Attitude Ground System (AGS) for the Magnetospheric Multiscale (MMS) Mission

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MMS Overview

• Recall from Conrad’s presentation earlier today

• MMS launch: March 13, 2015 on an Atlas V from Space Launch Complex 40, Cape Canaveral, Florida

• MMS Observatory Separation: five minute intervals spinning at 3 rpm approximately 1.5 hours after launch

• MMS Science Goals: study magnetospheric plasma physics and understand the processes that cause power grids, communication disruptions and Aurora formation

• Mission: 4 identical spacecraft in tetrahedral formation with variable size
  – 1.2 x 12 R_E in Phase 1, with apogee on dayside to observe bow shock
  – 1.2 x 25 R_E in Phase 2, with apogee on nightside to observe magnetotail
Challenges

- Tight attitude control box, orbit and formation maintenance requirements

- Maneuvers on thrusters every two weeks
  - Delta-H
    - Spin axis direction and spin rate maintenance
  - Delta-V
    - Orbit and Formation maintenance
    - Mission phase transitions

- AGS support
  - Smart targeting prediction of Spin-Axis attitude in the presence of environmental torques to stay within the science attitude
  - Determination of the spacecraft attitude and spin rate (sensitive to knowledge of inertia tensor)
  - Calibrations to improve attitude determination results and improve orbit maneuvers
    - Mass properties (Center of Mass, and inertia tensor for nutation and coning)
    - Accelerometer bias (sensitive to the accuracy of the rate estimates)
    - Sensor alignments
Spin-Axis Orientation and Control Box

- Attitude and orbit adjustment maneuvers are nominally planned to occur at 14-day intervals for a total of 52 maneuvers over the 2-year planned mission duration.

\[ \alpha (\Delta t) = \cos^{-1} \left[ \cos (\phi \Delta t) \sin^2 \theta + \cos^2 \theta \right] \]
Attitude Ground System (AGS)

- MATLAB-based with a library of functionalities and core software from the Multi-mission Three-Axis Stabilized Spacecraft (MTASS) system
  - MTASS used at NASA/Goddard Space Flight Center to support a wide variety of missions

- Requirements:
  - Definitive attitude and spin rate history
    - 3-axis attitude solutions with accuracy of 0.1 deg, $3\sigma$ with star sensors
    - Spacecraft body rate accuracies (transverse) to meet accelerometer bias requirements
  - Accelerometer bias with an accuracy of 2 micro-g ($3\sigma$) with AMS
  - Validation of the onboard attitude, body rates, and accelerometer bias estimates
  - Prediction of spin axis attitude for 10 weeks with maneuver targeting capability
  - Sensor Interference prediction
  - Inertia tensor, center of mass, and sensor alignment calibrations
  - Trending of attitude, body rates, accelerometer bias, and mass property calibration results
Attitude and Body Rate Determination

- "SpinKF"
  - 7 parameter state vector with angular momentum in body and inertial frames, and spin-phase instead of quaternion and rate
  - Accuracy better than 0.1 deg, $3\sigma$ on all three axes
  - Solutions highly dependent on the sensor alignment and inertia tensor (coning) calibration results
Kalman Filter Tuning

- Optimize SpinKF performance by adjusting the angle random walk and rate random walk parameters within the process noise.
- Prior to launch:
  - Using data from a simple rigid body MMS simulator and the MMS constellation high-fidelity simulator (CHIFI).
  - Standard deviations of the star camera residuals reduced by decreasing the rate random walk process noise by an order of magnitude.
- After launch:
  - Star tracker transverse noise is near specification of 20 arc-sec.
  - Noise about the boresight approx. 3-times higher than expected.
  - Improved Z-axis residual by 2-10% with star sensor noise parameter increased to 200 arc-sec depending on process noise parameter choice.
  - Process noise parameters varied widely over several orders of magnitude.
Nutation and Vibration Damping

- After damping, angular momentum aligned with major principal axis
- Causes of nutation and vibrations:
  - Thruster burns
  - Rapidly changing gravity-gradient torque every perigee pass
  - Spin-rate changes due to boom contraction/expansions from temperature changes upon entrance and exit of Earth’s shadows

<table>
<thead>
<tr>
<th>Deployment Status</th>
<th>MMS1 Decay Time (hrs)</th>
<th>MMS2 Decay Time (hrs)</th>
<th>MMS3 Decay Time (hrs)</th>
<th>MMS4 Decay Time (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mag Boom Deployed (SDP and ADP Stowed)</td>
<td>0.38</td>
<td>0.41</td>
<td>0.46</td>
<td>0.44</td>
</tr>
<tr>
<td>Mag Boom and SDP Deployed (ADP Stowed)</td>
<td>10.0</td>
<td>12.8</td>
<td>4.3</td>
<td>8.2</td>
</tr>
<tr>
<td>All Deployed</td>
<td>6.5</td>
<td>11.5</td>
<td>5.4</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Example of MPA Offset Angles

Logarithm of the MPA offset angle and its linear fit (red line).
Earth Albedo Sensor Interference

- Unexpected periodic star tracker interference post -Z-axis ADP boom deployment
- Higher incident of flagged bad data points from the star tracker
- Hypothesis: glint or diffuse reflection of sunlight and Earth albedo in the star tracker from the ADP boom
  - Interference not observed until deployment of -Z-axis ADP boom
  - Interference occurred near every perigee (max. effect of Earth Albedo)
  - Interference correlated with spin-phase correlated with geometry of spacecraft
- Time-dependent illumination from the spacecraft position relative to Earth
Spin-Axis Prediction and Maneuver Targeting

- 10-week prediction of spacecraft attitude and spin rate
- account for the Sun and target box geometry and the seasonally changing environmental torques
- Environmental Torque Model: spin-averaged and orbit-averaged gravity-gradient torque

$$\tau_{gg} = \frac{3}{2} \frac{\mu}{a^3 (1-e^2)^{3/2}} (I_Z - I_t)(\hat{Z} \cdot \hat{h})(\hat{Z} \times \hat{h})$$

Angle between predicted and observed angular momentum

Error (deg) vs. Time (days)
Shadow Period Attitude Optimization

- Shadow period means orbits with eclipse lasting more than 2 hours and lasting approx. two months
- No maneuvers to maintain power levels while assuring science attitude
- Achieve best possible attitude prior to last maneuver before shadow period
  - Minimize the angle between the spin-axis direction and center of the box over the duration of the shadow period

\[ C = \left( \sum_{i=1}^{N} \left( \cos^{-1}(v_i \cdot w_i) \right)^2 \right)^{1/2} \]

Spin-axis trajectory during shadow period
Conclusions

• AGS functionalities essential for MMS mission support
  – Onboard attitude and body rate validation
  – Star tracker alignment calibration
  – Major principal axis direction calibration (coning)
  – Smart targeting to for maneuver planning to maintain science attitude
• AGS capabilities enabled proper identification of error sources affecting attitude and body rate estimation, from thermal variations to sensor interference
• Special analysis to support the mission:
  – Long-term planning for long shadow periods
  – Earth Albedo Interference prediction due to unexpected star tracker sensor noise
• SpinKF performed very well despite the high dependency with accuracy of start tracker alignments and knowledge of inertia tensor
• Iterations between the star tracker alignment and inertia tensor calibrations due to their coupling
  – Star sensor alignments defined the body frame
  – Major principal axis direction calibration performed relative to the body gframe
• AGS predicted with high degree of accuracy (0.01 deg) the precession of the angular momentum for up to a month