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 alignment errors
- Conclusions and future work

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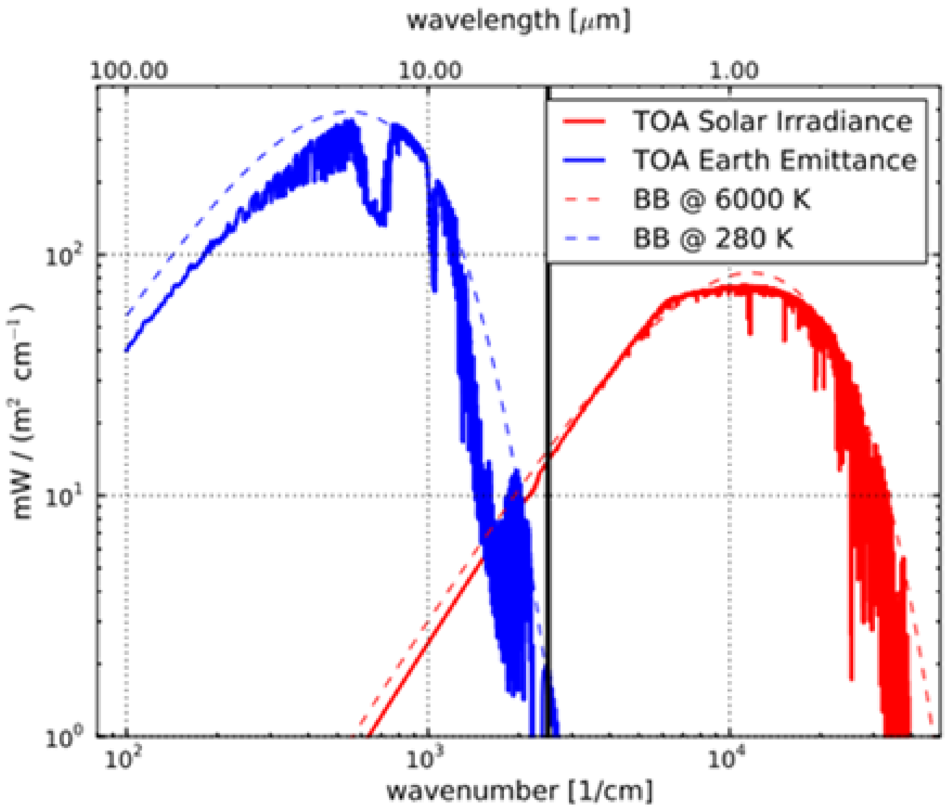
Earth Infrared (IR) Emission

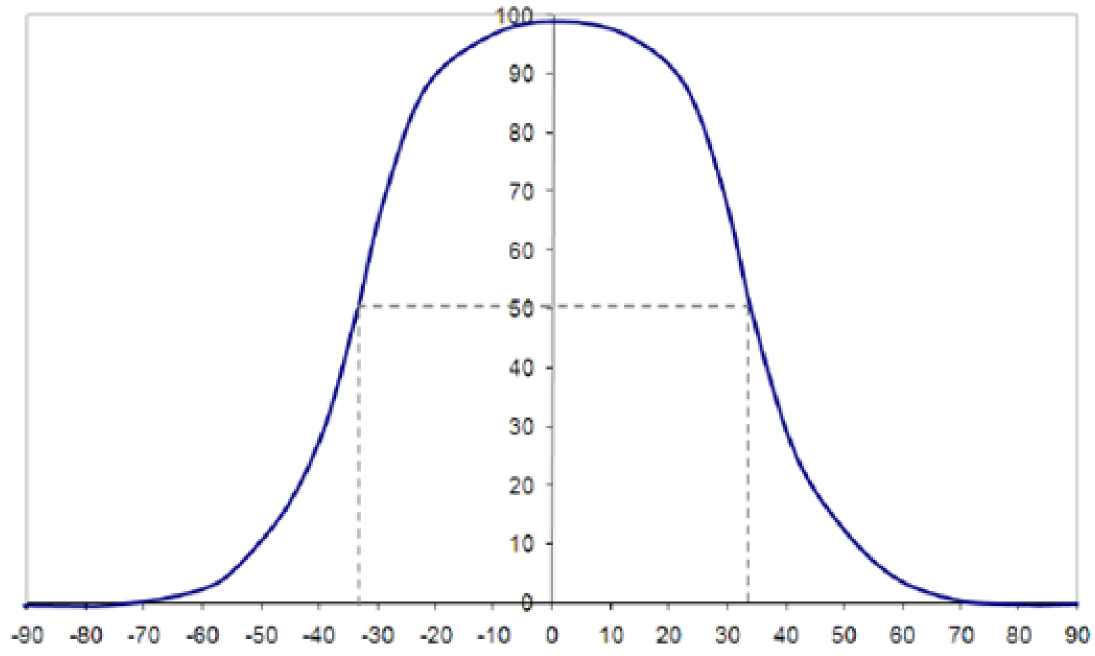


The solar irradiance and the Earth's spectral emittance (for a clear sky standard atmosphere)

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 um (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

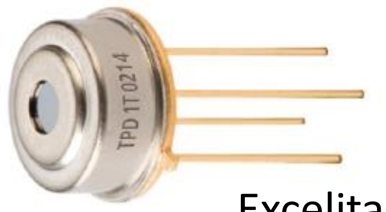
Thermopile Detectors



Relative Responsitivity (%)

Angle of incidence (°)

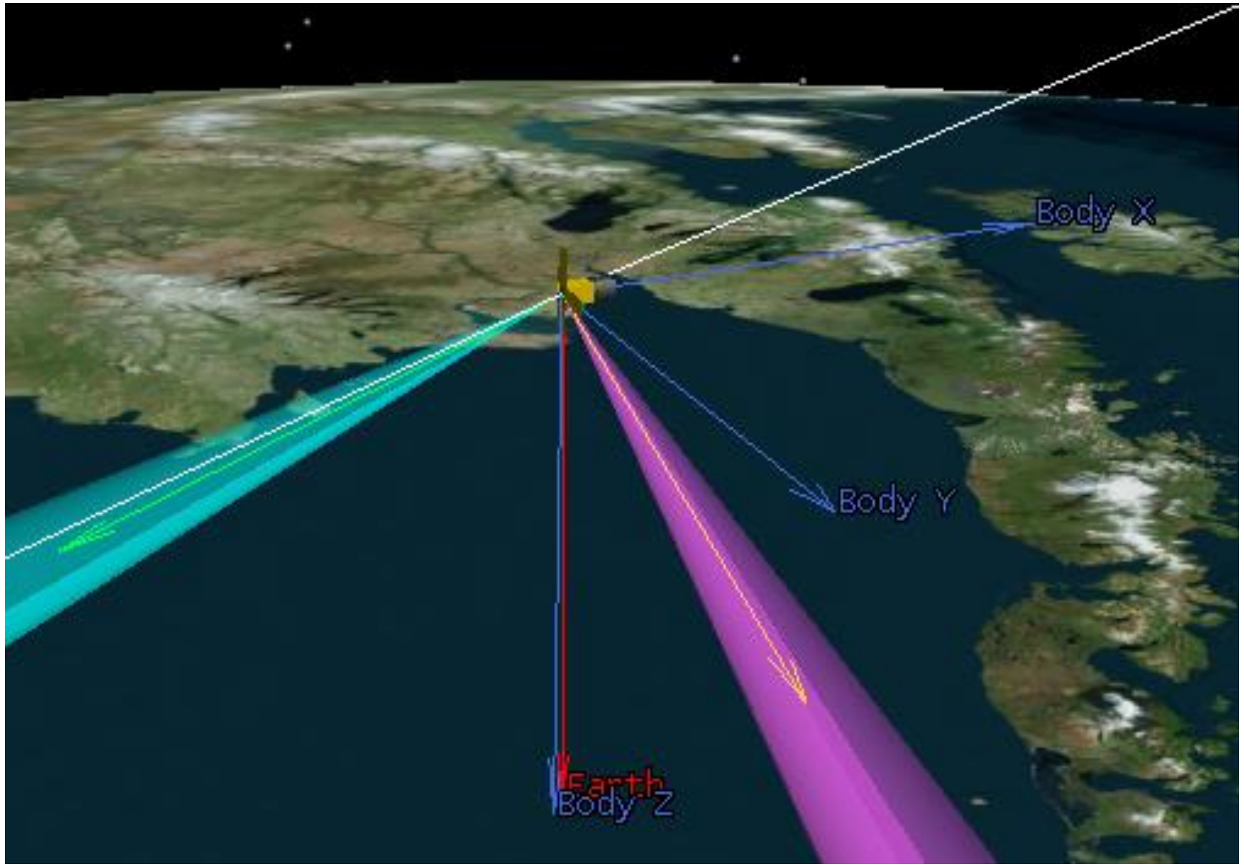
Standard thermopile sensor sensitivity



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)

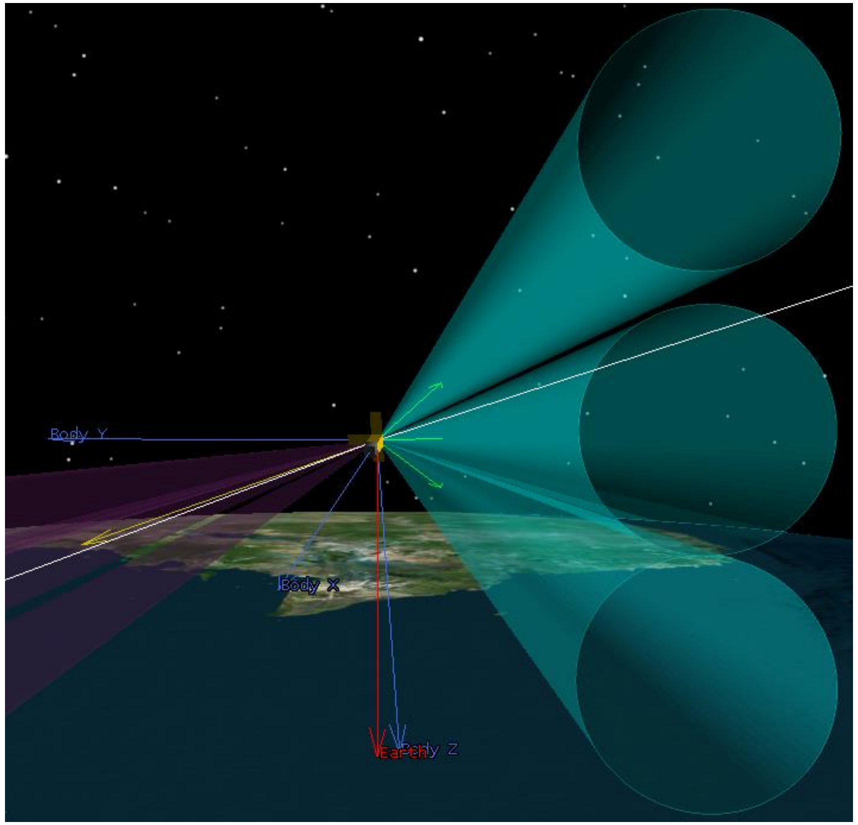


STK model of MicroMAS satellite

- 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



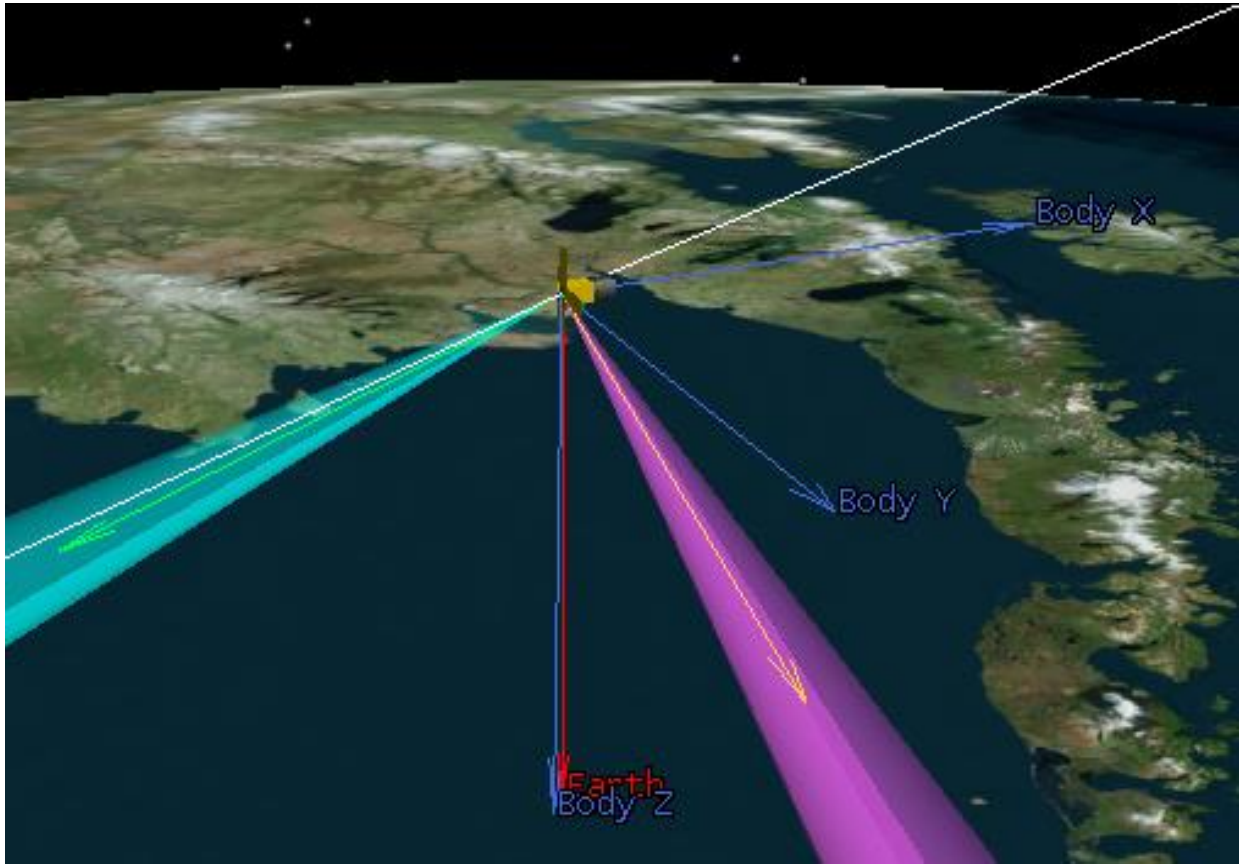
"Space" sensor
- "cold" reference
- 0% obscuration

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 alignment uncertainties

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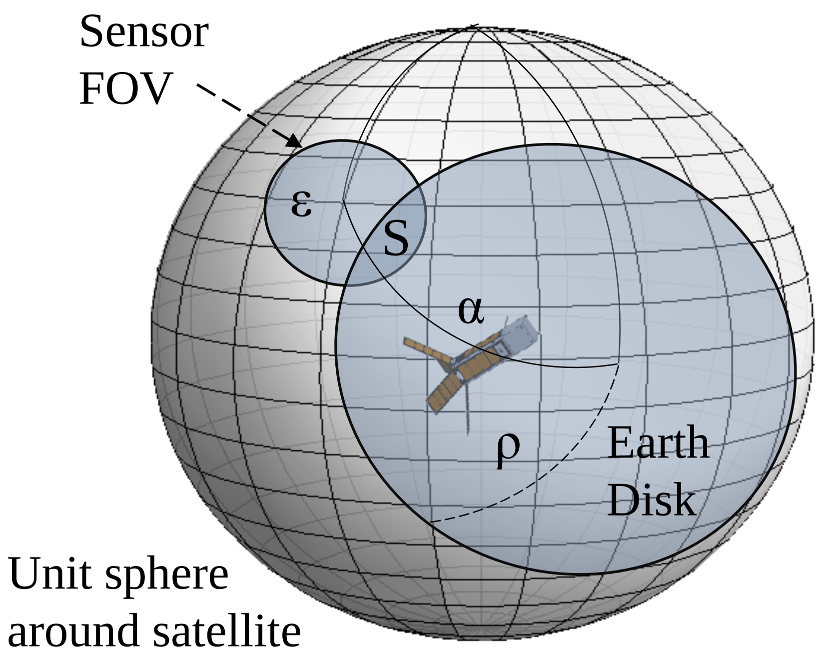
1. Sensor reading to sensor obscured area



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

Simple model:

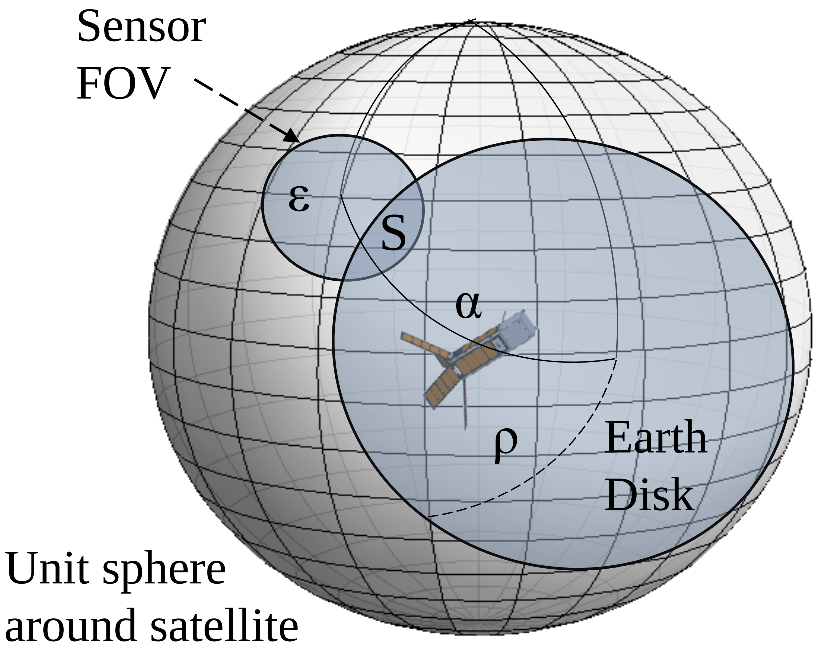
- Earth IR emission is relatively constant within sensor FOV
- Earth shape is circular
- Sensor responsitivity is uniform within FOV
- Satellite altitude is constant

(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

2. Sensor obscured area to nadir angle



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

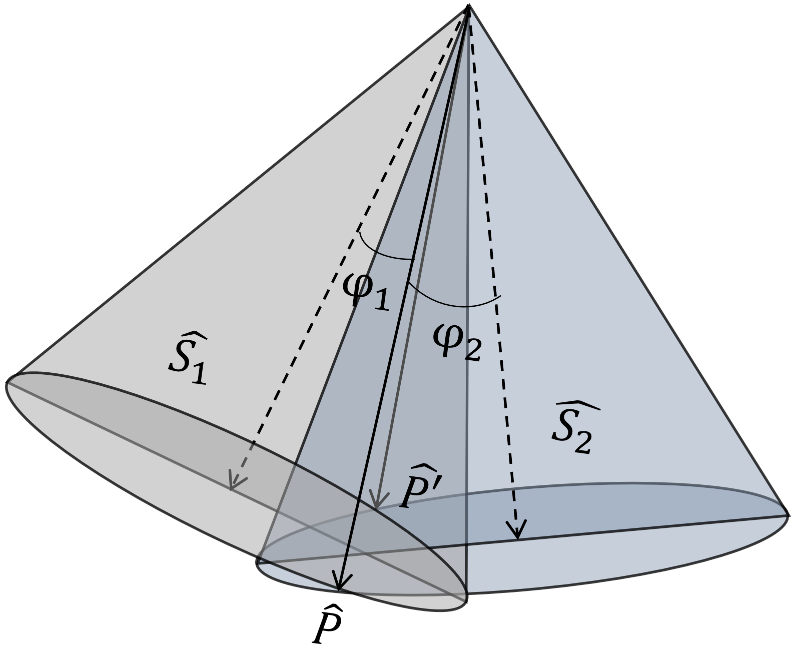
ε = sensor FOV radius (constant)
ρ = Earth disk radius (assume constant for this analysis)
α = angle between nadir and sensor boresight
S = overlap area between sensor FOV and Earth disk

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

J. Wertz. Spacecraft Attitude Determination and Control. 1978

3. Nadir angles to nadir vectors

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



Geometric representation of the solutions

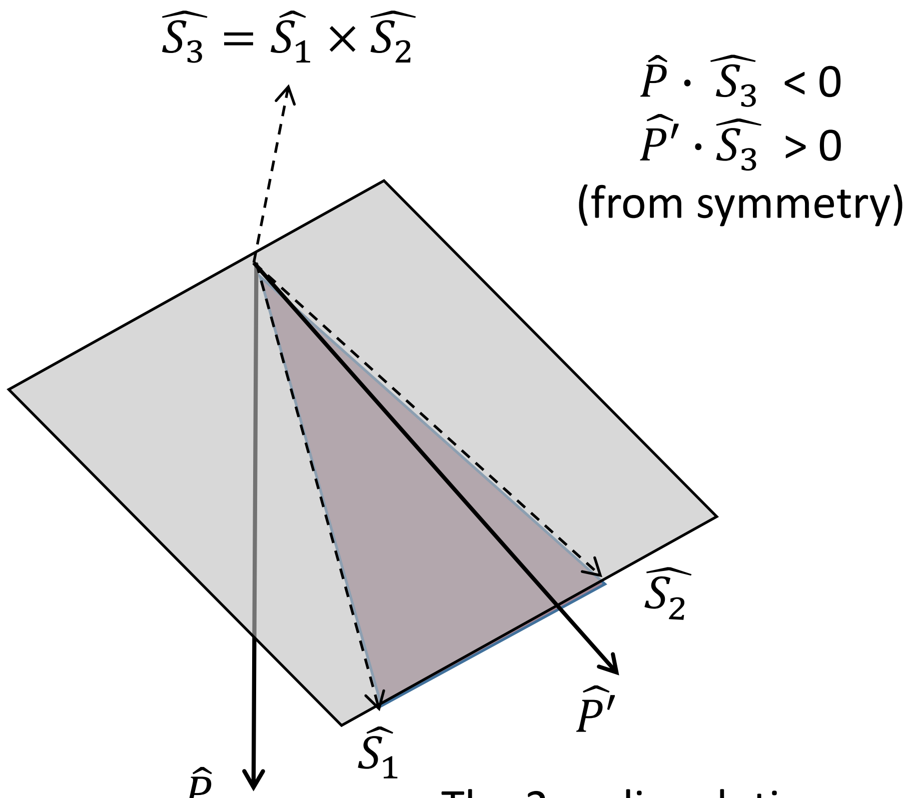
$$\begin{cases} \hat{P} \cdot \widehat{S_1} = \cos(\varphi_1) \\ \hat{P} \cdot \widehat{S_2} = \cos(\varphi_2) \\ |\hat{P}| = 1 \end{cases}$$

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

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)

4. Resolve ambiguity



The 2 nadir solutions can be distinguished as being below and above surface containing $\widehat{S_1}$ and $\widehat{S_2}$

- Acquire lock:
  - Need another attitude sensor (coarse) to resolve ambiguity
  - Use EHS for fine attitude knowledge
- Maintain lock:
  - Always choose nadir vector below $\widehat{S_1}$ - $\widehat{S_2}$ plane ($\hat{P} \cdot \widehat{S_3} < 0$)

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  - Gaussian responsivity
  - Altitude correction
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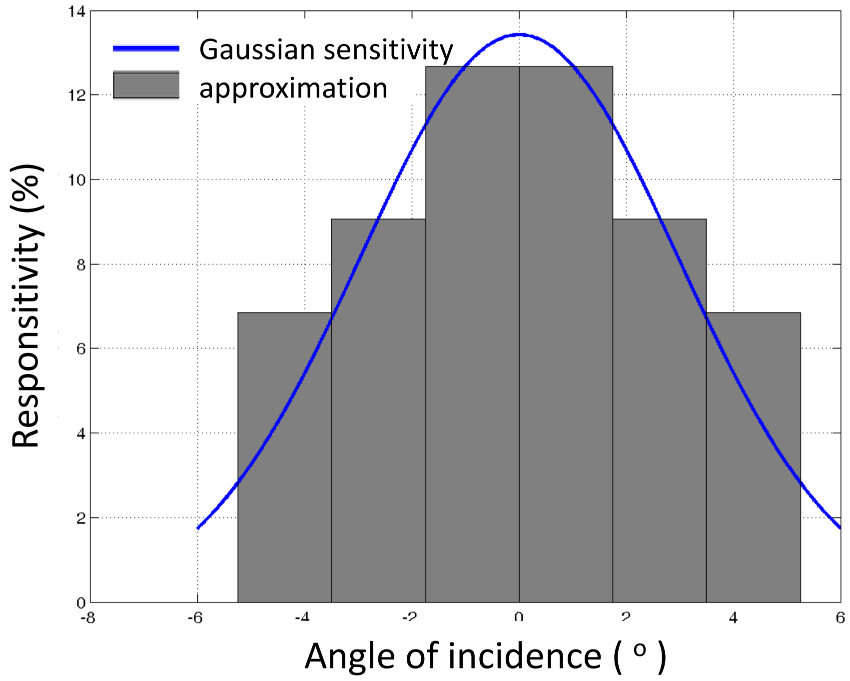
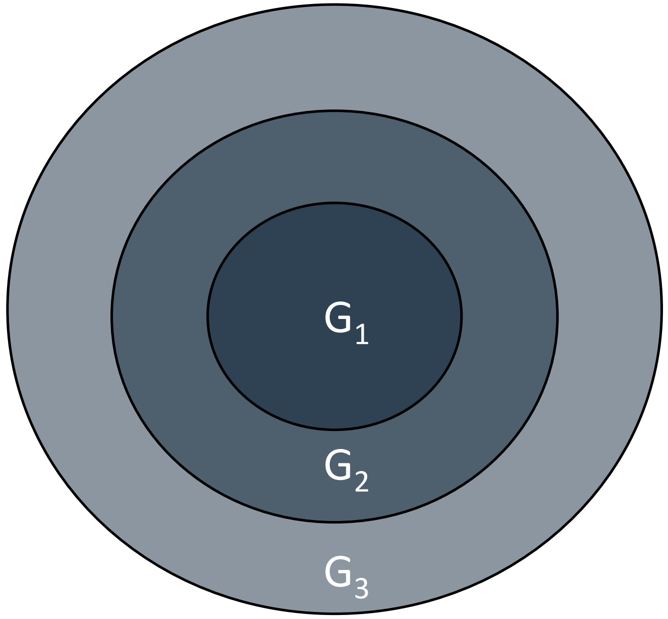
Sensor Gaussian approximation model



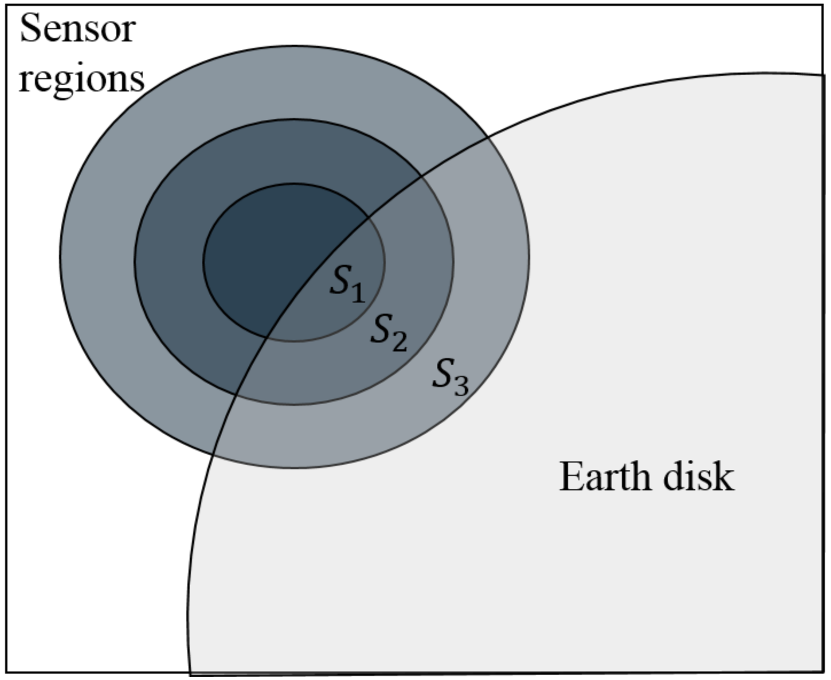
Sensor responsitivity 2D approximation



Sensor responsitivity 3D approximation

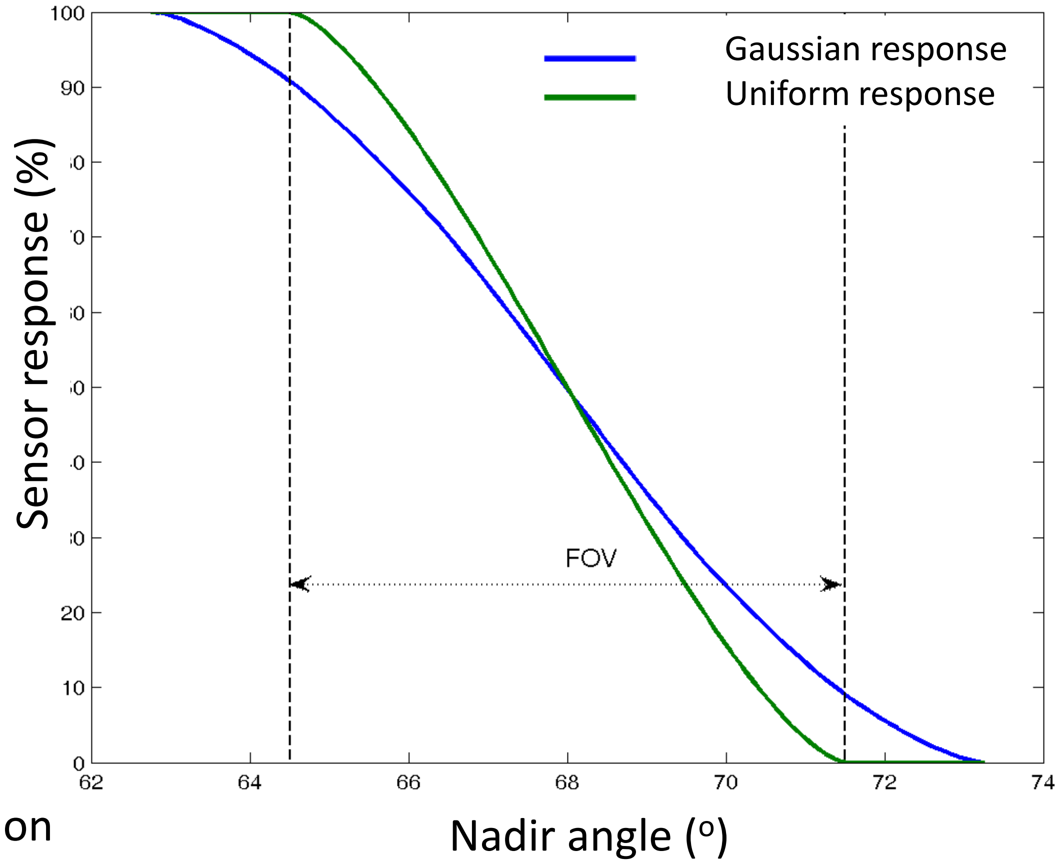
- Gaussian responsitivity curve can be approximated with piece-wise constant function
- Sensor field can be divided into regions of constant sensitivity with corresponding weight factor

Sensor Gaussian approximation model

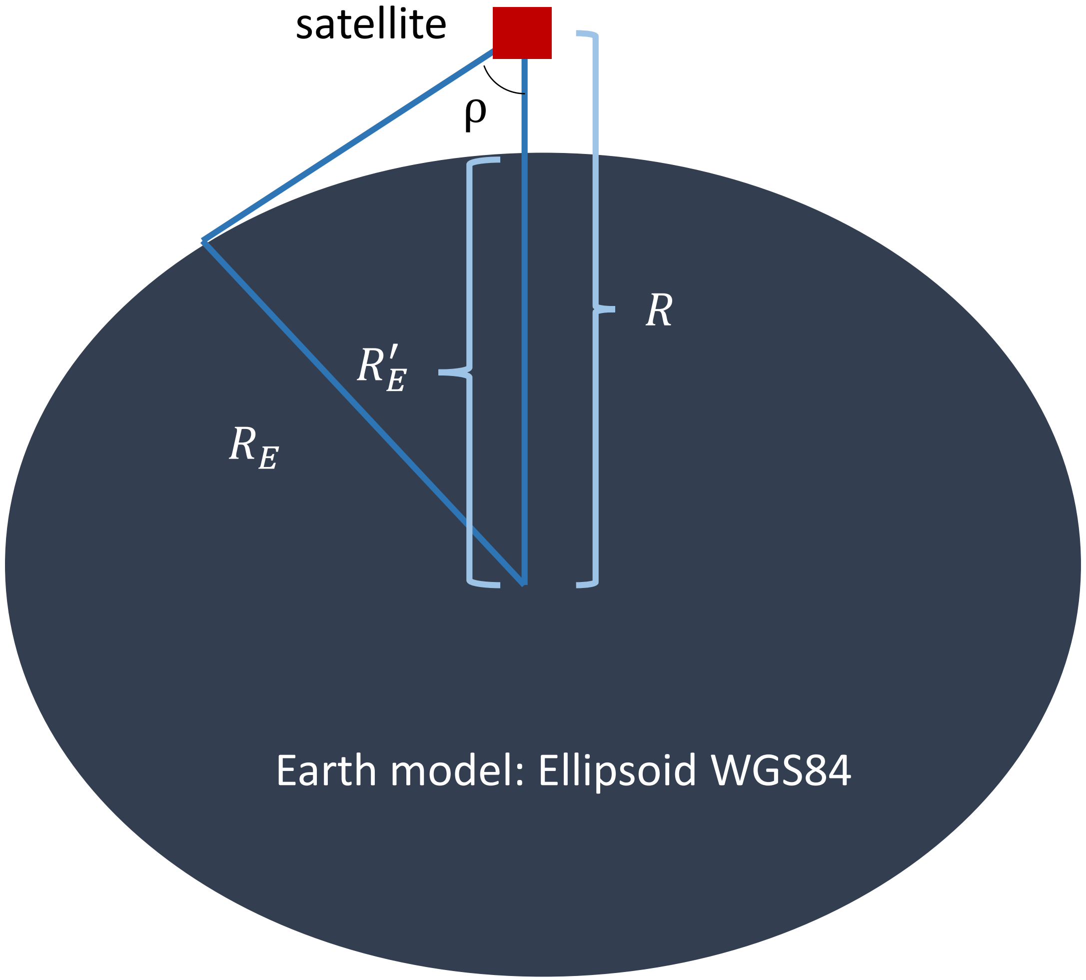


$$S = S_1 G_1 + S_2 G_2 + S_3 G_3$$

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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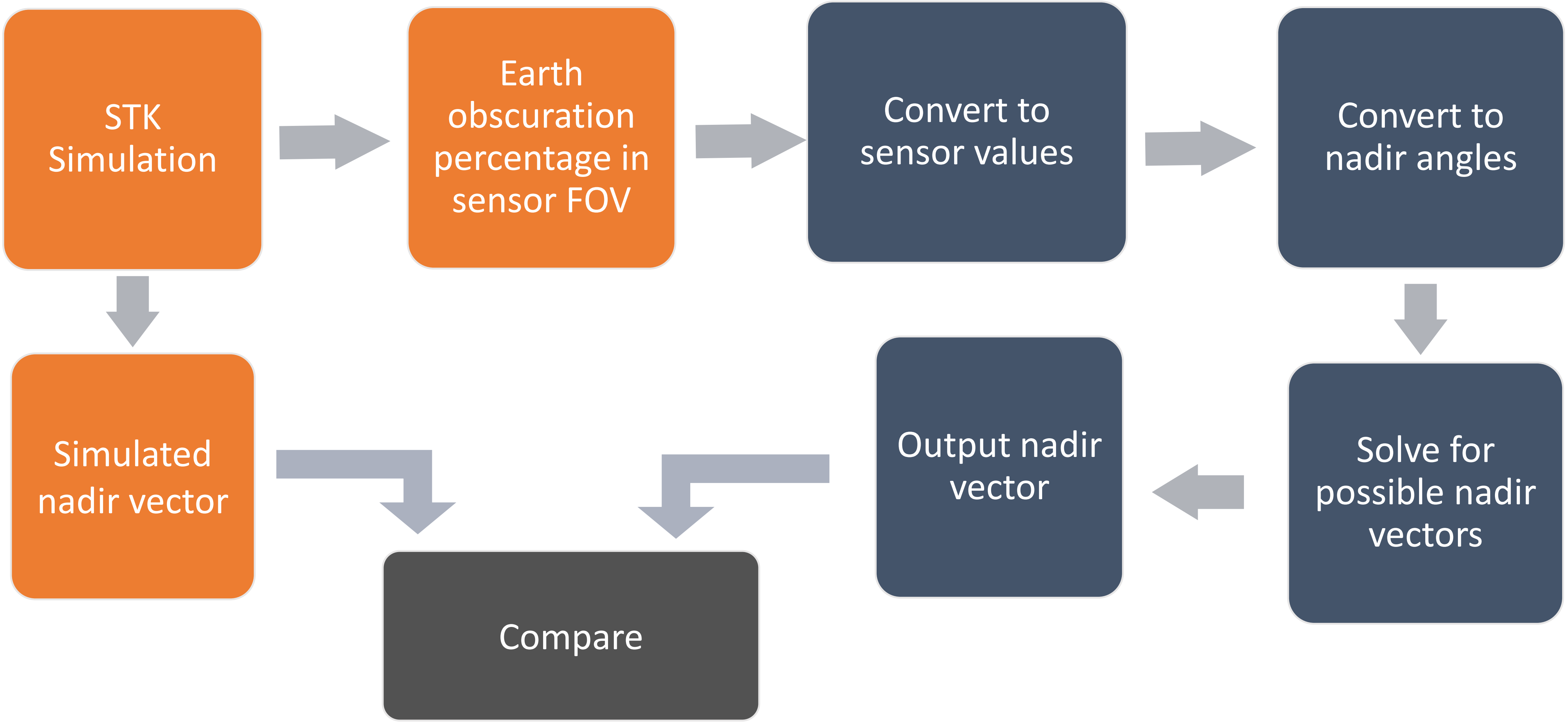
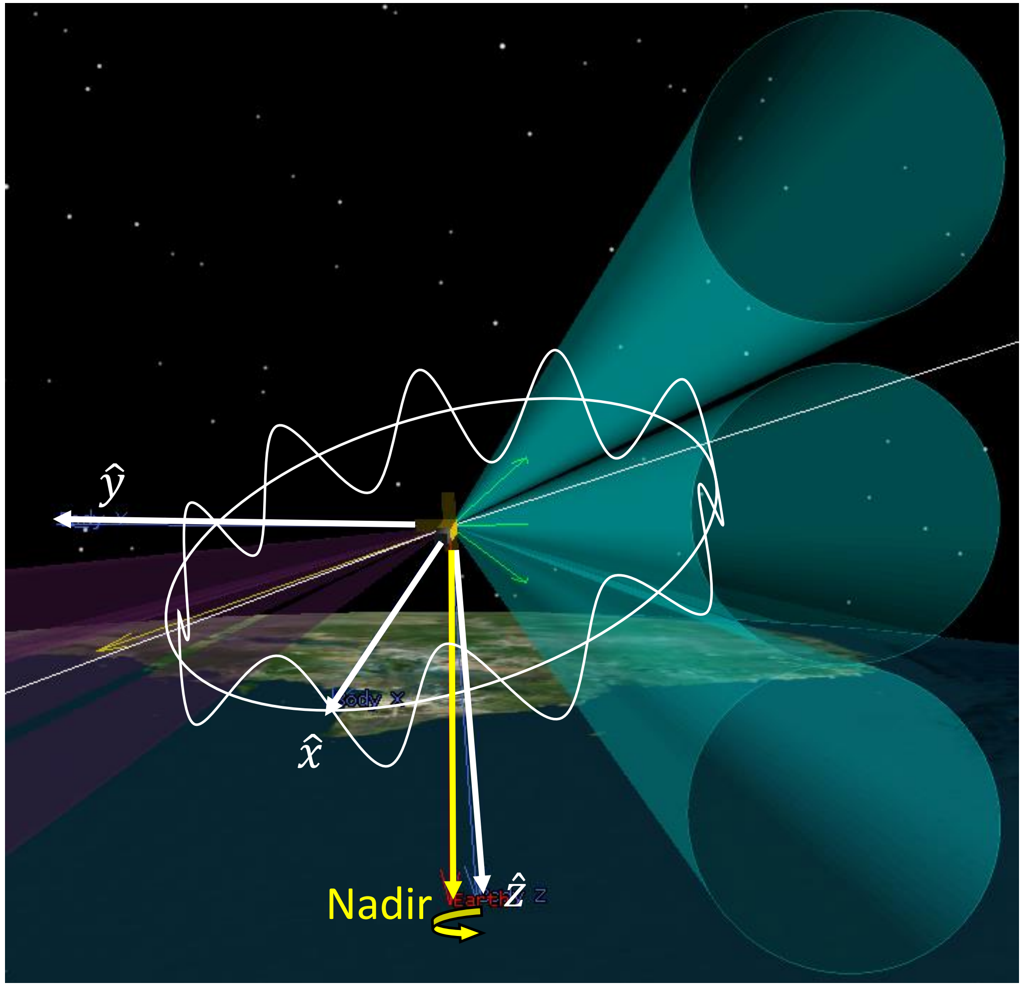
Testing with STK System Simulation



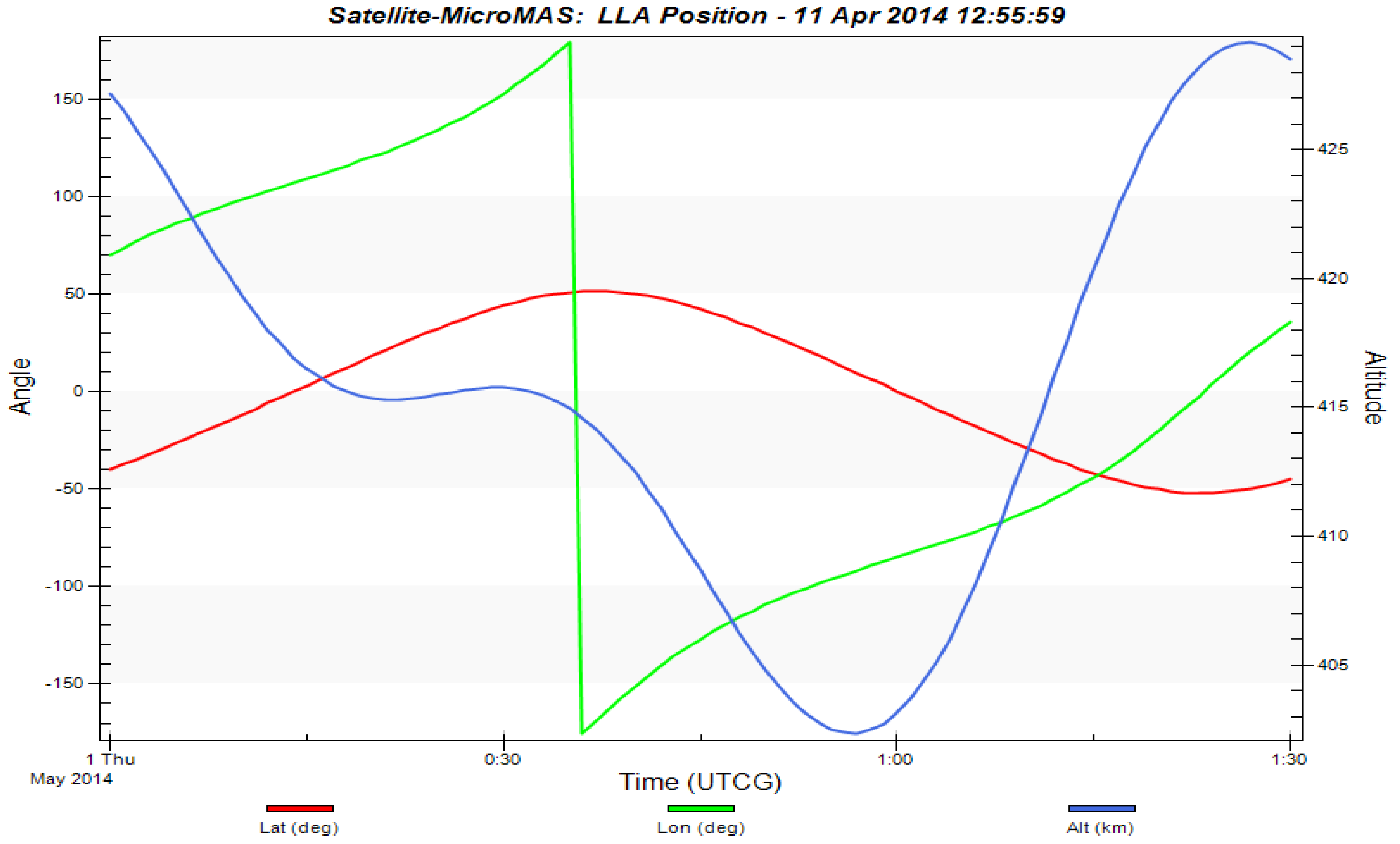
Satellite Tool Kit Simulation Scenario



- 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

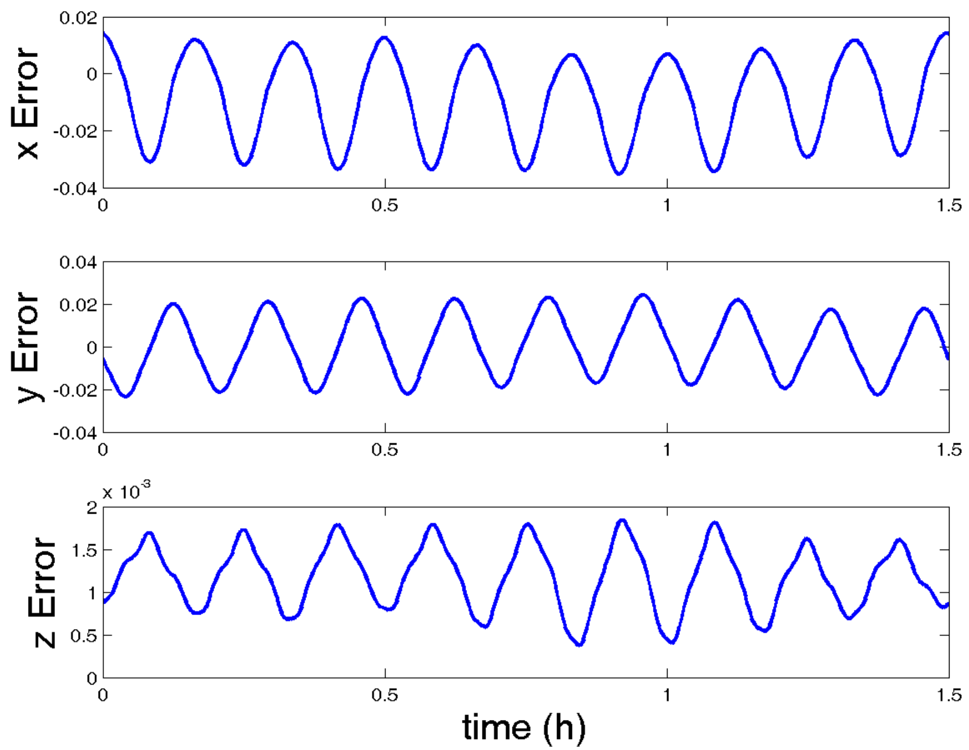


- ISS Orbit
- High Precision Orbit Propagator (HPOP)
  - Including environmental perturbations
- Altitude range:

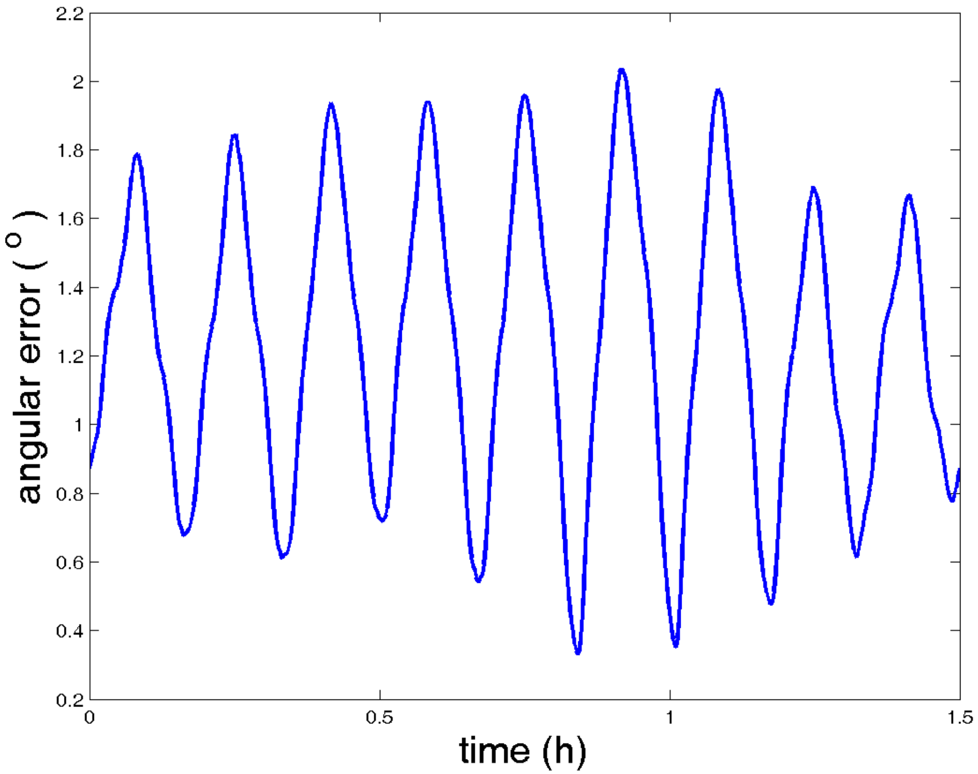
~ 400 km – 430 km

Simulation Results: Uniform Sensor

- Sensor sensitivity: Uniform
- No altitude correction



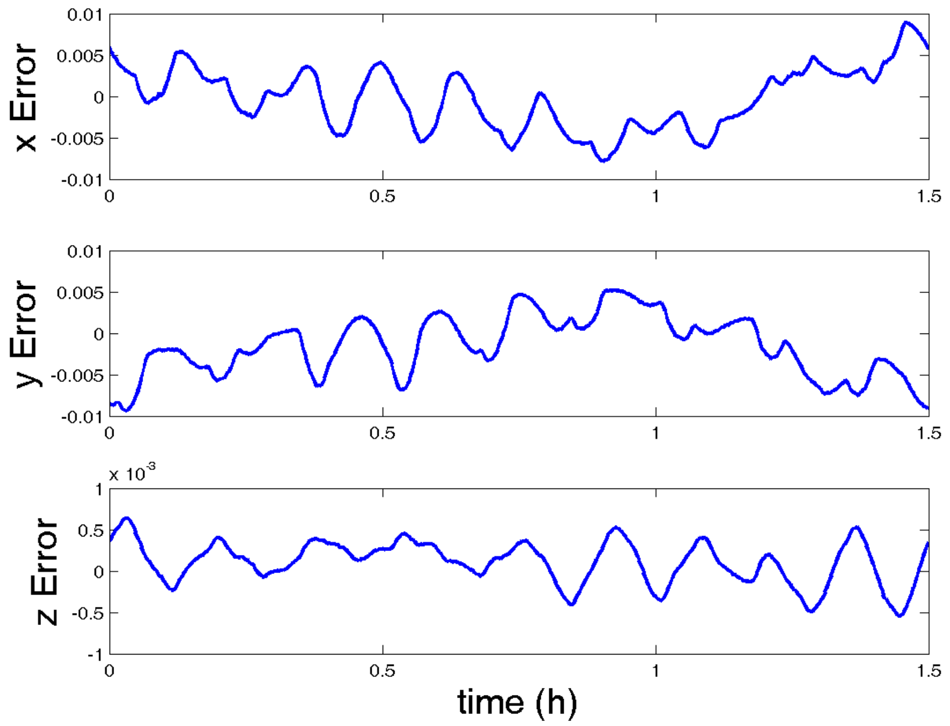
Angular error: (1.23 +/- 0.43) º

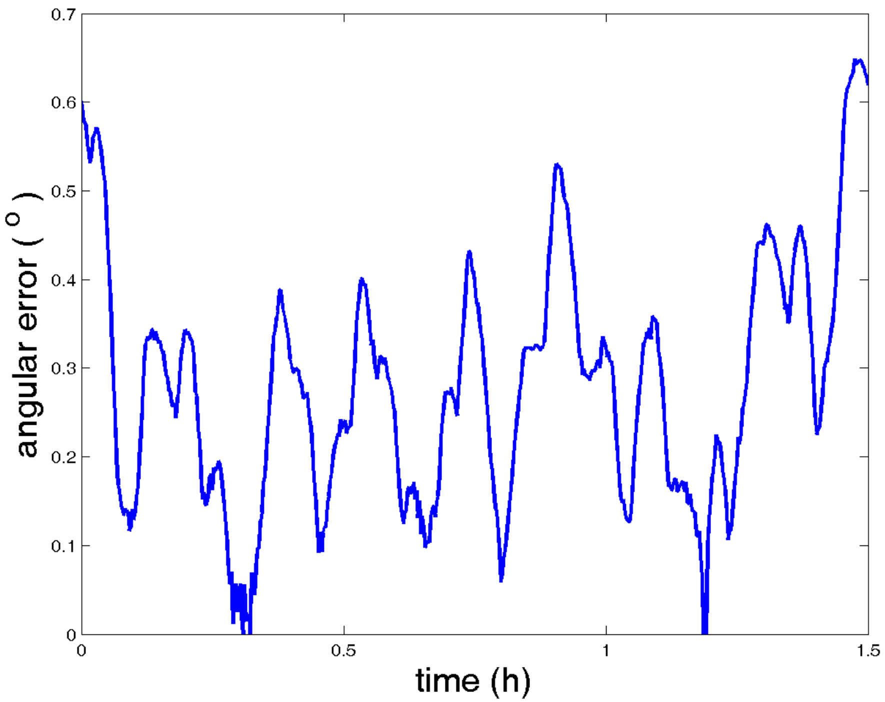


Simulation Results: Gaussian Sensor

- Sensor sensitivity: Gaussian
- No altitude correction

Angular error: (0.28 +/- 0.14) °

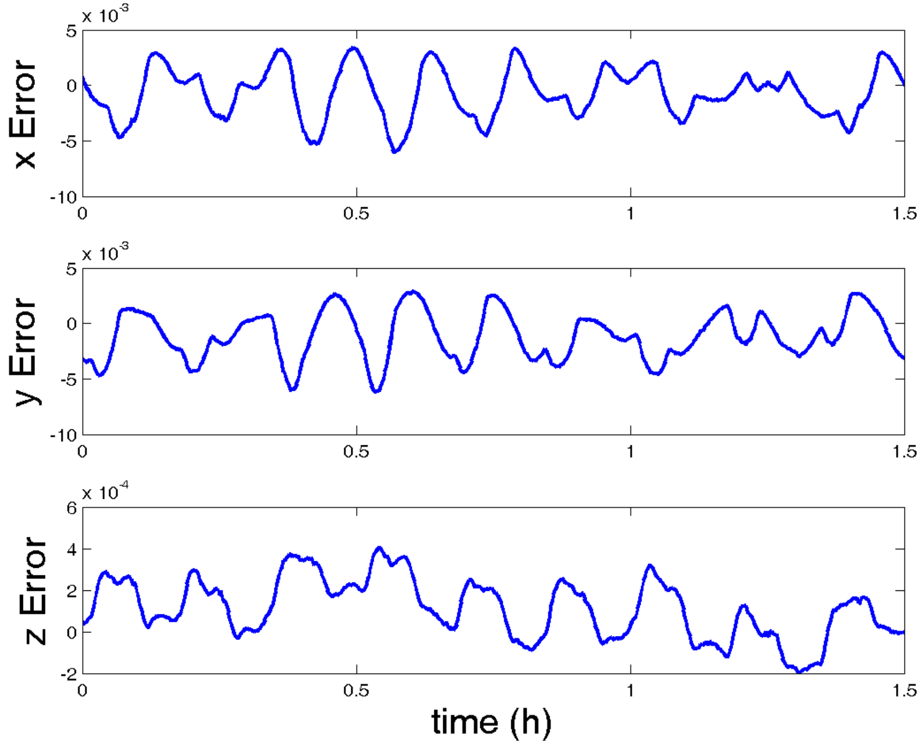


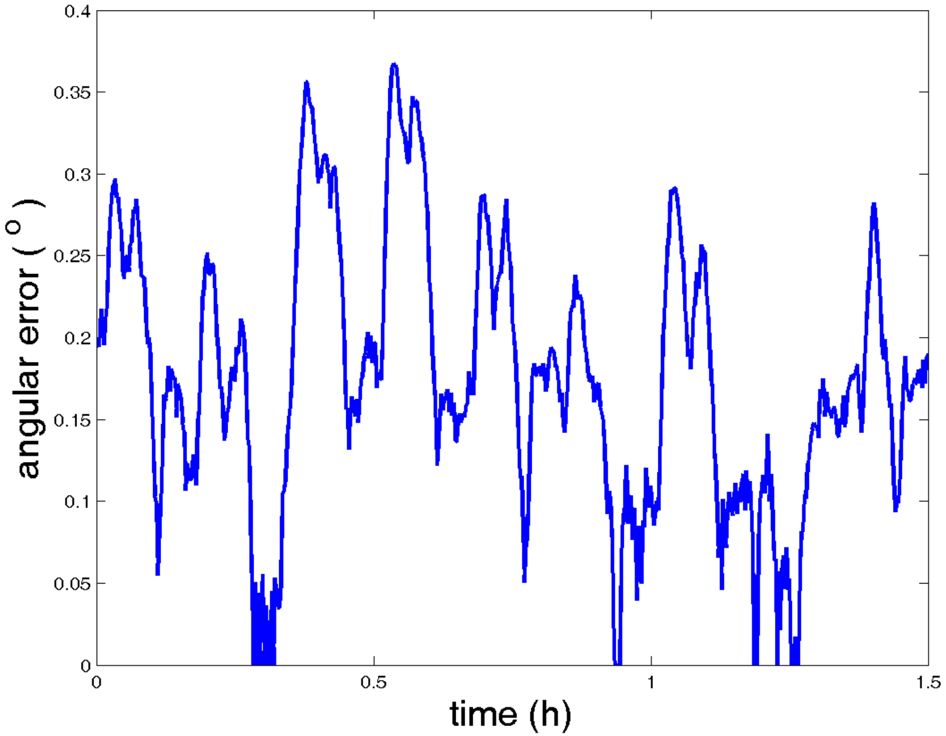


Simulation Results: Gaussian + Altitude

- Sensor sensitivity: Gaussian
- Altitude correction

Angular error: (0.18 +/- 0.082) °





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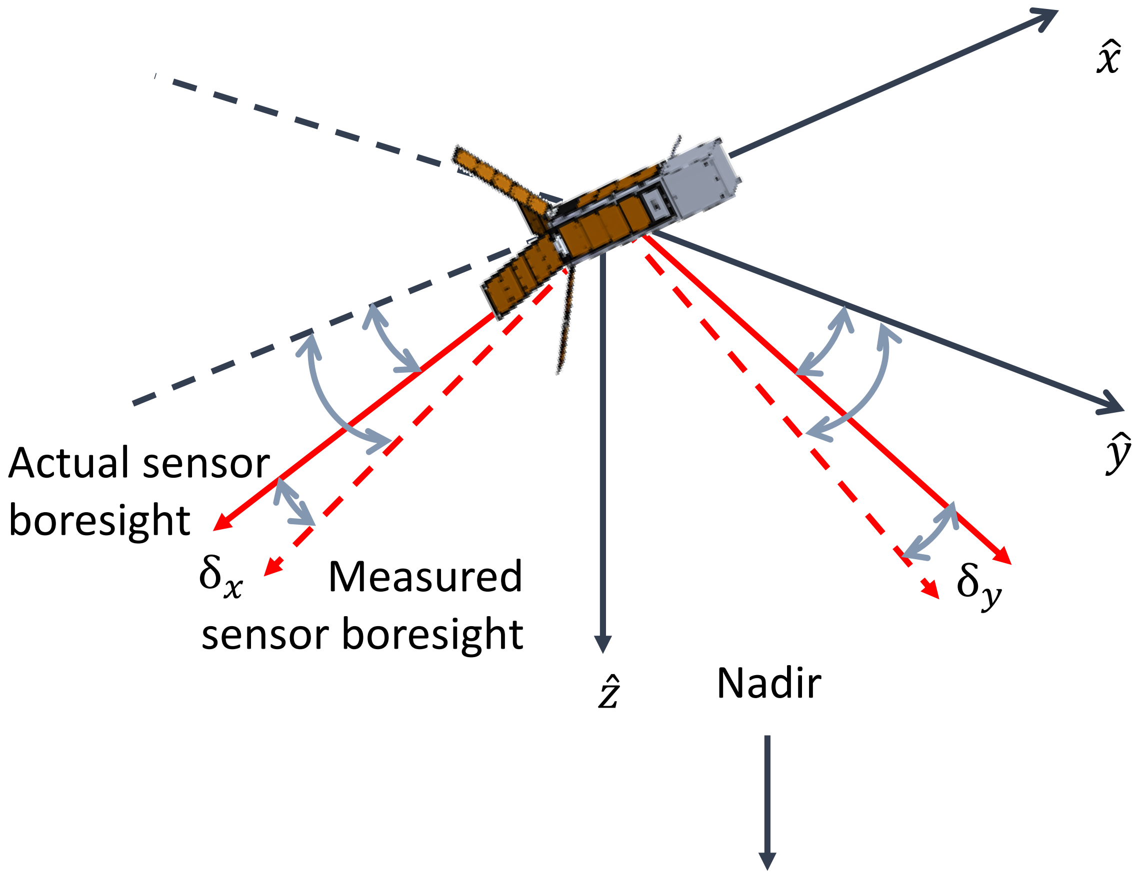
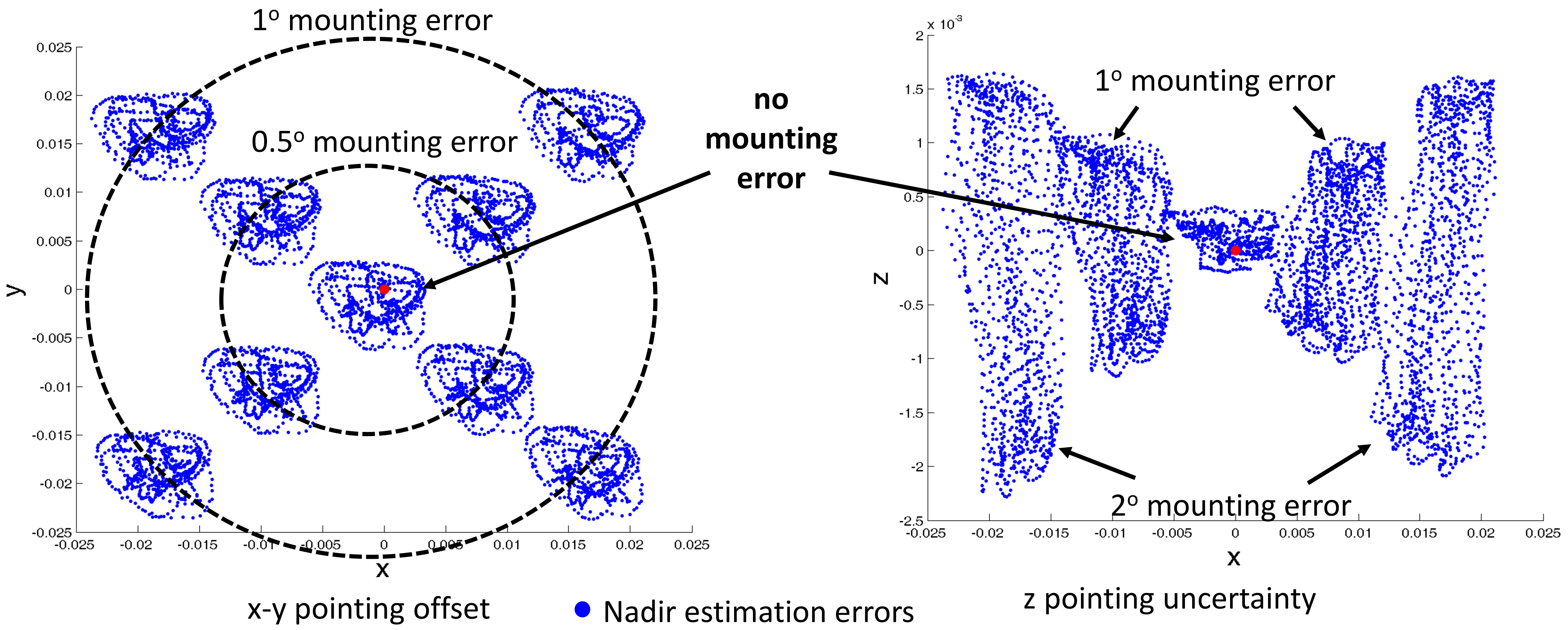
Sensor alignment errors



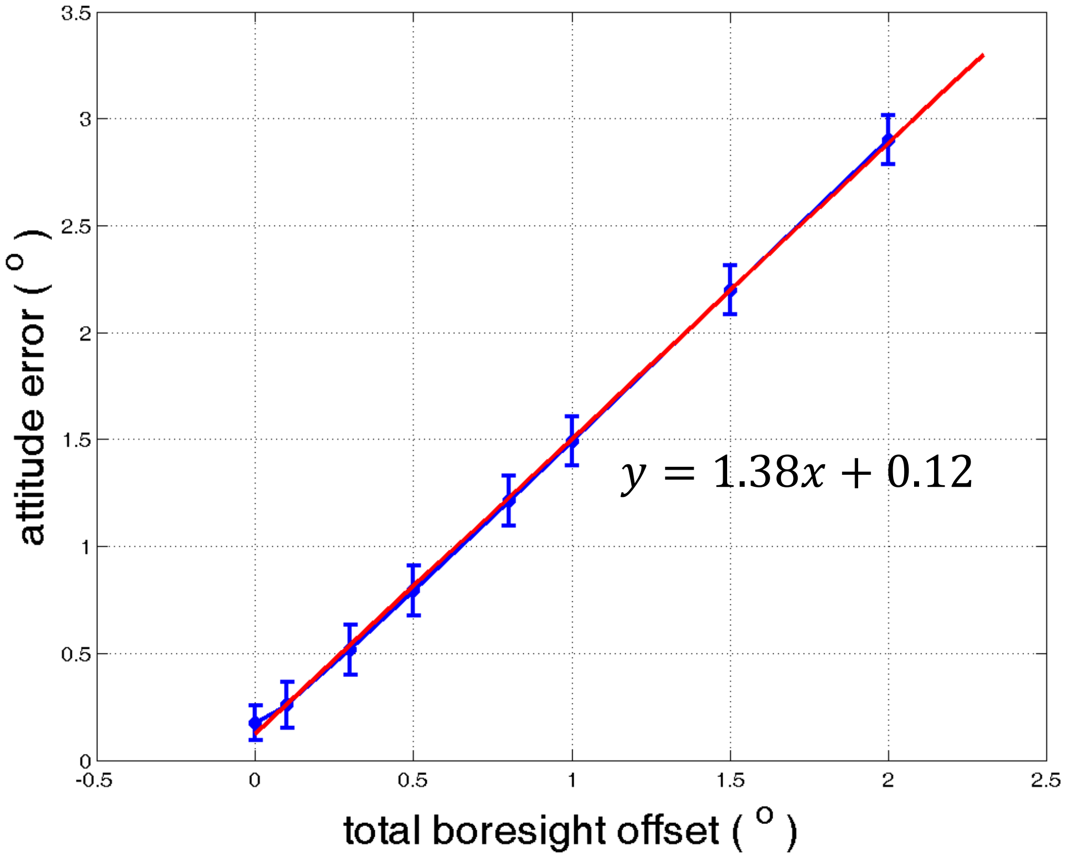
- Assume perfect mounting in and
- Mounting error occurs only in ("dip" angle)
- Total mounting error sum of offsets/misalignments on both mounts (δ_x+ δ_y)

Sensitivity to alignment errors



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

Boresight measurement sensitivity



- Nadir estimation error sensitivity to alignment error follows **linear correlation**
- 1^o boresight offset leads to 1.4^o 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

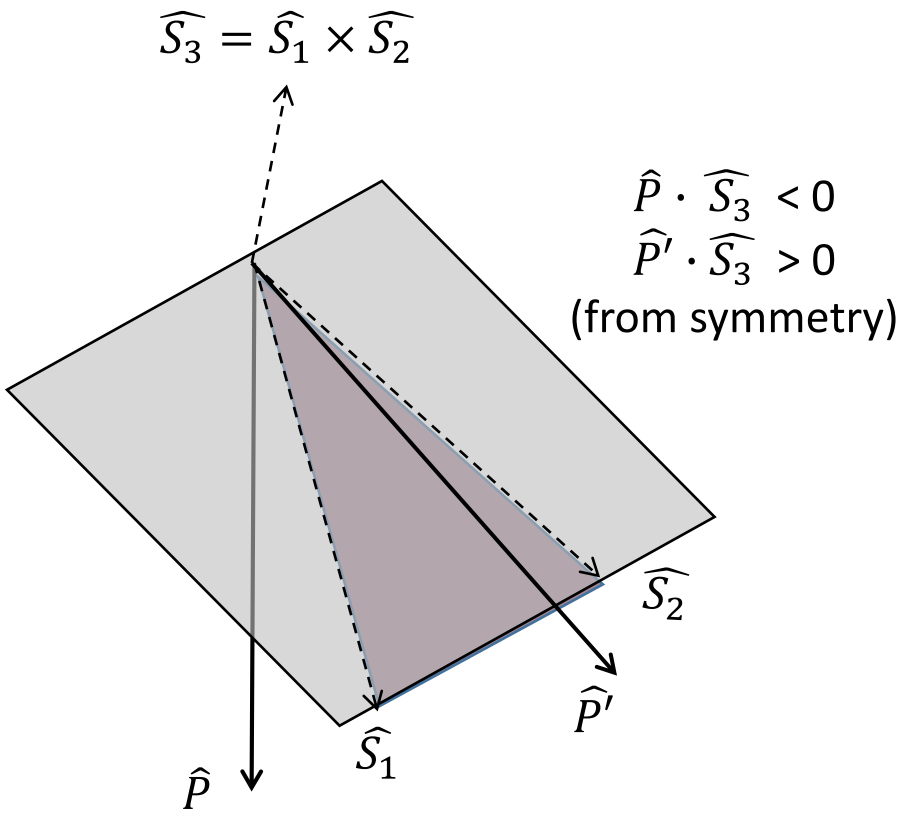
Future work

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

Q&A

Back-up slides

Proof that P and P' are on opposite side of plane containing S1 and S2



$\hat{P} \times \widehat{S_3} = \hat{P} \times (\widehat{S_1} \times \widehat{S_2}) = \widehat{S_1}\,(\hat{P} \times \widehat{S_2}) - \widehat{S_2}\,(\hat{P} \times \widehat{S_1})$

$= \widehat{S_1}\cos(\phi_2) - \widehat{S_2}\cos(\phi_1)$

= constant

$= \widehat{P'} \times \widehat{S_3}$

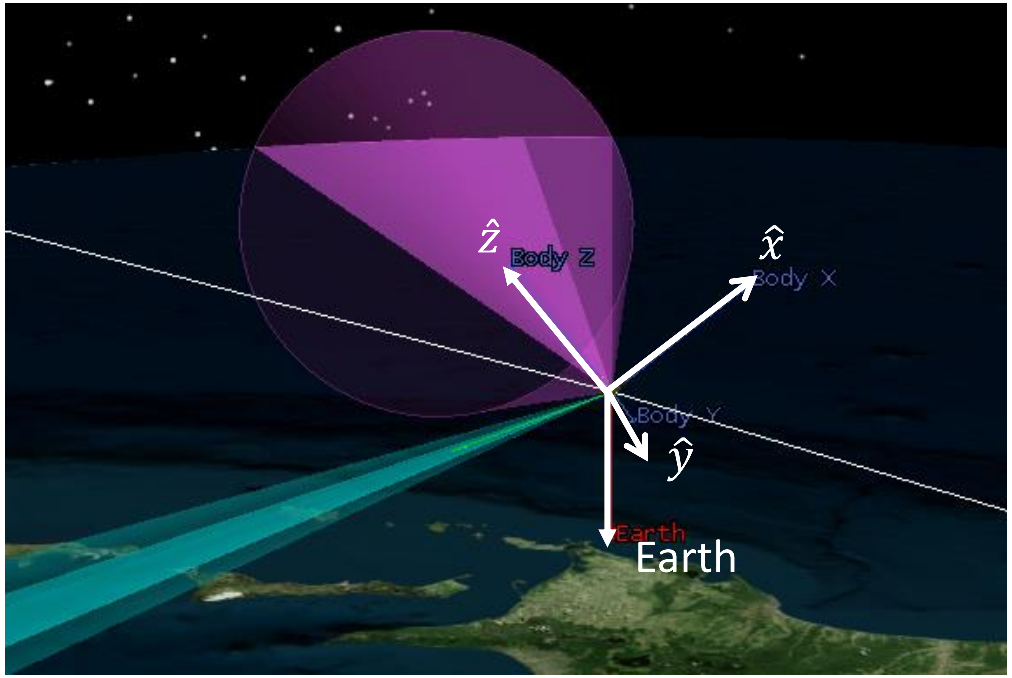
-> $\|\hat{P} \times \widehat{S_3}\| = \|\widehat{P'} \times \widehat{S_3}\|$

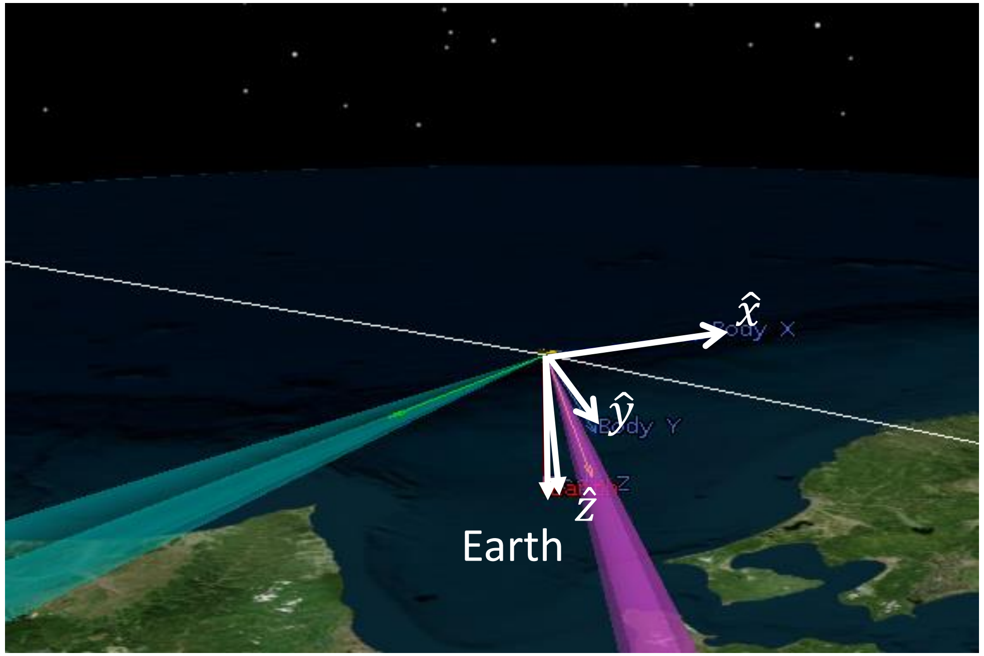
-> $\sin(\hat{P}, \widehat{S_3}) = \sin(\hat{P}', \widehat{S_3})$

-> P and P' belongs to different half-space divided by S1-S2 plane

The 2 nadir solutions can be distinguished as being below and above surface containing $\widehat{S_1}$ and $\widehat{S_2}$

2-sensor configuration ambiguity





Both attitudes yield the same sensor readings