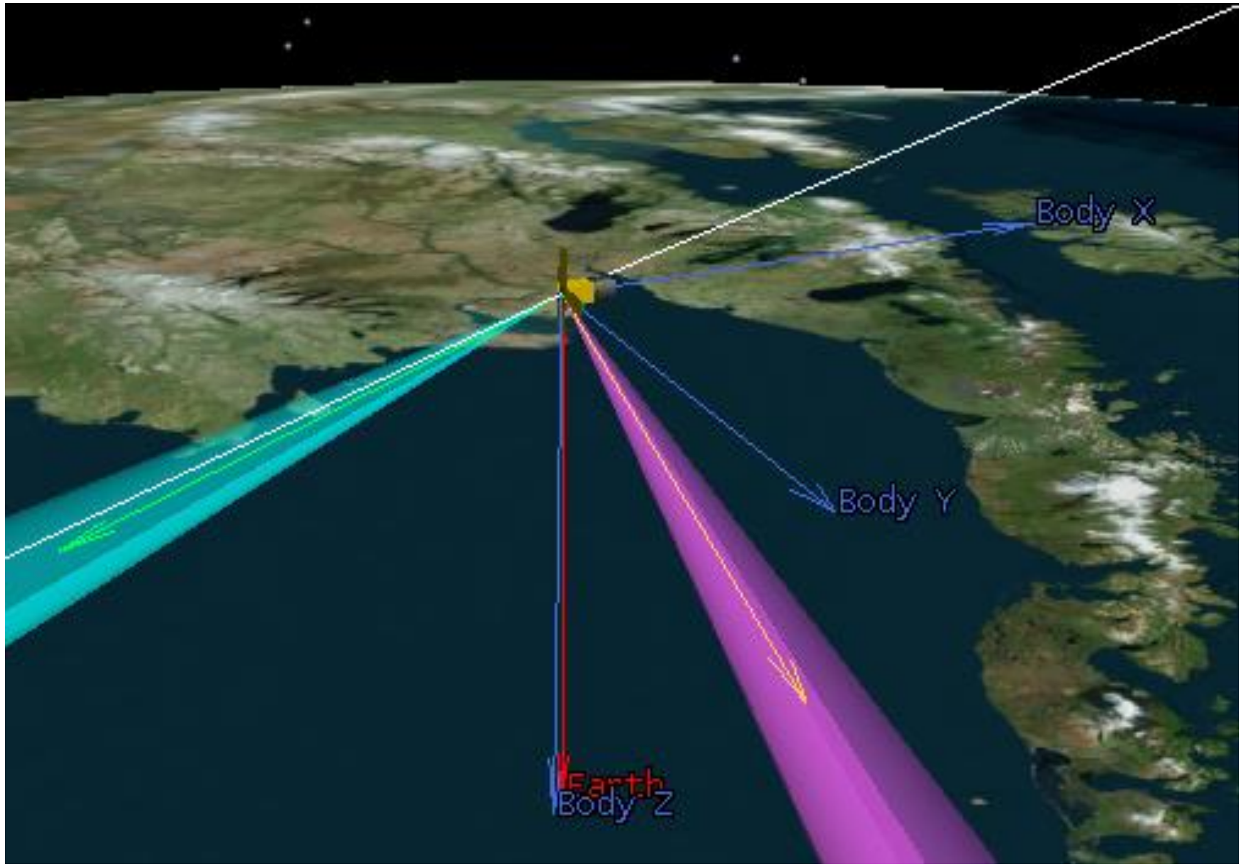
Standard thermopile sensor sensitivity



Excelitas thermopile detector
TPD 1T 0214 G9 / 3850

- Thermopiles convert thermal energy into electrical energy
- Filters can be integrated to reduce transmission spectral band width
- Sensor sensitivity has Gaussian characteristics
- Effective field of view can range from fine (7° – 10° with lens) to coarse (60° – 70°)

IR Earth Horizon Sensors (EHS)

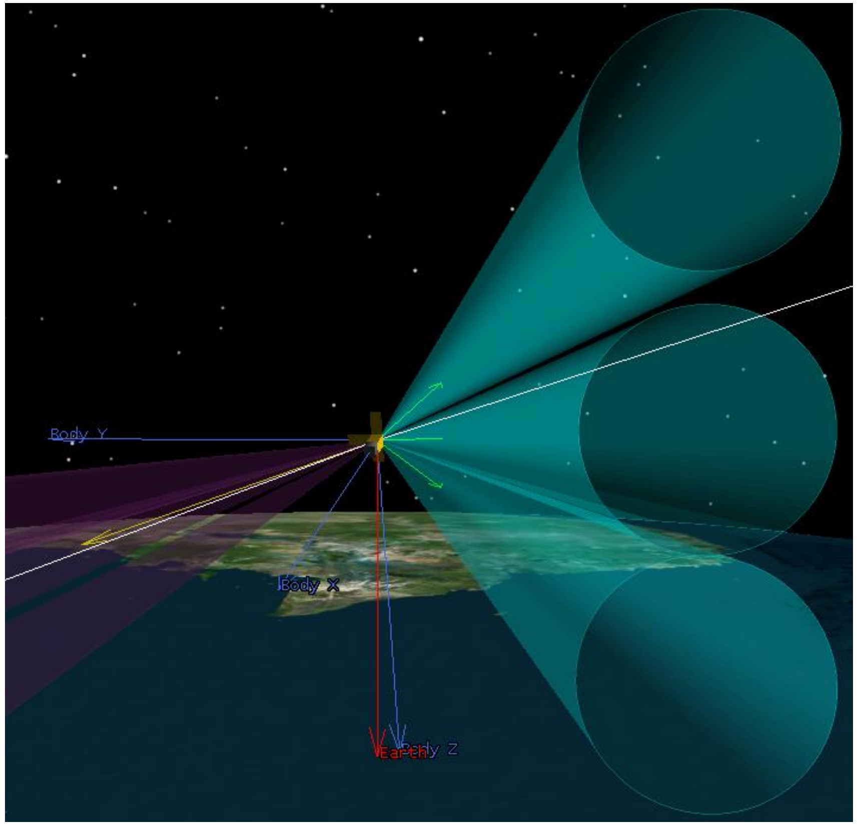


STK model of MicroMAS satellite

- Thermopiles can be mounted on satellites to detect Earth's IR radiation
- For fixed body-mounted sensors, mounting orientation depends on orbit
- Valid horizon sensing achieved when sensor FOV partially obscured by Earth
- IR EHS still work in eclipse periods (not possible with visible camera EHS)

Earth-limb-space Sensor Configuration

3 sensors/mount



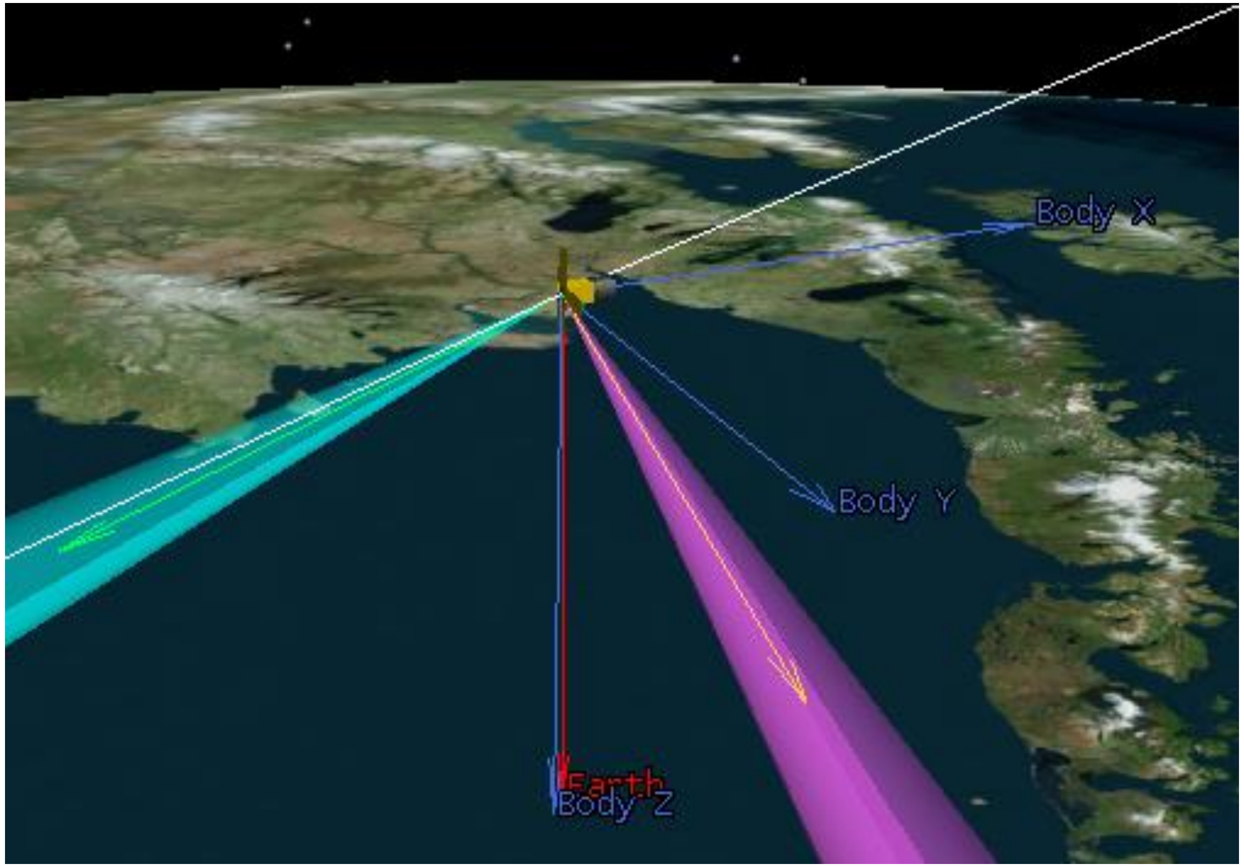
“Space“ sensor
  - “cold” reference
  - 0% obscuration

Horizon sensor
  - Partial obscuration

“Earth“ sensor
  - “hot” reference
  - 100% obscuration

- Use “Space” and “Earth” as reference for middle horizon sensors
- Mitigate the effects of variation in Earth’s IR signal
- Coarse pointing using other attitude sensors required for EHS readings to be valid

Objectives



STK model of MicroMAS satellite

Given 2 valid horizon sensor readings from distinct mount directions:

- Estimate nadir vector with high accuracy (using only limited satellite computational resources)
- Evaluate the accuracy of the estimation through simulation results
- Analyze the sensitivity of estimation with mounting uncertainties

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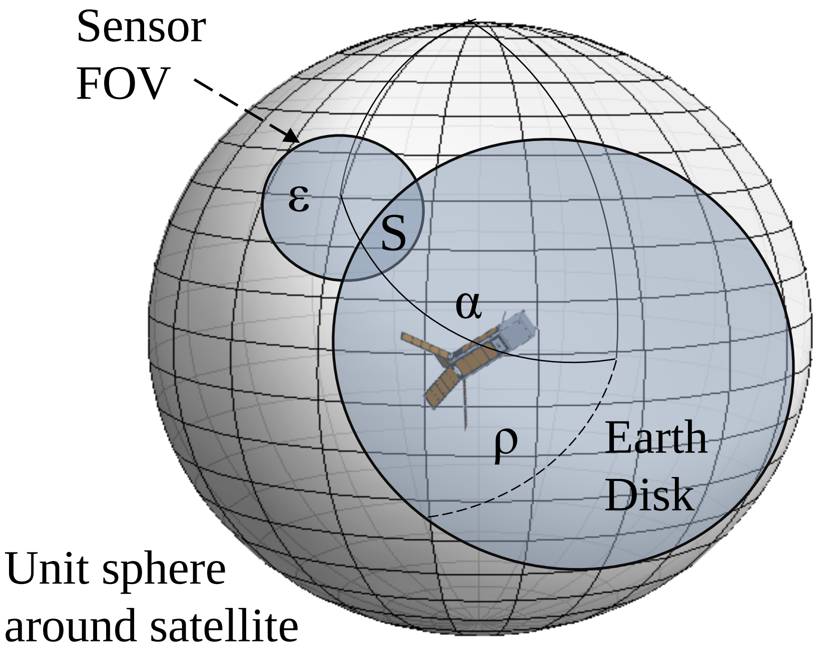
Convert sensor reading to obscured area



Spacecraft-centered celestial sphere with projections of sensor FOV and Earth disk

Simple model:

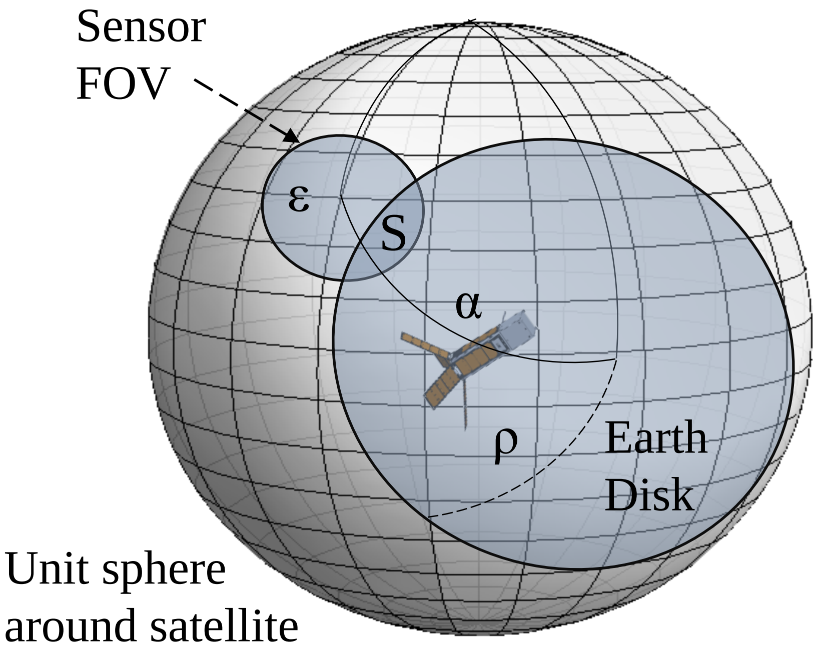
- Earth IR emission is relatively constant within sensor FOV
- Earth shape is circular
- Sensor responsitivity is uniform within FOV
- Satellite altitude is constant

} will be refined in next section

Sensor reading is approximately proportional to the area obstructed by Earth in sensor FOV.

ε = sensor FOV radius
ρ = Earth disk radius
α = angle between nadir and sensor boresight
S = overlap area between sensor FOV and Earth disk

Convert sensor obscured area to nadir angle



Spacecraft-centered celestial sphere with projections of sensor FOV and Earth disk

ε = sensor FOV radius (constant)
ρ = Earth disk radius (assume constant for this analysis)
α = angle between nadir and sensor boresight
S = overlap area between sensor FOV and Earth disk

$$S(\alpha) \propto 2\left[\pi - \cos(\rho)\,\mathrm{acos}\left(\frac{\cos(\varepsilon)-\cos(\rho)\cos(\alpha)}{\sin(\rho)\sin(\alpha)}\right) - \cos(\varepsilon)\,\mathrm{acos}\left(\frac{\cos(\rho)-\cos(\varepsilon)\cos(\alpha)}{\sin(\varepsilon)\sin(\alpha)}\right) - \mathrm{acos}\left(\frac{\cos(\alpha)-\cos(\varepsilon)\cos(\rho)}{\sin(\varepsilon)\sin(\rho)}\right)\right]$$

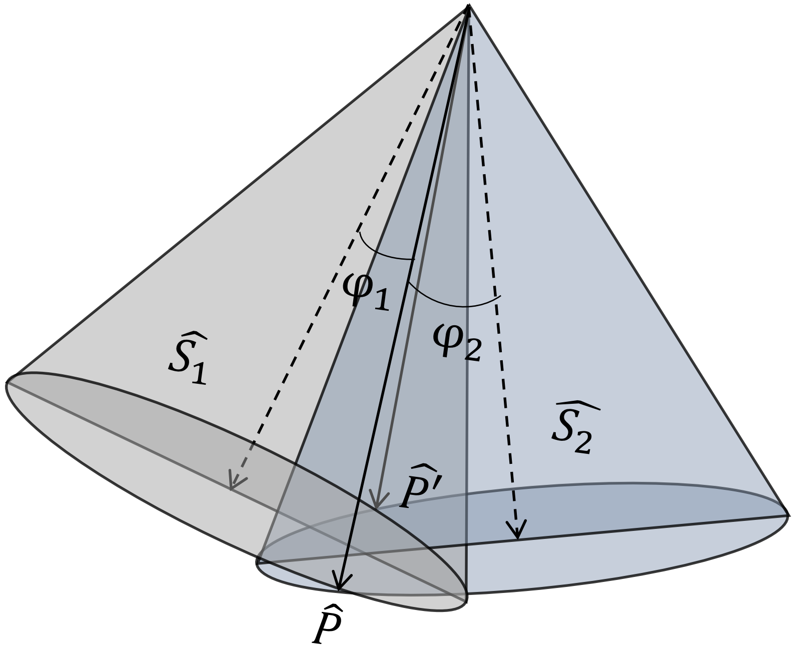
J. Wertz. Spacecraft Attitude Determination and Control. 1978

Compute possible nadir vectors from nadir angles

- Sensor boresights: $\widehat{S_1}, \widehat{S_2}$
- Nadir angles: φ_1, φ_2
- Possible nadir vector: $\hat{P}$, $\hat{P}\,'$

$$\begin{cases} \hat{P} \cdot \widehat{S_1} = \cos(\varphi_1) \\ \hat{P} \cdot \widehat{S_2} = \cos(\varphi_2) \\ \left|\hat{P}\right| = 1 \end{cases}$$

$$\begin{cases} P_x\ S_{1x} + P_y\ S_{1y} + P_z\ S_{1z} = \cos(\varphi_1) \\ P_x\ S_{2x} + P_y\ S_{2y} + P_z\ S_{2z} = \cos(\varphi_2) \\ P_x^2 + P_y^2 + P_z^2 = 1 \end{cases}$$

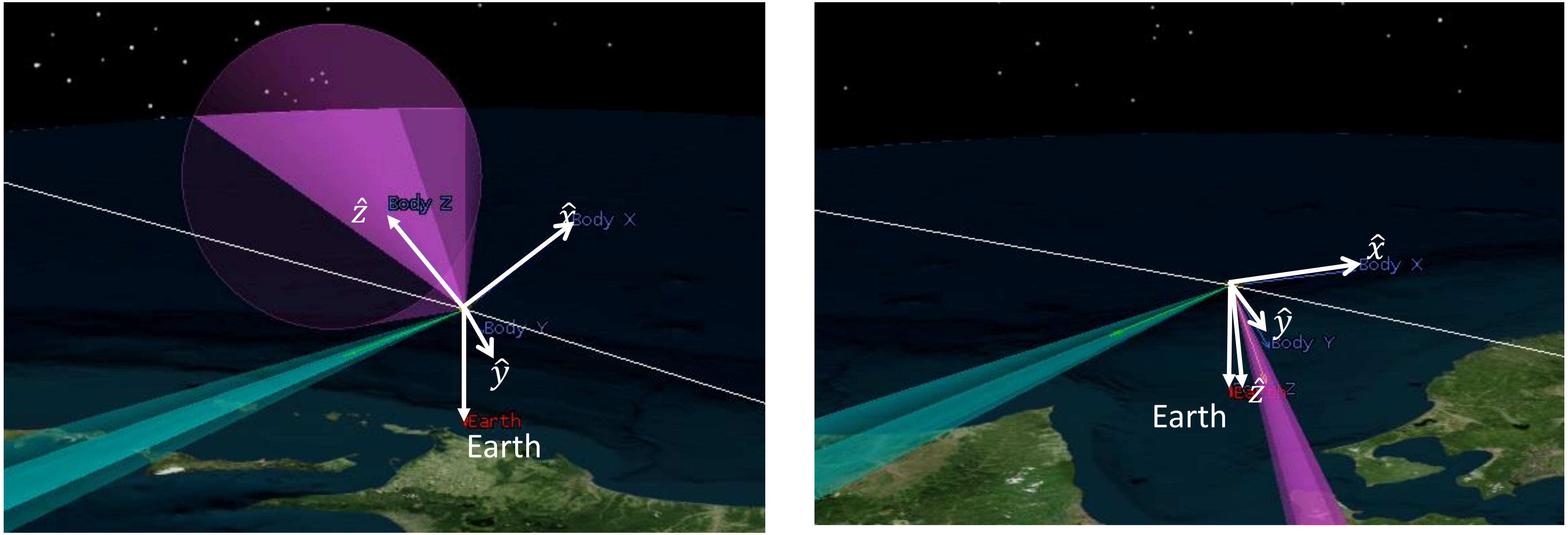


Geometric representation of the solutions

System of equations can be solved analytically
Contains a 2nd order equation → maximum of 2 solutions

Assume low sensor noise and correct calibration
→ 2 possible nadir vectors (ambiguity)

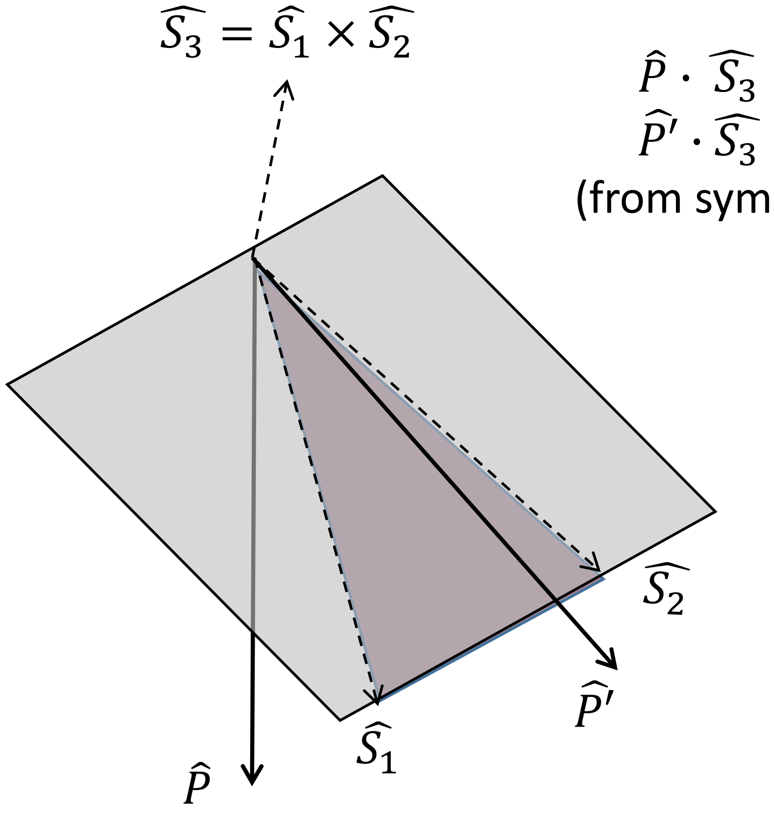
Attitude ambiguity visualization from 2-sensor configuration



Both attitudes yield the same sensor readings

The two possible nadir vectors are separated by 120^o in the satellite's body frame

Resolve ambiguity



$\hat{P} \cdot \widehat{S_3} < 0$

$\widehat{P'} \cdot \widehat{S_3} > 0$

(from symmetry)

- Acquire lock:
  - Need another attitude sensor (coarse) to resolve ambiguity
  - Use EHS for fine attitude knowledge
- Maintain lock:
  - Solutions can be distinguished by being on opposite sides of the plane containing $\widehat{S_1}$ and $\widehat{S_2}$
  - Compare nadir solutions to past valid nadir vectors (assuming low disturbance level)

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  - Gaussian responsitivity
  - Altitude correction
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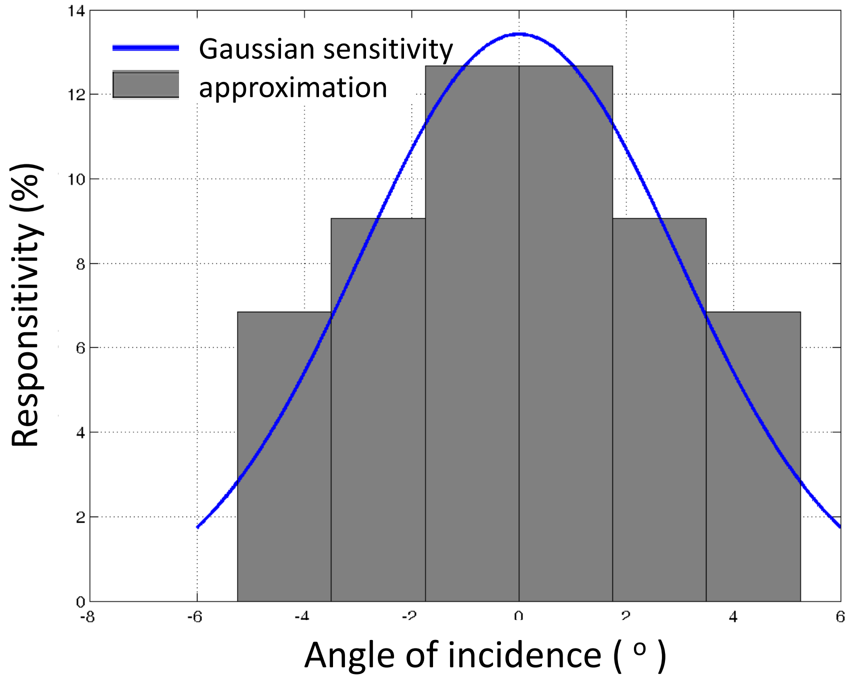
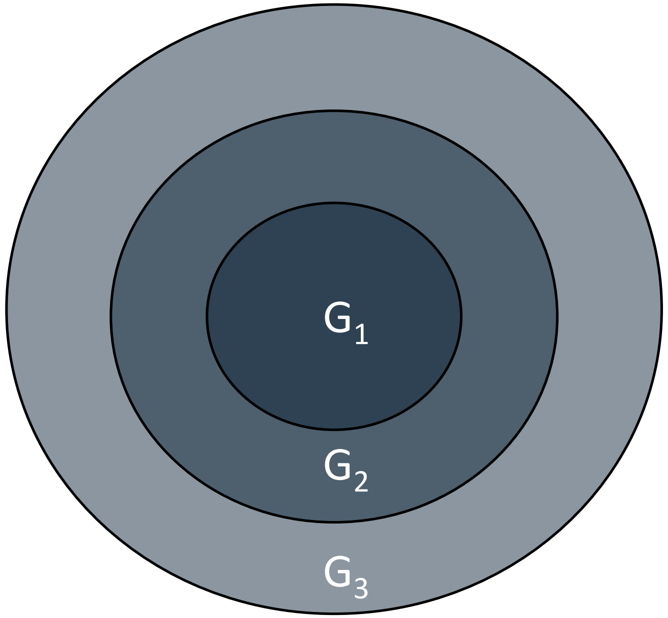
Sensor Gaussian approximation model



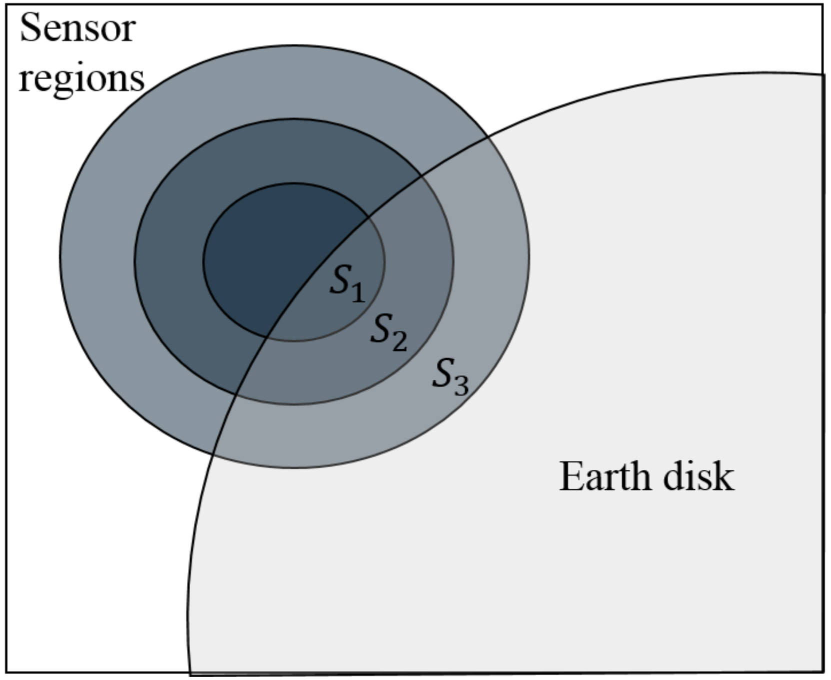
Sensor responsitivity 2D approximation

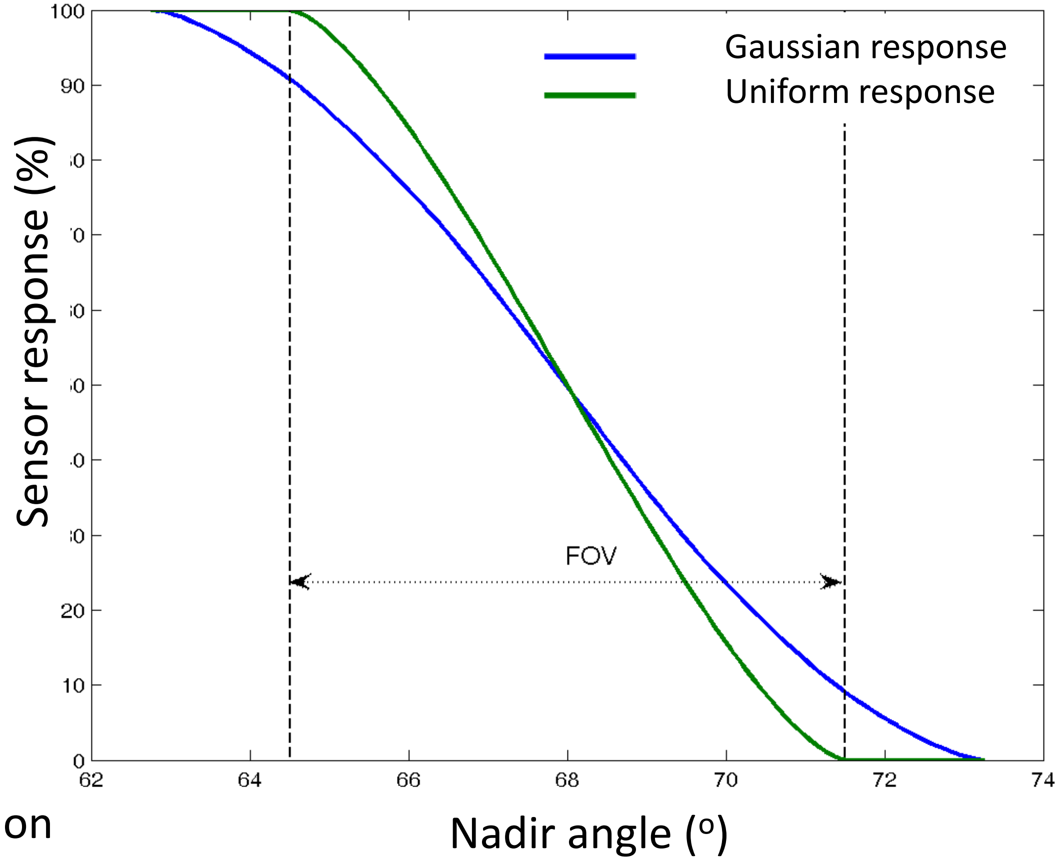


Sensor responsitivity 3D approximation

- Gaussian responsitivity curve can be approximated with piece-wise constant function
- Sensor field can be divided into regions of constant sensitivity with corresponding weight factor

Sensor Gaussian approximation model

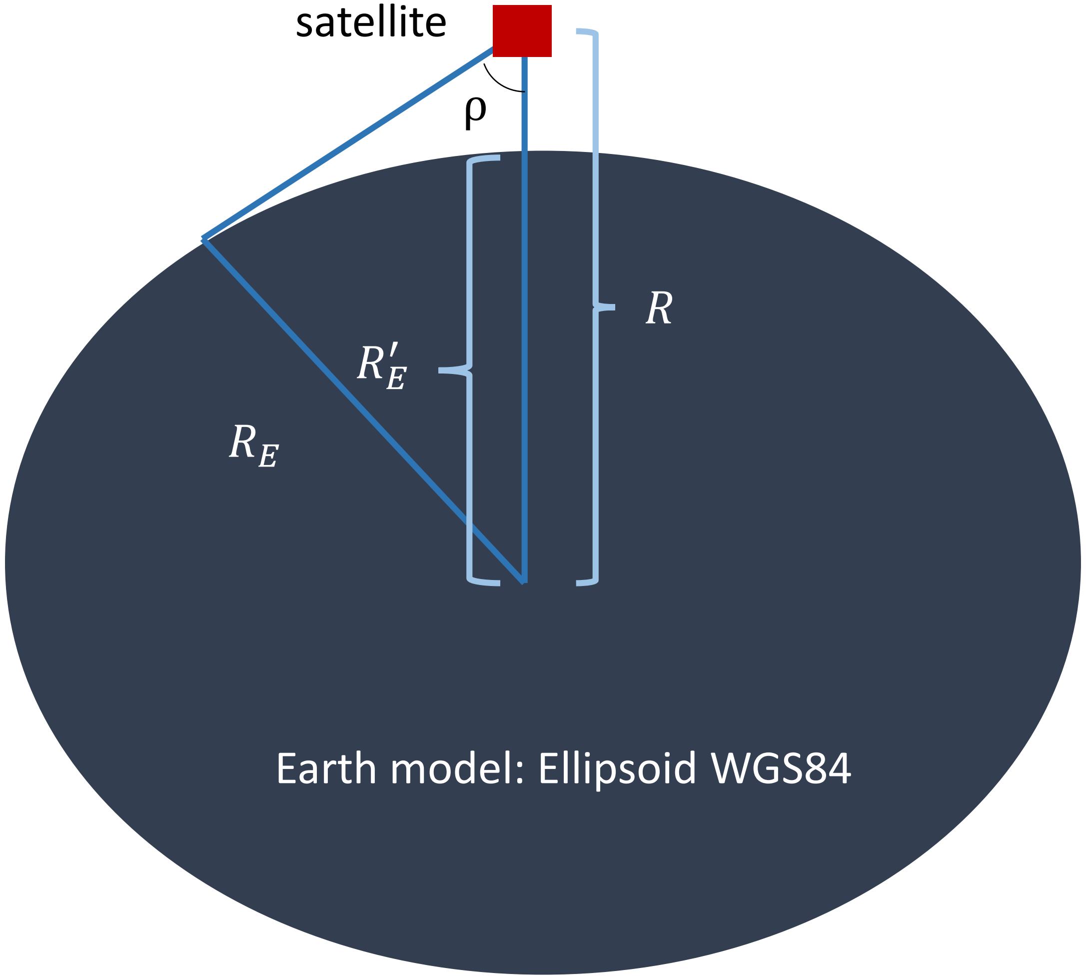




$$S = S_1G_1 + S_2G_2 + S_3G_3$$

S_1, S_2, S_3: overlap area of Earth disk with each sensor region
G_1, G_2, G_3: Gaussian weighting factors

Altitude Correction



- Important for de-orbiting phase of missions and for satellites in high-eccentricity orbit
- Earth disk radius:

$$\rho \cong \sin^{-1}\left(\frac{R'_E(\vec{x})}{R\,(\vec{x})}\right)$$

where:

$\vec{x}$ = satellite position (from GPS or TLE)

$R'_E(\vec{x})$ = Earth radius from WGS84 model

$R\,(\vec{x})$ = Orbit radius

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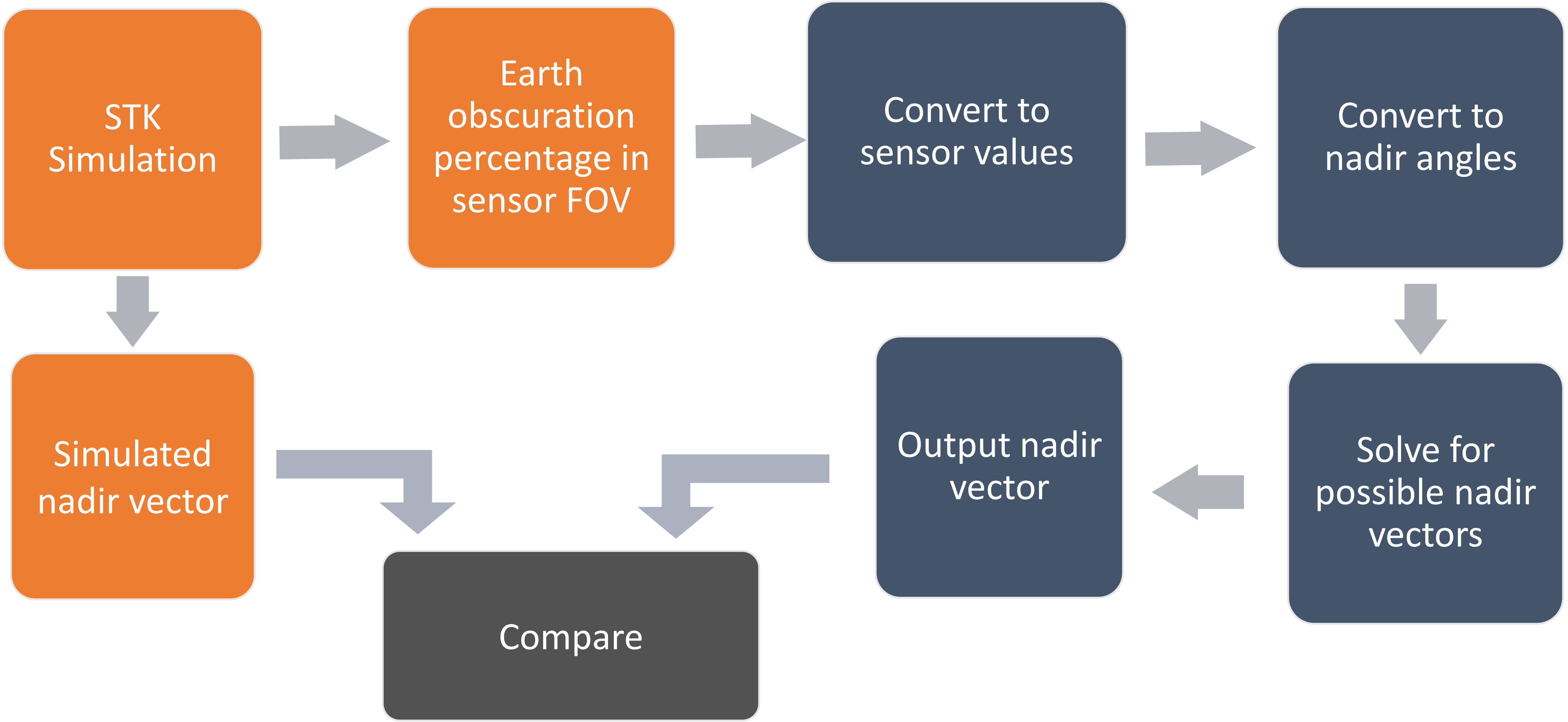
Testing with STK System Simulation



STK Simulation

Earth obscuration percentage in sensor FOV

Convert to sensor values

Convert to nadir angles

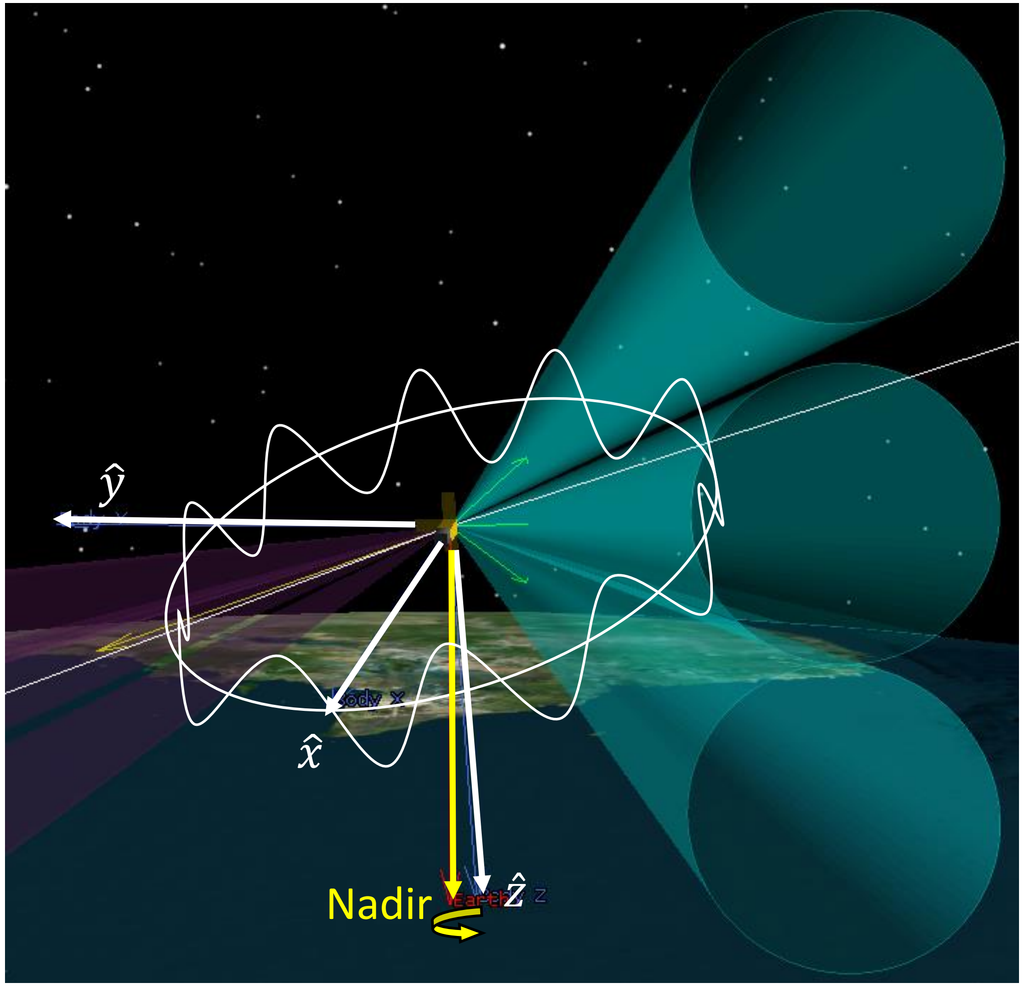
Solve for possible nadir vectors

Output nadir vector

Simulated nadir vector

Compare

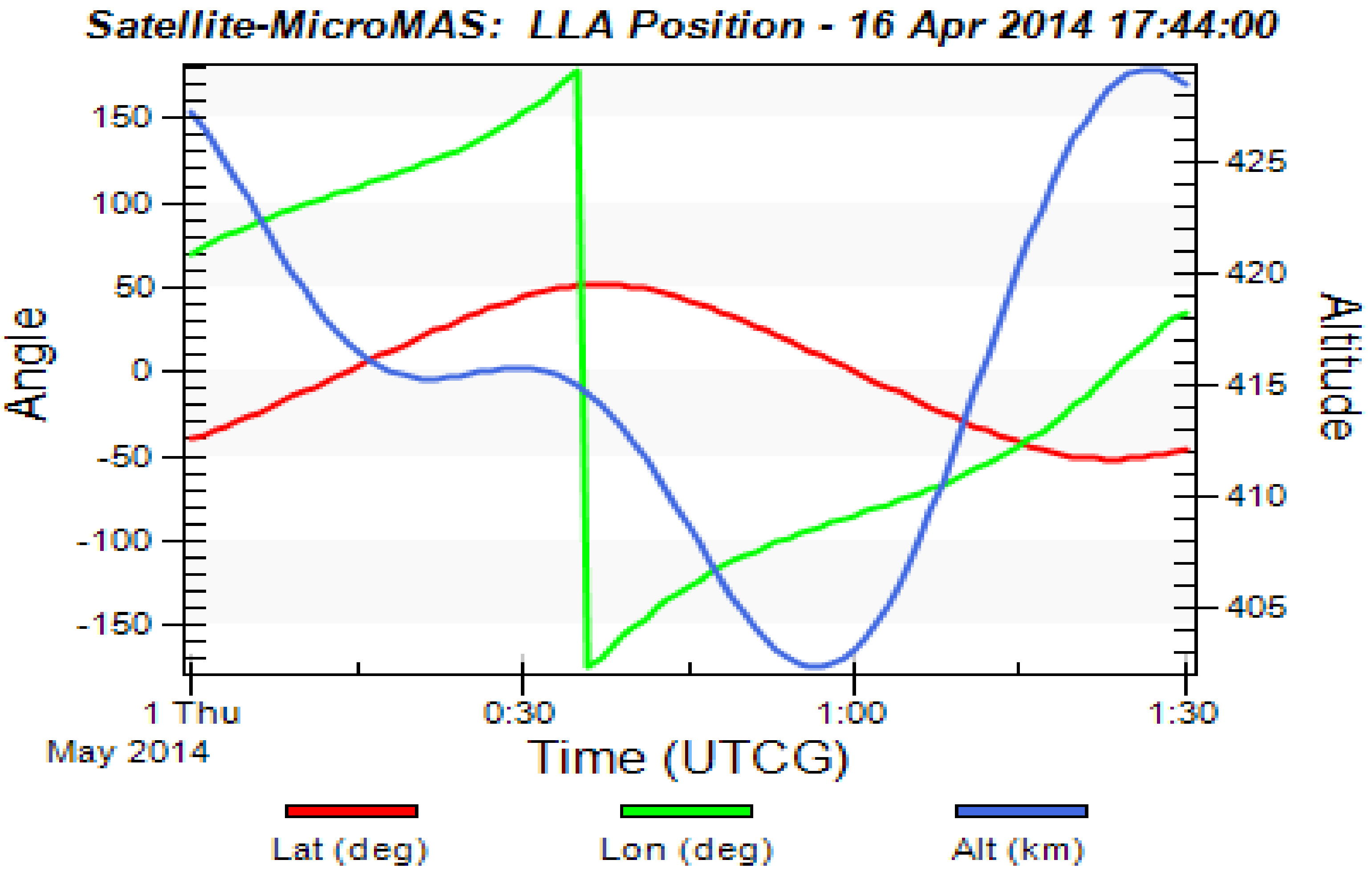
Satellite Tool Kit Simulation Scenario



- Spacecraft sensor model
  - sensor FOV: 10^o
  - mount directions: $-\hat{x}$, $+\hat{y}$
  - horizon sensor dip angle: 20^o
- Attitude setting
  - Attitude: Spin aligned around nadir
  - Spin rate : 0.1 rev/min
  - Nutation levels: 4^o

→ Satellite's z-axis oscillates around nadir vector with maximum offset of 4^o.

Simulation Scenario Orbit Profile



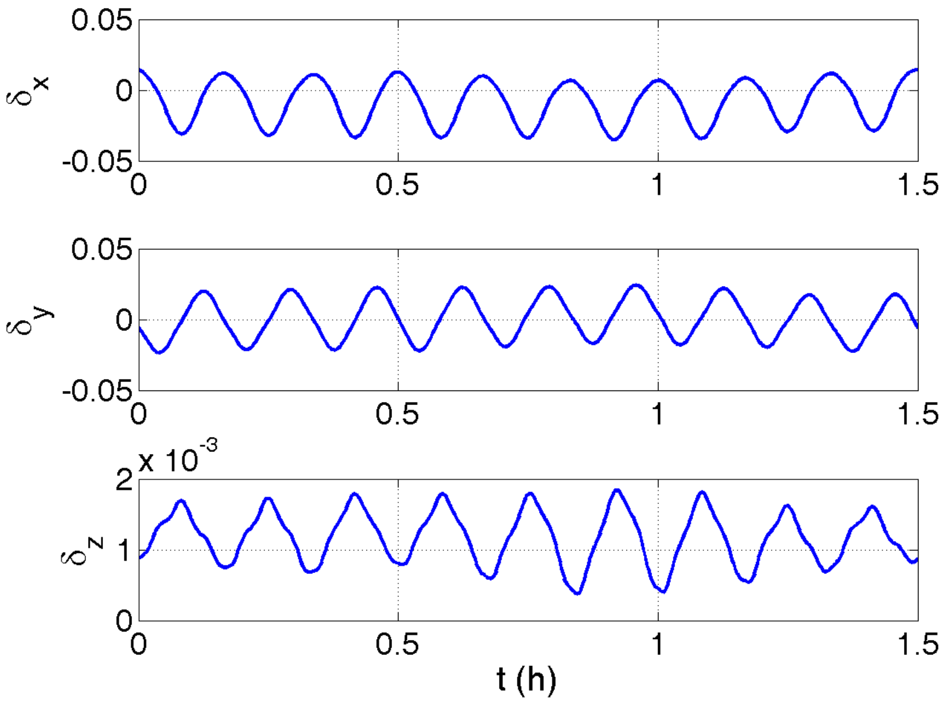
- ISS Orbit
- High Precision Orbit Propagator (HPOP)
  - Including environmental perturbations
- Altitude range:

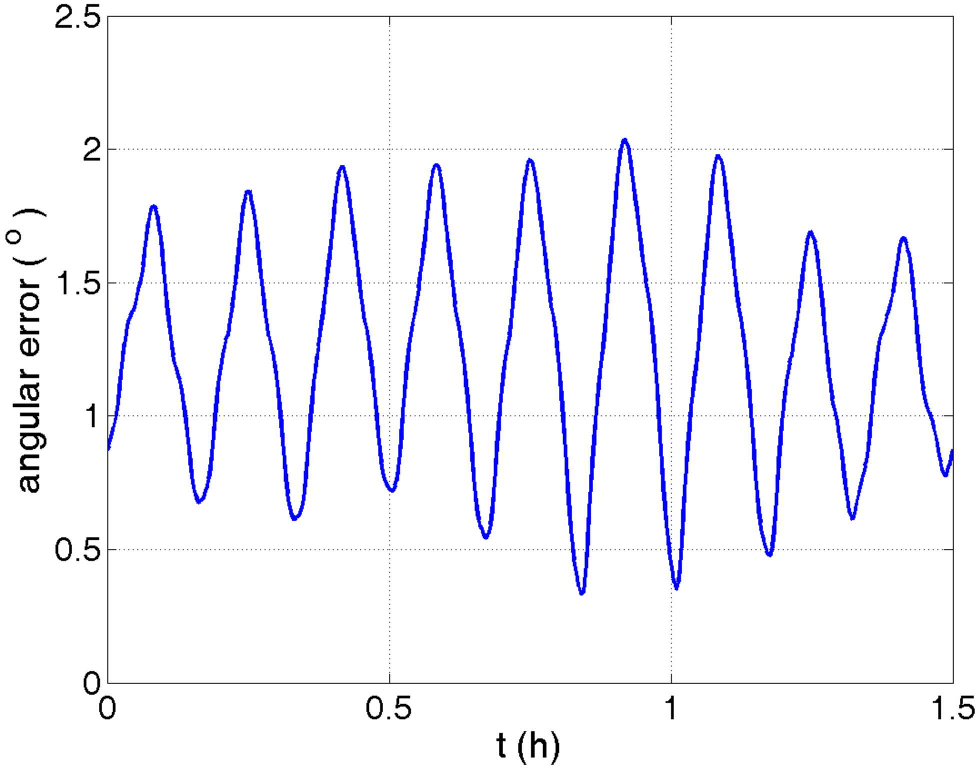
~ 400 km – 430 km

Simulation Results

- Sensor sensitivity: Uniform
- No altitude correction

Angular error: (1.23 +/- 0.43) º

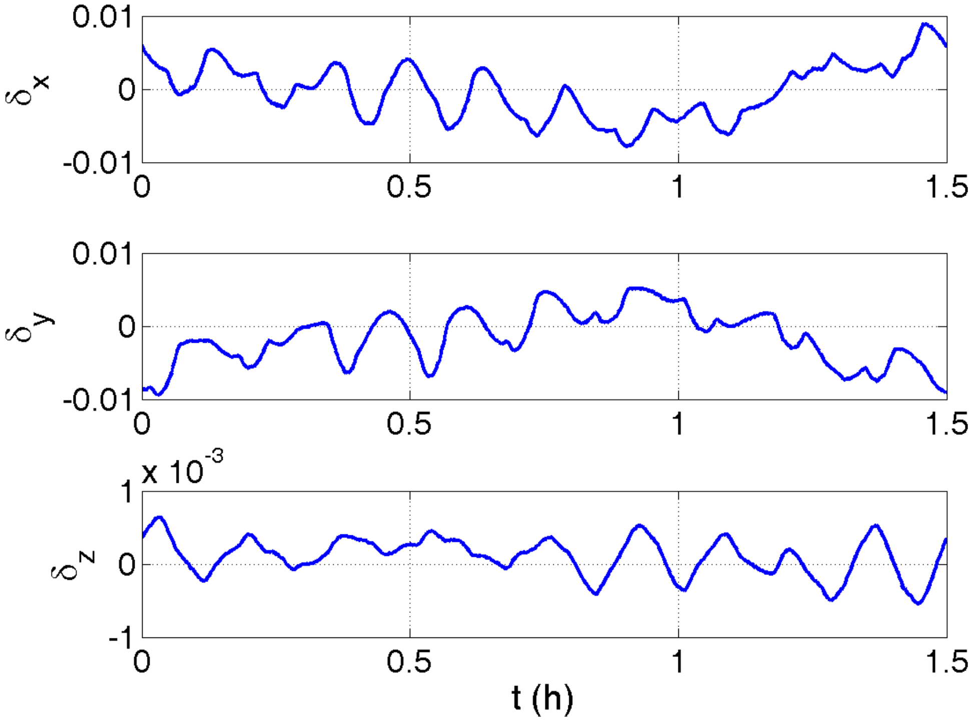


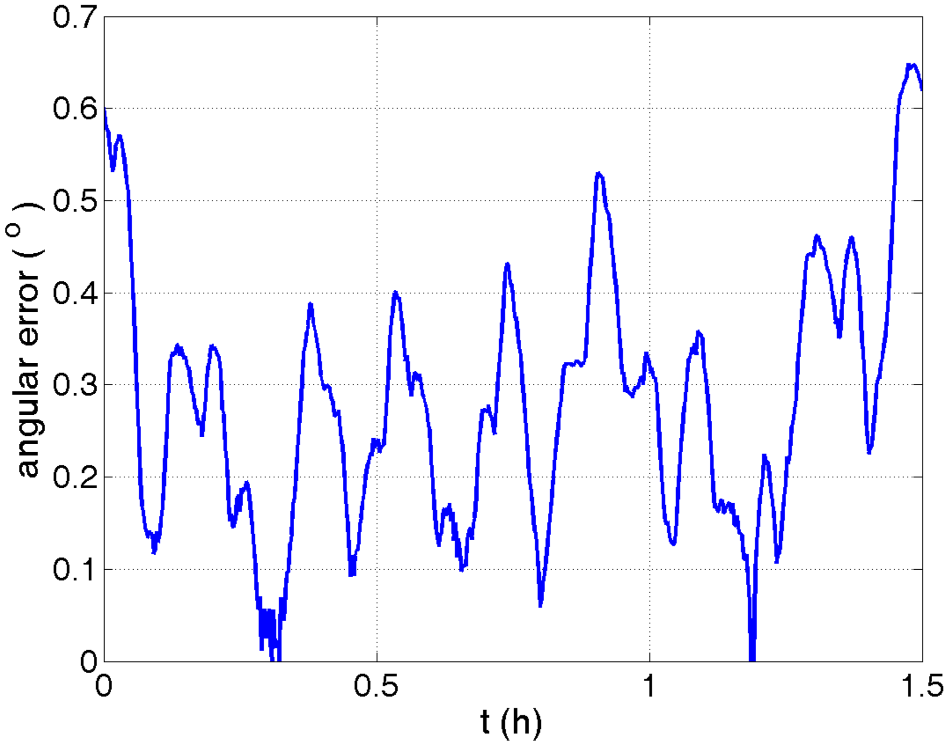


Simulation Results

- Sensor sensitivity: Gaussian
- No altitude correction

Angular error: (0.28 +/- 0.14) ^{o}

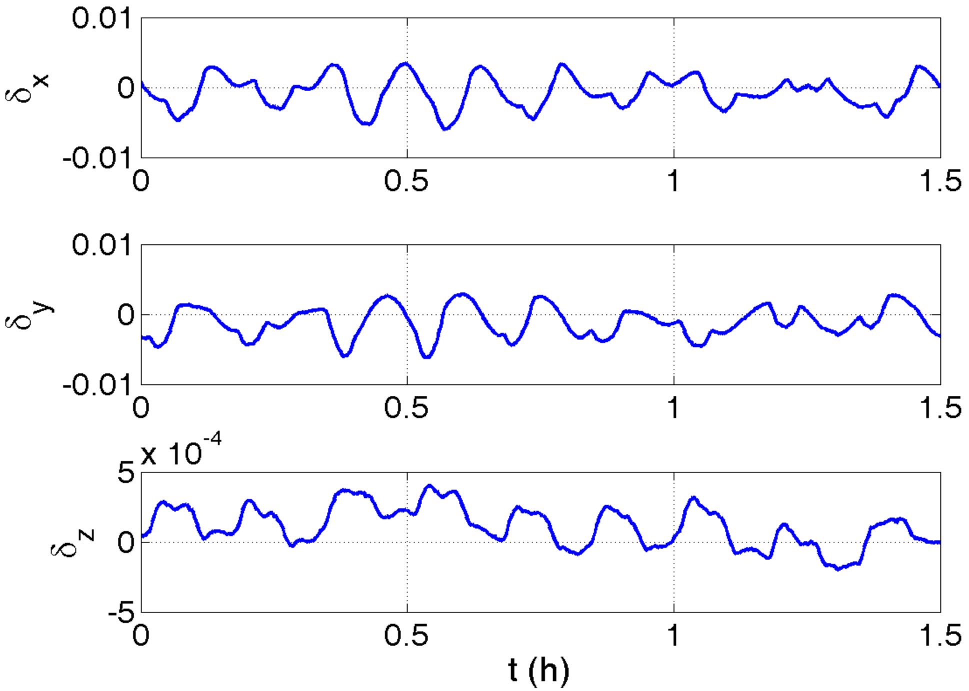


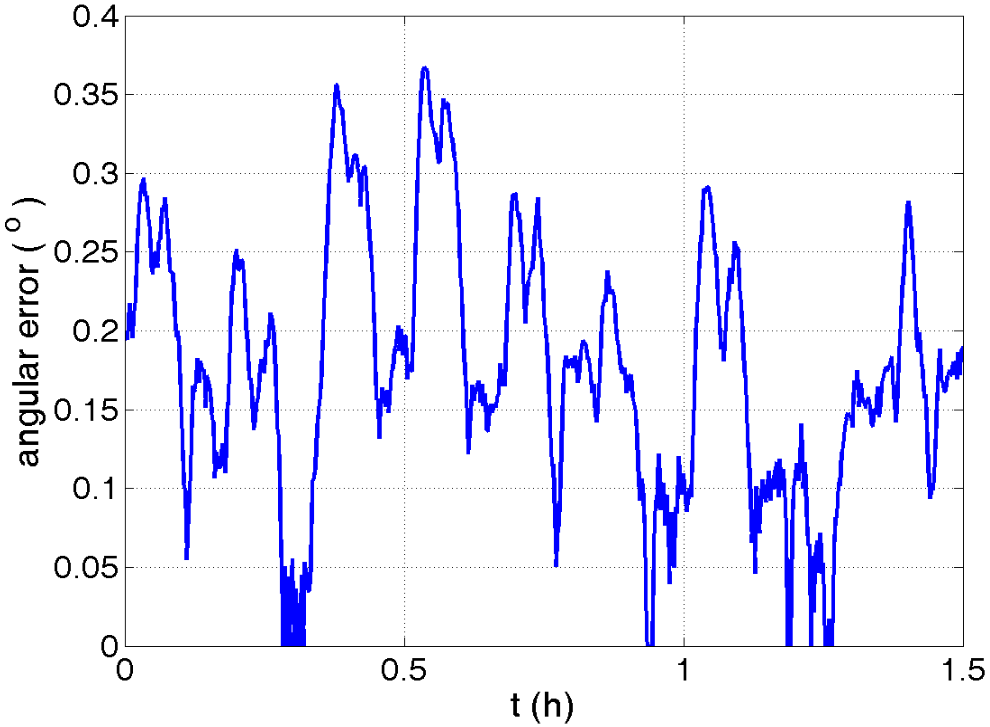


Simulation Results

- Sensor sensitivity: Gaussian
- Altitude correction

Angular error: (0.18 +/- 0.082) °





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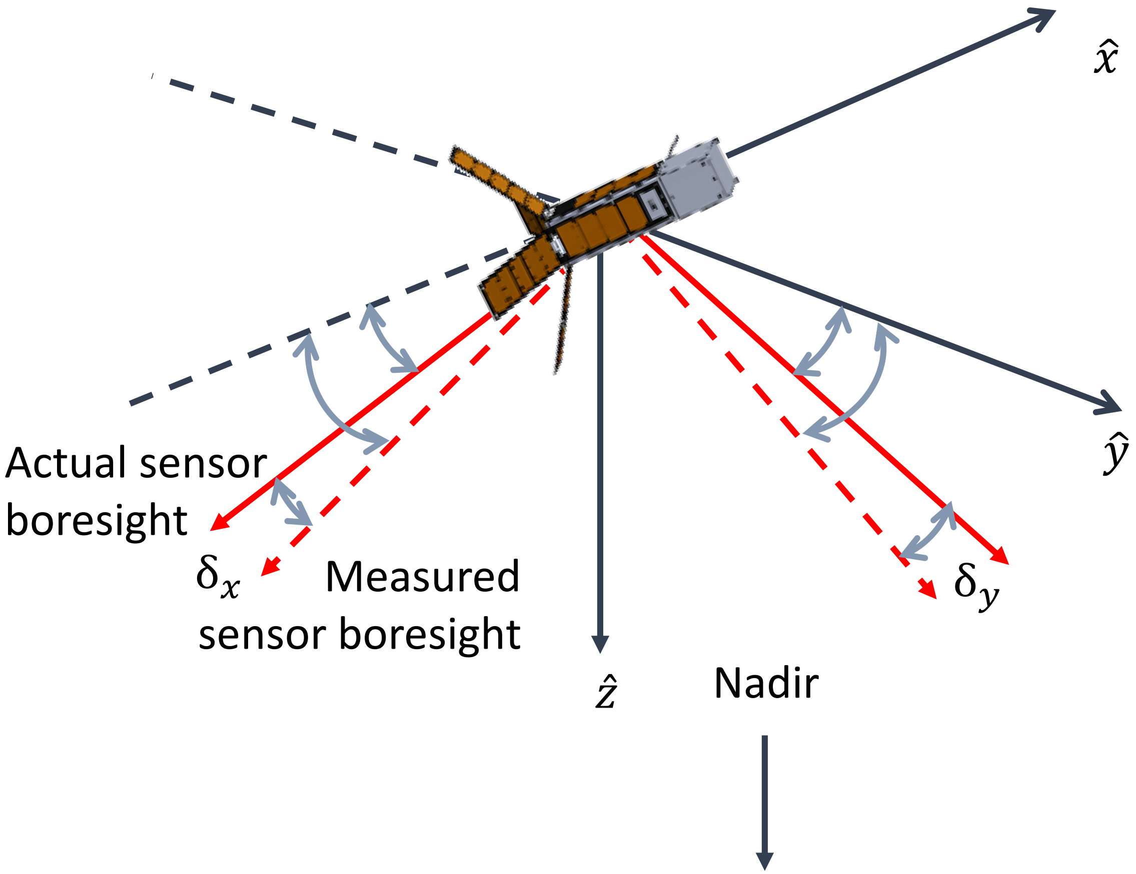
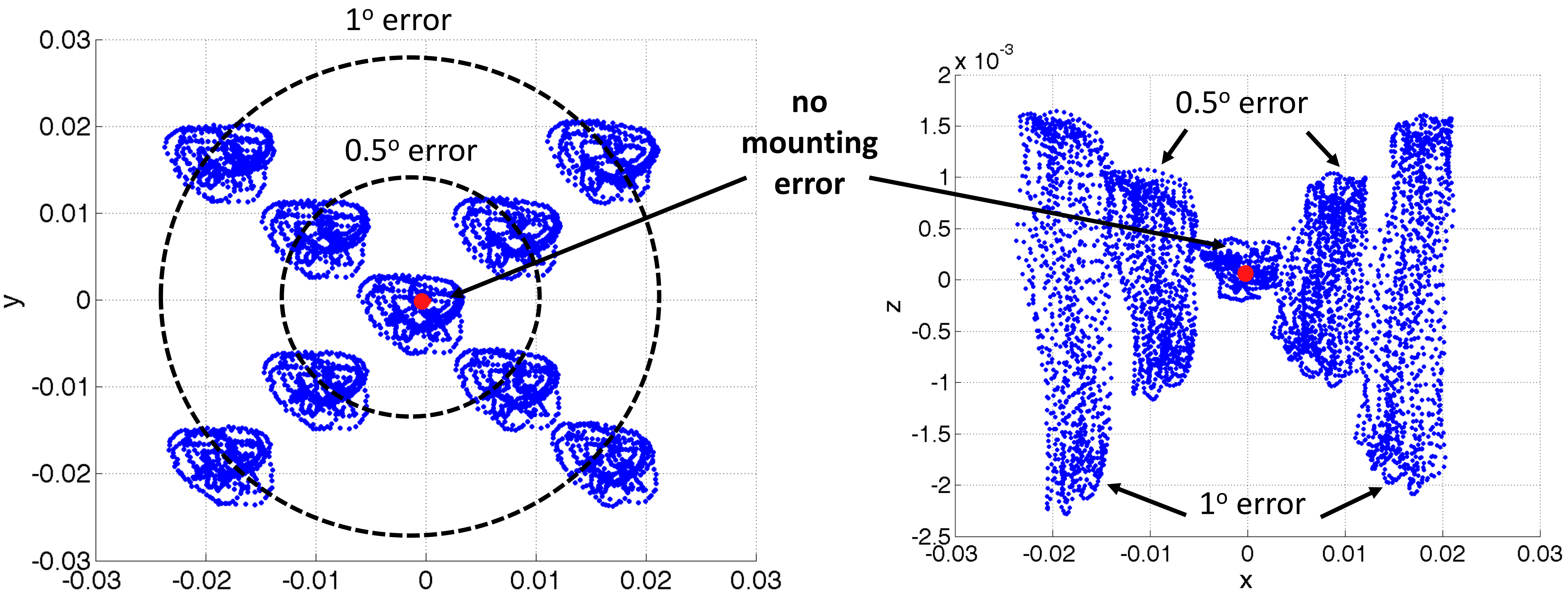
Sensor alignment errors



- Assume perfect mounting in $\hat{x}$ and $\hat{y}$
- Mounting error occurs only in $\hat{z}$ ("dip" angle)

Sensitivity to alignment errors



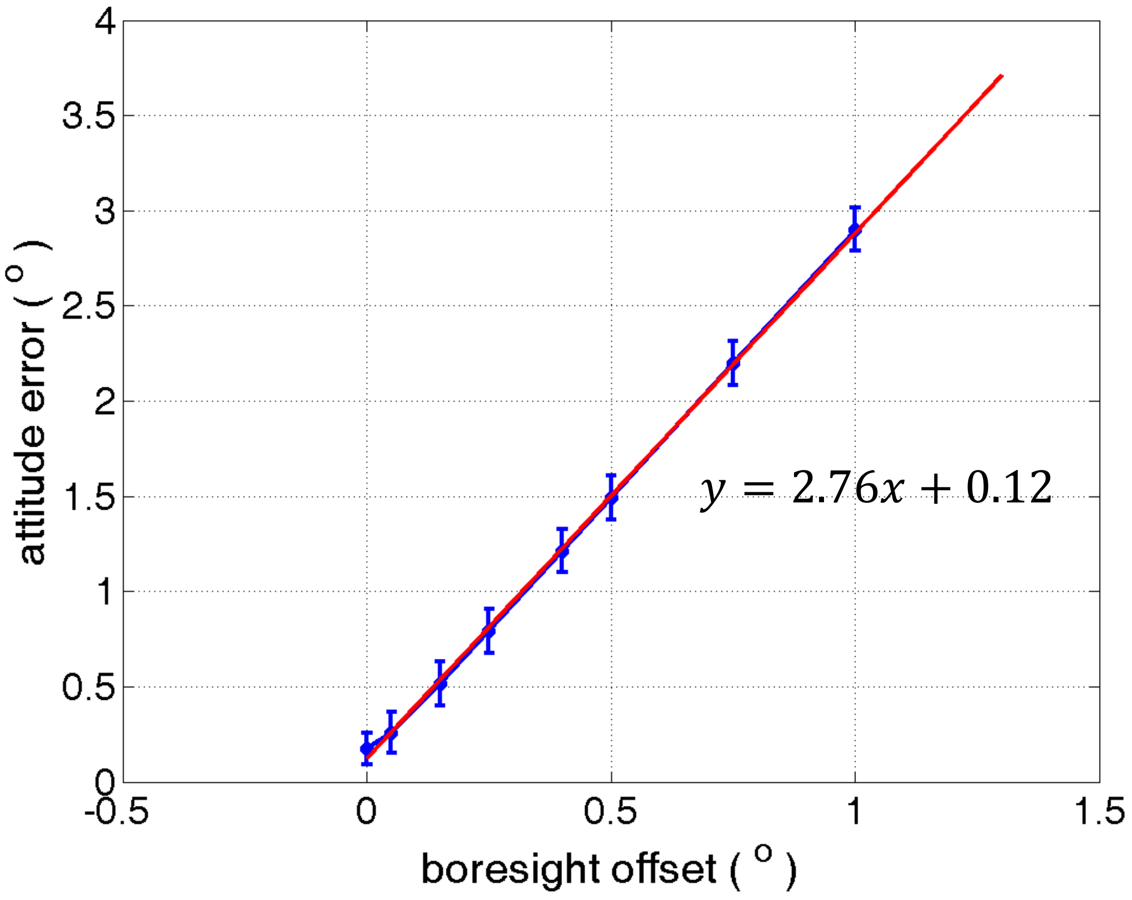
x-y pointing offset

z pointing uncertainty

● Nadir estimation errors

● Nadir direction – centered at (0,0,0)

Boresight measurement sensitivity



- Nadir estimation error sensitivity to alignment error follows **linear correlation**
- 0.25° boresight offset on each mount leads to an additional 0.7° in attitude error
- x and y errors are more dominant than z errors

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Conclusion and Future Work

Conclusion

- Nadir vector estimation method from EHS was presented
- Estimation accuracy was verified through simulations to be 0.2^{o} (assuming perfect sensor response and alignment)
- Nadir estimation error increases linearly with sensor alignment errors

Future work

- Quantify the effects of sensor response error
- Verify attitude accuracy from satellite data

Q&A