Magnetospheric Multiscale Mission Attitude Dynamics: Observations from Flight Data

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Summary of Presentation

• MMS: four helioscience spacecraft flying in formation

• Spinners (3.05 RPM); 60 m wires

• Thrusters for attitude, orbit control

• Star camera attitude sensors

• Summary of presentation:
  - Spin axis targeting
  - Effects of environmental torques
  - Effects of active potential control device (jets of Indium ions) on observed spacecraft spin rate
  - Derivation of effective thrust
  - Analysis of MMS4 impact event in Feb. 2016, using attitude data
Spin Axis Target

- Spin axis (body Z-axis) must be near ecliptic pole
- This attitude ensures sunlight does not fall on upper deck
  - Upper deck illumination would cause emission of photoelectrons that would perturb the local plasma and field measurements
- However, spin axis needs some tilt towards the Sun
  - Tilt prevents shadows from pre-amplifiers on wire booms from crossing the spherical detectors at ends of wire booms
    - Shadows cause momentary interruption of photo-emissive electron cloud around detector spheres, again perturbing field measurements
- Target box for science ops is isosceles trapezoid, roughly 2.5 deg × 2.5 deg with center tipped 3.5 deg toward Sun
Environmental Torques

• MMS Attitude Ground System (AGS) predicts when spin axis will drift to the edge of the target box
  – AGS plans attitude slews to center or to opposite edge of box to maximize time between maneuvers
  – Spin axis drift depends on seasonally changing environmental torques
  – Very rough order-of-magnitude estimates of torques
    • Gravity-gradient: $10^{-4}$ N-m
    • Solar pressure: $10^{-6}$ N-m
    • Aerodynamic drag: $10^{-7}$ N-m
  – So, only gravity-gradient (GG) torque is used in AGS predictions
**Predicted Precession of Spin Axis**

- AGS predicts GG drift of the spin axis direction
  - Early mission, after all booms deployed, drift was 0.05 deg per orbit (orbital period was close to 24 hours)
  - Plot shows accumulated drift error for 35 days with no maneuvers
  - Error in drift prediction was approximately 0.00034 deg per orbit
Seasonal Variation of Precession

- Magnitude and direction of GG precession vary seasonally
  - Orbit normal drifted approx. 21 deg during one year, affecting GG torque
  - Target box center follows the Sun motion of one deg per day
  - Attitude maneuvers are performed every 2 to 4 weeks to stay in target box
  - Plots show seasonal variation of magnitude of precession per orbit and angle between direction of precession and motion of box center
- GG precession is helping when angle is near zero (i.e., longer time between maneuvers), but GG magnitude is smallest then (so it doesn’t help much)
- Avg. time between maneuvers was 30 days for the months when angle was small, and was 22.5 days for the entire post-commissioning time span

**Graphs:**
- Magnitude of G-G Precession per Orbit
- Angle Between Motion of Target Box Center and G-G Precession Direction

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Observed Change In Spin Rate

- Distinct spin rate change observed at ASPOC (Active Spacecraft Potential Control Investigation) turn on and duty cycle changes

![Graph showing spin rate changes over time with annotations for ASPOC turn on and duty cycle changes.]

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ASPOC Characteristics

- Purpose is to neutralize buildup of positive floating potential produced by the spacecraft/environment interaction
- Strong potential created between emitter and extractor
- Indium atoms ionized and accelerated by this electric field

- 2 active emitters on each Spacecraft
- Location produces a coupled negative (against direction of S/C rotation) torque
Determining Empirical Thrust

- Time between maneuvers defined as a sample
- Using average deceleration, center of mass, moment of inertia, and emitter energy an empirical emitter thrust is calculated
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Summary of MMS4 Impact Event

• MMS4 relevant data observations:
  - Failure of one shunt resistor
  - Accelerometers detected spacecraft disturbance
  - Star cameras “blinded” by non-star objects; reset by fault detection
  - Small attitude excursions (change in spin axis direction; nutation etc.)
  - Science instruments detected plasma around spacecraft

• MMS4 state at event:
  - Radius 48,176 km (7.553 $R_E$): 6,012 km greater than GEO radius
  - Latitude -21.2 deg: 17,403 km below equatorial GEO plane
  - 4,414 km below Ecliptic
  - Orbital speed 2.661 km/s

• Geometry of event:
  - Impact, possibly oblique, on bottom face of spacecraft

• Goals of analysis: to the (limited) accuracy possible with given data
  - Identify candidate impactor sources
  - Estimate likely approach direction
  - Estimate likely relative speed and mass of impactor
  - Estimate likely kinetic energy of initial impact

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Impact Location (Shunt Resistor)
Analysis Methodology

• Use relative sizes of initial spikes in accelerometer signals caused by event to estimate velocity direction of impactor relative to MMS.

• Use change in MMS spin axis direction produced by event, together with known spacecraft angular momentum, to derive the transverse angular momentum applied to MMS by impactor.

• From known impact point on spacecraft and estimated approach direction, this allows the linear momentum \(mv_{\text{rel}}\) of impactor relative to MMS CM to be computed.

• From known position on orbit of impact, the MMS orbital velocity at the time of the event is known.

• For assumed impactor population, can hence find estimated speed of impactor relative to MMS.

• From the known linear momentum \(mv_{\text{rel}}\) and relative speed \(v_{\text{rel}}\), we can then estimate the mass \(m\) of the impactor.

• Use these to estimate kinetic energy of initial impact, \(T=0.5mv_{\text{rel}}^2\).
**X-axis:** Initial spike -0.8 micro-g

*Note:* All three axes only sampled every 30 s, so actual first motion may not be observed

**Y-axis:** Initial spike 2.8 micro-g

**Z-axis:** Initial spike -1.7 micro-g

Resulting relative velocity direction estimate: 30.3 deg below spin plane

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Rotation Rates, Transverse and Axial

Transverse: Nutation/boom vibration evident

Note brief dropout resulting from star cameras being blinded/resetting

Axial: No change in spin rate evident

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Pointing Angle Before Event

MMS4 Before Impact: Angle from Major Principal Axis to Ecliptic Pole

Time (sec since 2016033-13:22:00)
Angle (deg)

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FFT of Pointing Angle Before Event

Very low-frequency spike caused by gravity-gradient shift in spin axis at each perigee passage (perigee included in the pre-event, but not post-event, data set)

SDP in-plane twist/out-of-plane twist saddle/jellyfish (?)

System fundamental frequency

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Pointing Angle After Event

Vibration with period of ~400 s dominates response

MMS4 After Impact: Angle from Major Principal Axis to Ecliptic Pole

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FFT of Pointing Angle After Event

Magnitude of FFT of Angle Between MMS4 Principal Axis and Ecliptic Pole

- Dominant vibration with period approx. 400 s
- System fundamental frequency
- SDP in-plane twist
- SDP out-of-plane twist
- Saddle/jellyfish (?)
- Spin
- Nutation
- SDP out-of-plane twist (?)

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Possible Sources of Impactor - 1

• Two possible sources have been studied:
  - Micrometeoroid (dust particle)
  - Debris originating in GEO and perturbed by lunisolar gravitation plus solar radiation pressure (SRP) to point of impact

• Micrometeoroid (dust) population:
  - Overall mass range: \( \sim 10^{-14} \) to \( 10^{0} \) gm
  - Peak mass range: \( \sim 10^{-8} \) to \( 10^{-3} \) gm (\( \sim 2 \times 10^{-4} \) to 0.9 mm diameter)
  - Flux tails off quickly: \( \sim 10^{-3} \) as high at 1 mm diameter as at 0.1 mm*

* Fig. 2, “Micrometeoroid and Orbital Debris Environments for the International Space Station”, Peterson and Lynch, 2008
Possible Sources of Impactor - 2

- Debris originating in GEO: GEO spacecraft have inclinations that oscillate between 0 and ~15 deg, as a result of lunisolar perturbations. The impact latitude of -21.2 deg exceeds this range; the impact radius was also 6,012 km above GEO.

- However, objects released from GEO that have high area/mass ratios (> ~15 m$^2$/kg) experience significant solar radiation pressure (SRP) perturbations in eccentricity (and so radius) and inclination.

- References:
  - “Long-Term Dynamics of High Area-to-Mass Ratio Objects in High Earth Orbit”, Rosengren and Scheeres, 2013

- Possible debris source: multi-layer insulation (MLI). MLI degrades in GEO. See Tedlar thin film before, after 3 years simulated GEO*:

  ![MLI before](image1)
  ![MLI after](image2)

  - Representative MLI layer density 40 gm/m$^2$; area/mass 25 m$^2$/kg

* "Radiative Heat Trade-Offs for Spacecraft Thermal Protection", S. Franke, AFRL
Particle Mass, Kinetic Energy Estimates

- Linear momentum of impactor must produce observed change in spin axis direction of 0.00157 deg

- Mass, KE estimates differ for the two candidate particle sources, as a result of the different relative speeds between particle and MMS4

- Micrometeoroid:
  - “Typical” relative speed 15 km/s (very wide variation is possible)
  - Resulting estimated particle mass $8.48 \times 10^{-3}$ gm
  - Resulting kinetic energy 953.9 J (46.6% of muzzle energy of AK-47)

- Debris of GEO origin:
  - Orbital speed of debris at impact 2.661 km/s
  - Resulting relative speed ~4.292 km/s (depends on geometry)
  - Resulting estimated debris mass $2.96 \times 10^{-2}$ gm
  - If from an MLI layer with representative density 40 gm/m$^2$, this yields an area of $7.41 \times 10^{-4}$ m$^2$, e.g. a square 2.72 cm on a side
  - Resulting kinetic energy 272.9 J (13.3% of muzzle energy of AK-47)

- From this analysis, it is difficult to select between the candidates. Perhaps impact dynamics analysis can lead to a determination

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Angular Momentum

Transverse:
Nutation/boom vibration evident

Axial: No change in spin rate evident. Consistent with shunt location being close to spin axis
Pointing Angle After Previous Maneuver

- Oscillation at same ~400 s period is clearly visible
- Observed after all spacecraft maneuvers
- Must be wire boom dynamics excited by thrusting/impact acceleration of central spacecraft body