Infrared Earth Horizon Sensors for CubeSat Attitude Determination

Tam Nguyen
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
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
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
Earth Infrared (IR) Emission

- 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: $\sim 7 \times 10^{-5}$ sr
  - Earth solid angle: $\sim 4$ sr

Thermopile Detectors

Standard thermopile sensor sensitivity

Excilites 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)

- 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)

STK model of MicroMAS satellite
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

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

STK model of MicroMAS satellite
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
1. Sensor reading to sensor obscured area

Sensor FOV

Unit sphere around satellite

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

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

will be refined in next section

4/15/2014
Nguyen
2. Sensor obscured area to nadir angle

\[ S(\alpha) \propto 2[\pi - \cos(\rho) \cos(\varepsilon) + \frac{\cos(\varepsilon) - \cos(\rho) \cos(\alpha)}{\sin(\rho) \sin(\alpha)} - \\
\cos(\varepsilon) \cos(\alpha) - \frac{\cos(\rho) - \cos(\varepsilon) \cos(\alpha)}{\sin(\varepsilon) \sin(\alpha)} - \\
\frac{\cos(\alpha) - \cos(\varepsilon) \cos(\rho)}{\sin(\varepsilon) \sin(\rho)}] \]

\( \varepsilon = \) sensor FOV radius (constant)
\( \rho = \) Earth disk radius (assume constant for this analysis)
\( \alpha = \) angle between nadir and sensor boresight
\( S = \) overlap area between sensor FOV and Earth disk

J. Wertz. Spacecraft Attitude Determination and Control. 1978
3. Nadir angles to nadir vectors

- Sensor boresights: $\hat{S}_1, \hat{S}_2$
- Nadir angles: $\varphi_1, \varphi_2$
- Possible nadir vector: $\hat{P}, \hat{P}'$

\[
\begin{align*}
\hat{P} \cdot \hat{S}_1 &= \cos(\varphi_1) \\
\hat{P} \cdot \hat{S}_2 &= \cos(\varphi_2) \\
|\hat{P}| &= 1 \\
P_x S_{1x} + P_y S_{1y} + P_z S_{1z} &= \cos(\varphi_1) \\
P_x S_{2x} + P_y S_{2y} + P_z S_{2z} &= \cos(\varphi_2) \\
P_x^2 + P_y^2 + P_z^2 &= 1
\end{align*}
\]

System of equations can be solved analytically
Contains a 2\textsuperscript{nd} order equation $\rightarrow$ maximum of 2 solutions

Assume low sensor noise and correct calibration
$\rightarrow$ 2 possible nadir vectors (ambiguity)

Geometric representation of the solutions
4. Resolve ambiguity

- Acquire lock:
  - Need another attitude sensor (coarse) to resolve ambiguity
  - Use EHS for fine attitude knowledge

- Maintain lock:
  - Always choose nadir vector below $\hat{S}_1 - \hat{S}_2$ plane ($\hat{P} \cdot \hat{S}_3 < 0$)

$\vec{S}_3 = \vec{S}_1 \times \vec{S}_2$

$\hat{P} \cdot \hat{S}_3 < 0$

$\hat{P}' \cdot \hat{S}_3 > 0$

(from symmetry)

The 2 nadir solutions can be distinguished as being below and above surface containing $\hat{S}_1$ and $\hat{S}_2$.
Outline

• Background and objectives
• Nadir vector estimation using Earth Horizon Sensors (EHS)
• Model improvements
  • Gaussian responsitivity
  • Altitude correction
• System simulation and results
• Sensitivity to alignment errors
• Conclusions and future work
Sensor Gaussian approximation model

- Gaussian responsivity 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

Nadir angle (°)

Sensor response (%)

Gaussian response
Uniform response

Sensor FOV

Earth disk
Altitude Correction

Earth model: Ellipsoid WGS84

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

\[ \rho \approx \sin^{-1} \left( \frac{R_E'(\hat{x})}{R(\hat{x})} \right) \]

where:
\[ \hat{x} = \text{satellite position (from GPS or TLE)} \]
\[ R_E'(\hat{x}) = \text{Earth radius from WGS84 model} \]
\[ R(\hat{x}) = \text{Orbit radius} \]
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
Testing with STK System Simulation

1. STK Simulation
2. Earth obscuration percentage in sensor FOV
3. Convert to sensor values
4. Convert to nadir angles
5. Output nadir vector
6. Solve for possible nadir vectors
7. Simulated nadir vector
8. Compare
Satellite Tool Kit Simulation Scenario

- Spacecraft sensor model
  - sensor FOV: \(~10^\circ\)
  - mount directions: -\(\hat{x}\), +\(\hat{y}\)
  - horizon sensor dip angle: \(~20^\circ\)

- Attitude setting
  - Attitude: Spin aligned around nadir
  - Spin rate: 0.1 rev/min
  - Nutation levels: 4\(^\circ\)

→ Satellite’s z-axis oscillates around nadir vector with maximum offset of 4\(^\circ\).
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: $(1.23 \pm 0.43) ^\circ$
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: \((0.18 \pm 0.082)\)°
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
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 \((\delta_x + \delta_y)\)
Sensitivity to alignment errors

1° mounting error
0.5° mounting error
no mounting error

x-y pointing offset

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

1° mounting error
2° mounting error
z pointing uncertainty

4/15/2014
Nguyen
Boresight measurement sensitivity

- Nadir estimation error sensitivity to alignment error follows linear correlation
- 1° boresight offset leads to 1.4° attitude error
- x and y errors are more dominant than z errors

\[ y = 1.38x + 0.12 \]
• 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
Conclusion

• Nadir vector estimation method from EHS was presented
• Estimation accuracy was verified through simulations to be 0.2° (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 $S_1$ and $S_2$

\[ \hat{S}_3 = \hat{S}_1 \times \hat{S}_2 \]

\[ \hat{P} \cdot \hat{S}_3 < 0 \]
\[ \hat{P'} \cdot \hat{S}_3 > 0 \]
(from symmetry)

\[ \hat{P} \times \hat{S}_3 = \hat{P} \times (\hat{S}_1 \times \hat{S}_2) = \hat{S}_1 (\hat{P} \times \hat{S}_2) - \hat{S}_2 (\hat{P} \times \hat{S}_1) \]
\[ = \hat{S}_1 \cos(\phi_2) - \hat{S}_2 \cos(\phi_1) \]
\[ = \text{constant} \]
\[ = \hat{P'} \times \hat{S}_3 \]

\[ \Rightarrow \|\hat{P} \times \hat{S}_3\| = \|\hat{P'} \times \hat{S}_3\| \]
\[ \Rightarrow \sin(\hat{P}, \hat{S}_3) = \sin(\hat{P'}, \hat{S}_3) \]
\[ \Rightarrow P \text{ and } P' \text{ belongs to different half-space divided by } S_1-S_2 \text{ plane} \]

The 2 nadir solutions can be distinguished as being below and above surface containing $\hat{S}_1$ and $\hat{S}_2$. 

4/15/2014

Nguyen
Both attitudes yield the same sensor readings