



Magnetospheric Multiscale Mission Attitude Dynamics: Observations from Flight Data

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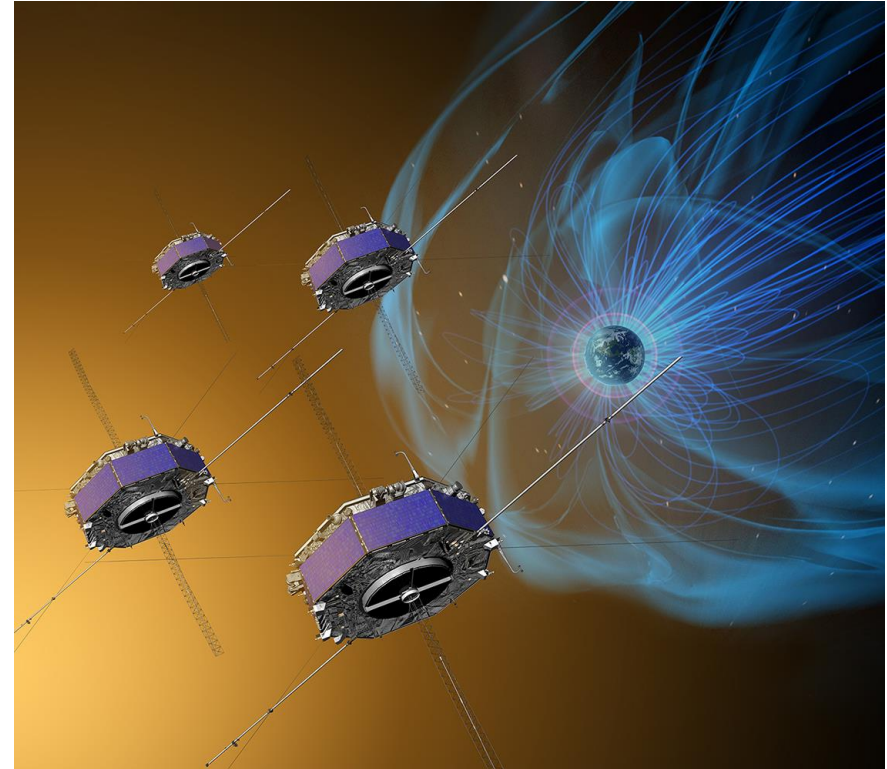
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Summary of Presentation

- 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



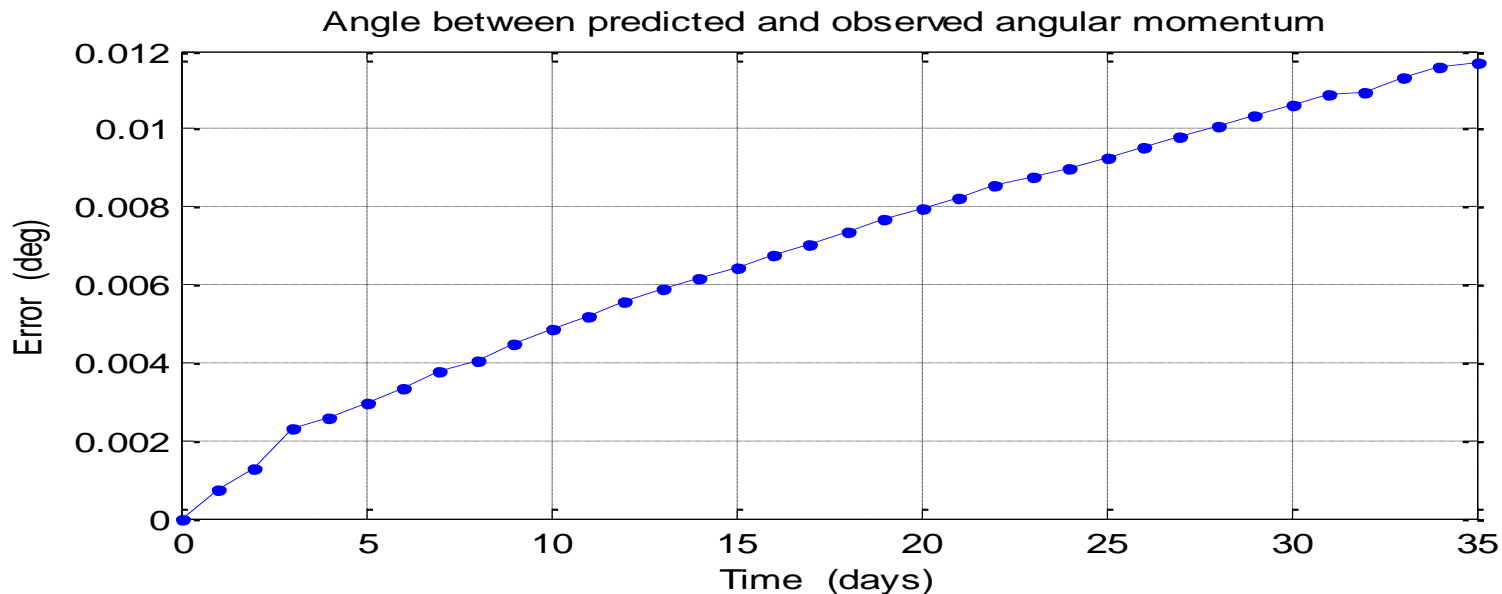
Environmental Torques

- 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

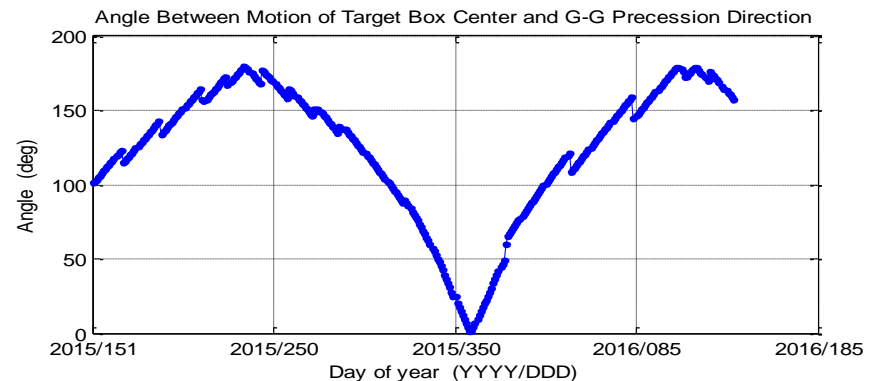
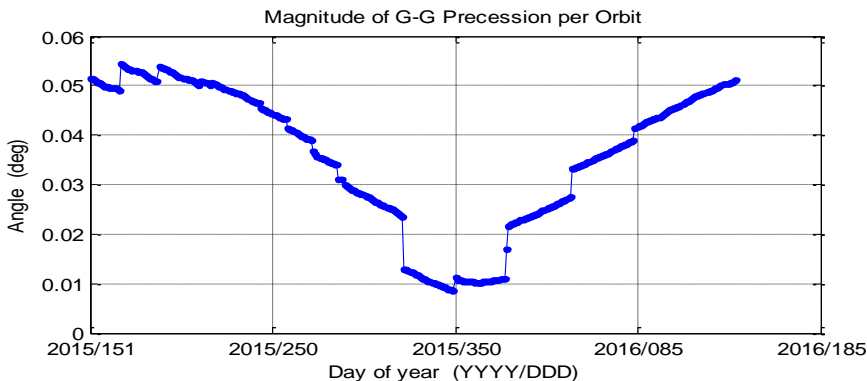
- AGS predicts GG drift of the spin axis direction
 - Early mission, after all booms deployed, drift was 0.05 deg per orbit (orbital period was close to 24 hours)
 - Plot shows accumulated drift error for 35 days with no maneuvers
 - Error in drift prediction was approximately 0.00034 deg per orbit





Seasonal Variation of Precession

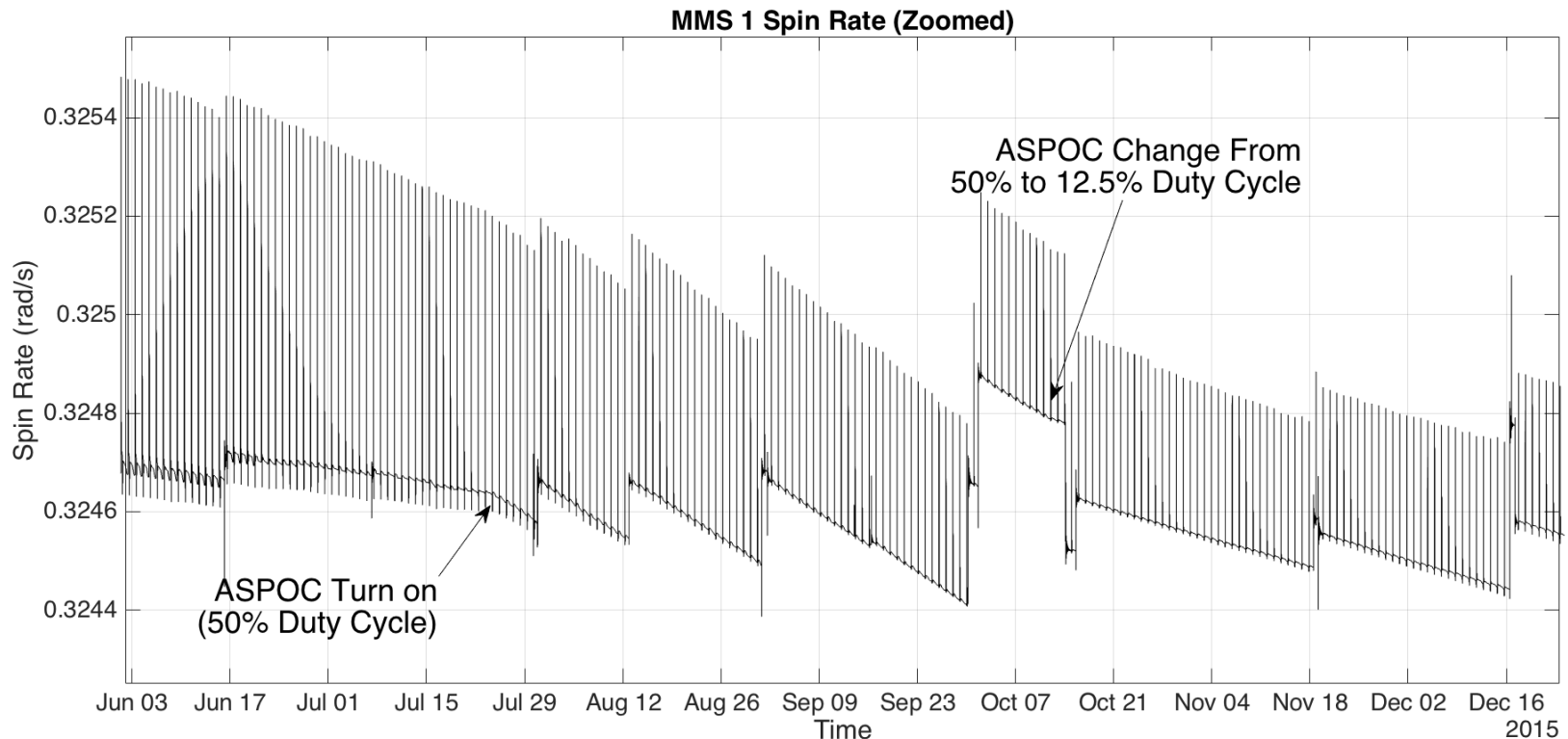
- Magnitude and direction of GG precession vary seasonally
 - Orbit normal drifted approx. 21 deg during one year, affecting GG torque
 - Target box center follows the Sun motion of one deg per day
 - Attitude maneuvers are performed every 2 to 4 weeks to stay in target box
 - Plots show seasonal variation 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





Observed Change In Spin Rate

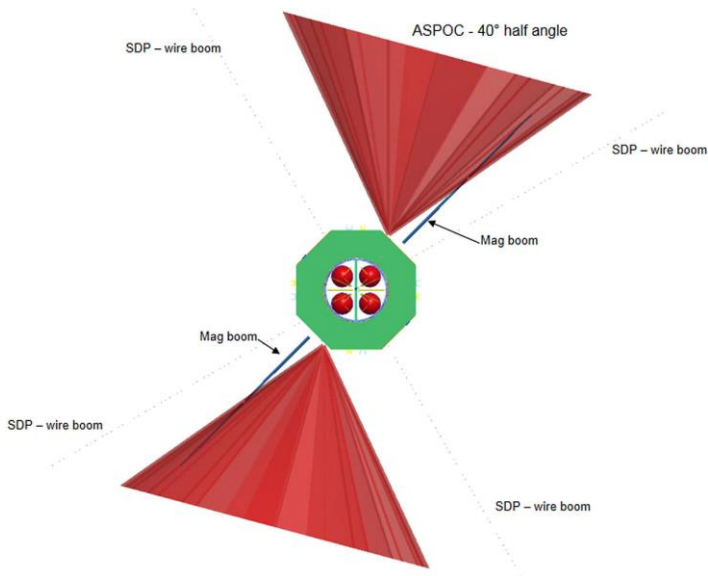
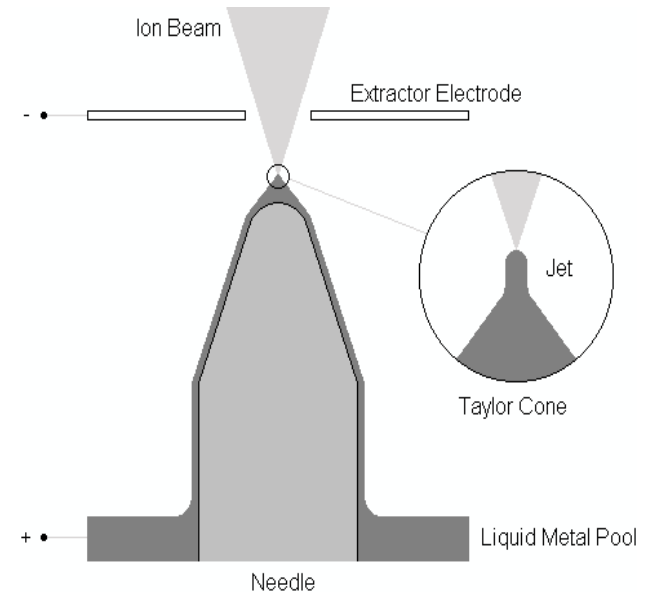
- Distinct spin rate change observed at ASPOC (Active Spacecraft Potential Control Investigation) turn on and duty cycle changes





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

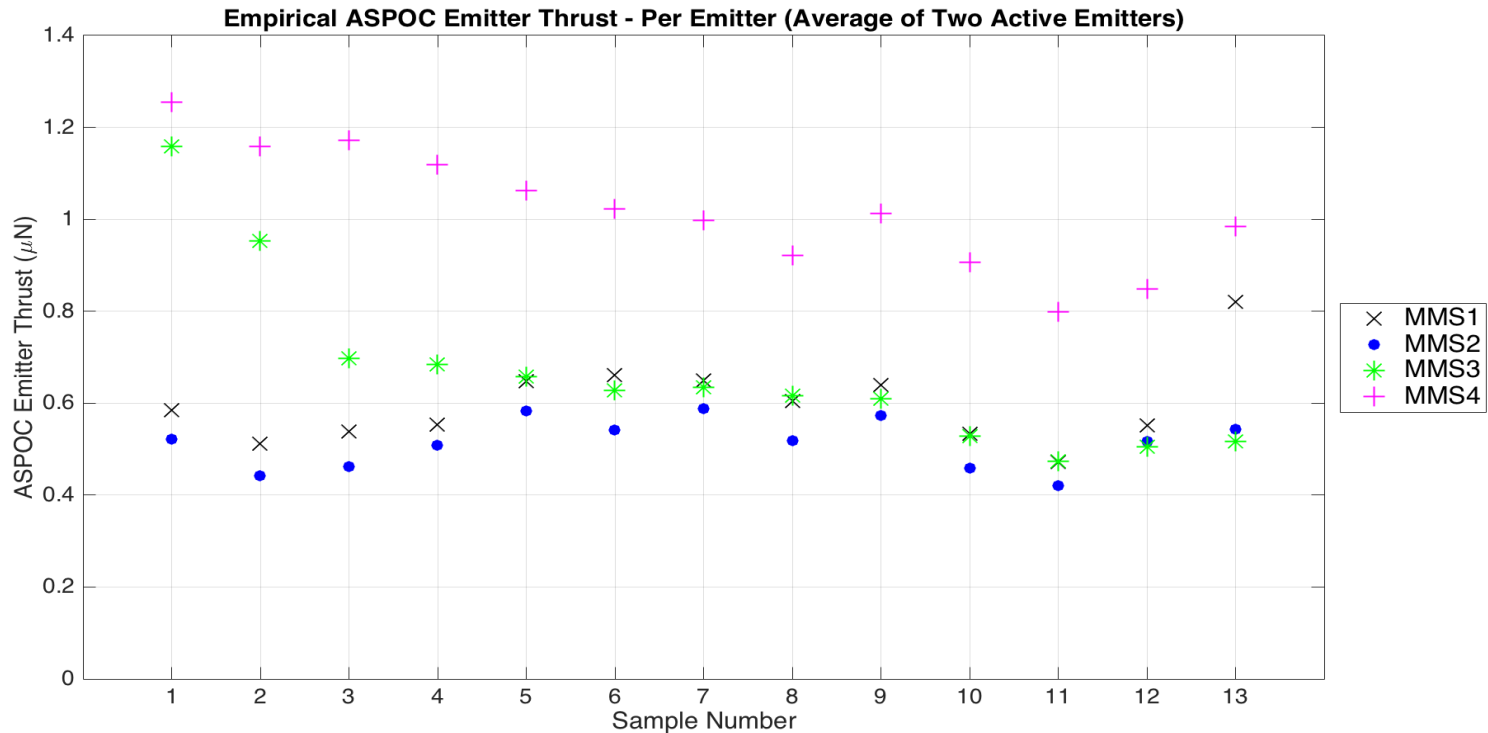


- 2 active emitters on each Spacecraft
- Location produces a coupled negative (against direction of S/C rotation) torque



Determining Empirical Thrust

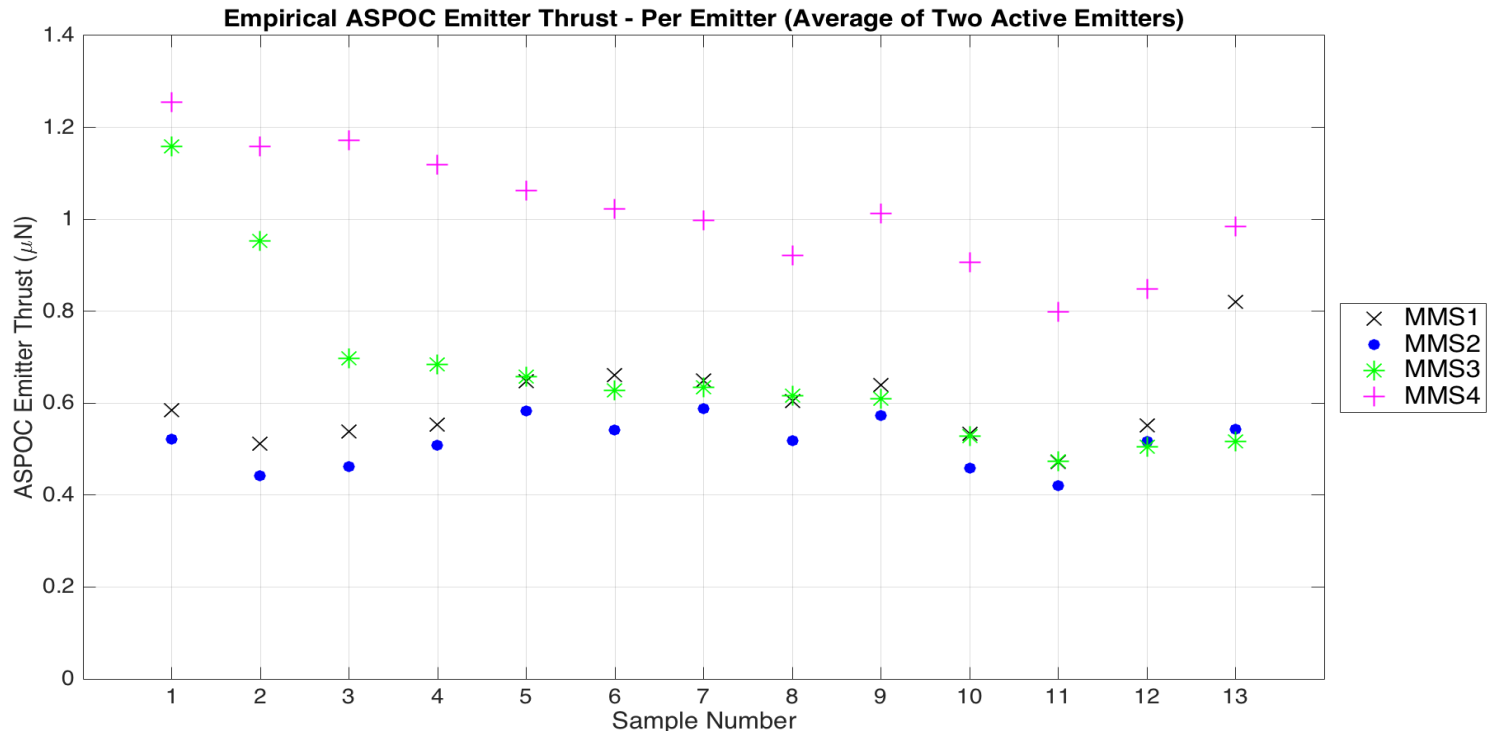
- Time between maneuvers defined as a sample
- Using average deceleration, center of mass, moment of inertia, and emitter energy an empirical emitter thrust is calculated





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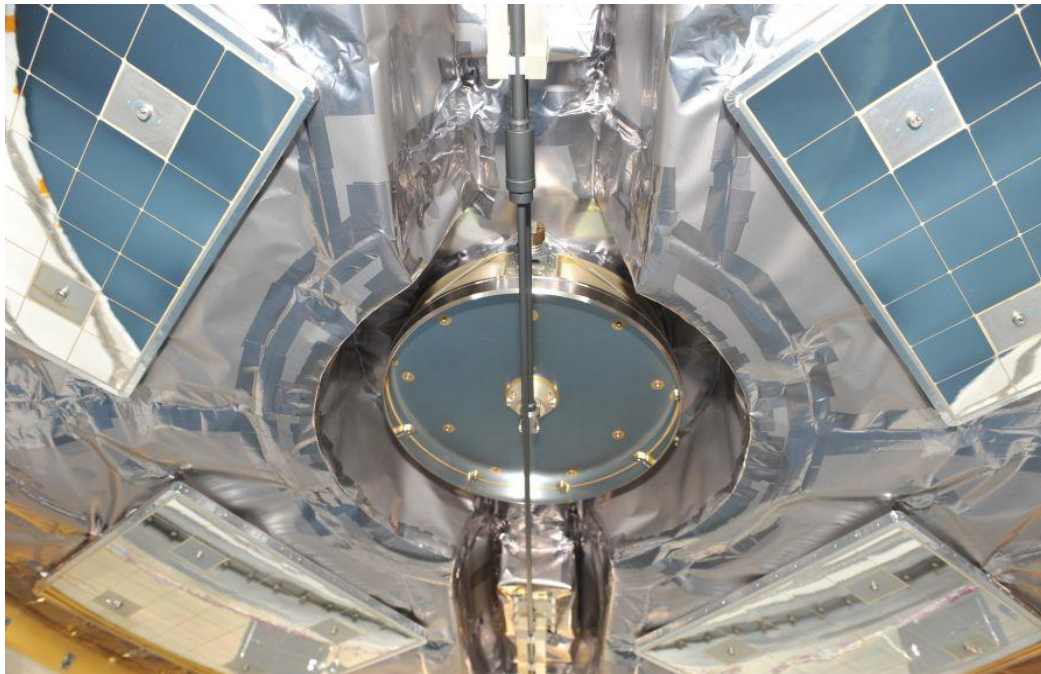
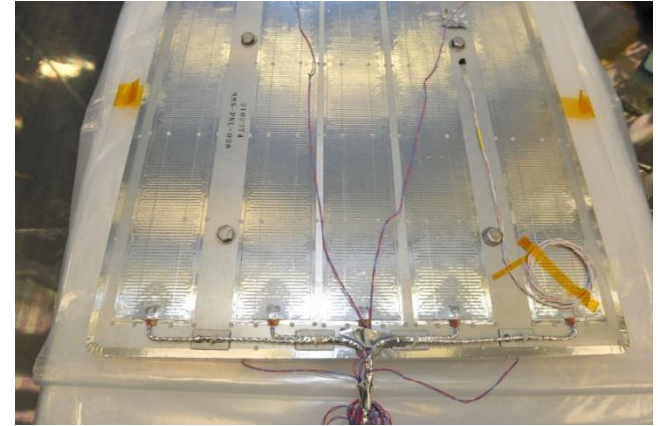


Summary of MMS4 Impact Event

- 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

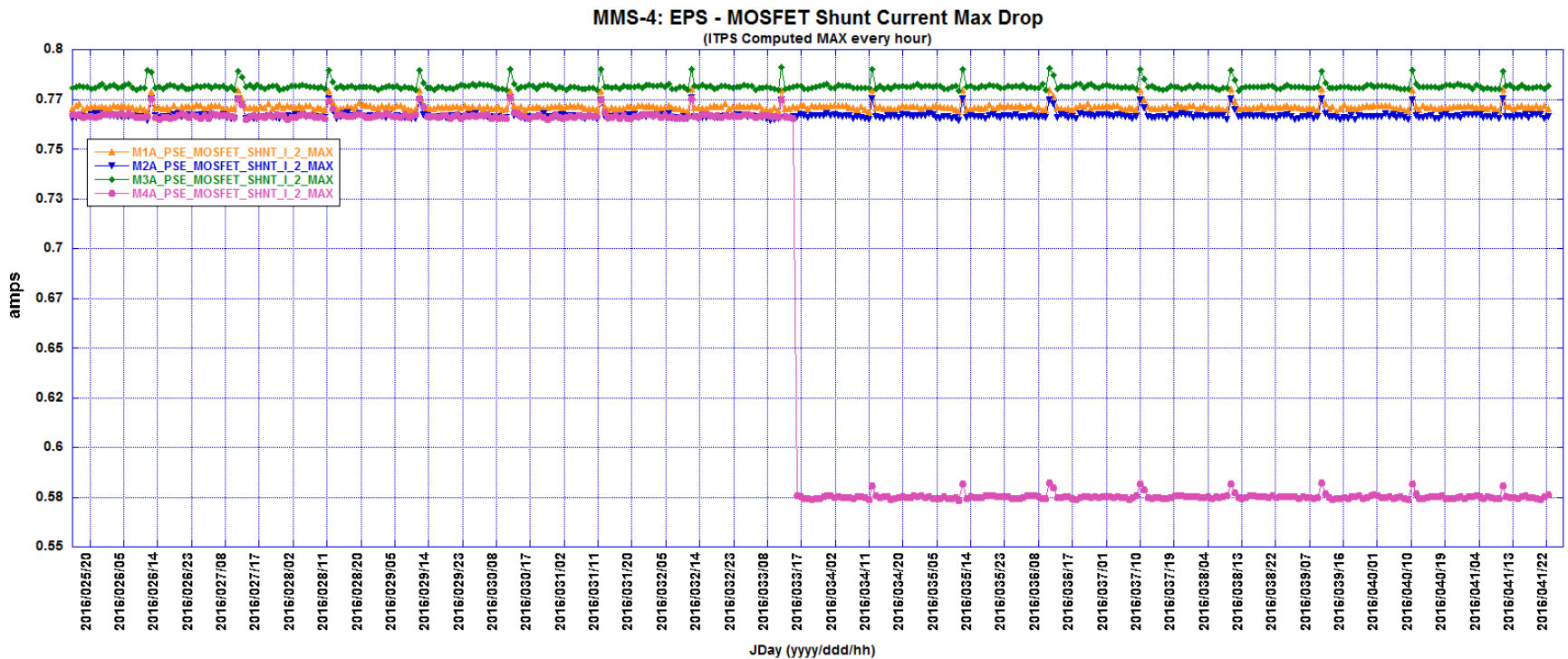


Impact Location (Shunt Resistor)





Shunt Resistor Data





Analysis Methodology

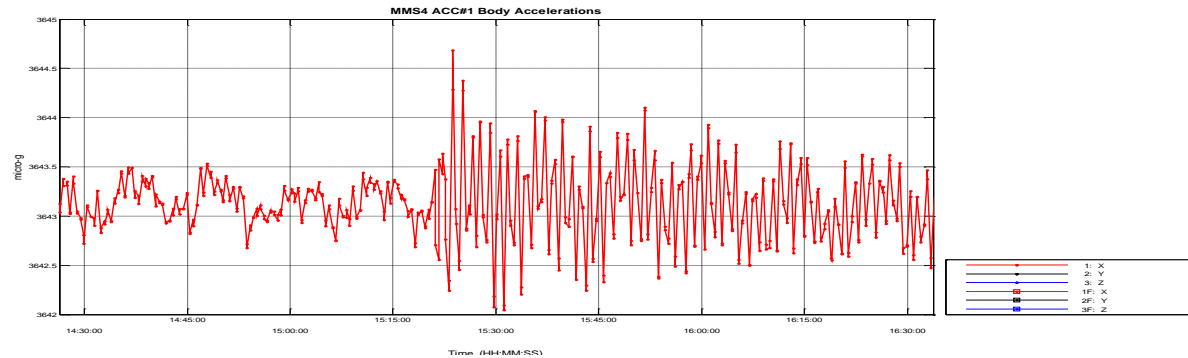
- Use relative sizes of initial spikes in accelerometer signals caused by event to estimate velocity direction of impactor relative to MMS
- Use change in MMS spin axis direction produced by event, together with known spacecraft angular momentum, to derive the transverse angular momentum applied to MMS by impactor
- From known impact point on spacecraft and estimated approach direction, this allows the linear momentum (mv_{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_{rel} and relative speed v_{rel} , we can then estimate the mass m of the impactor
- Use these to estimate kinetic energy of initial impact, $T=0.5mv_{rel}^2$



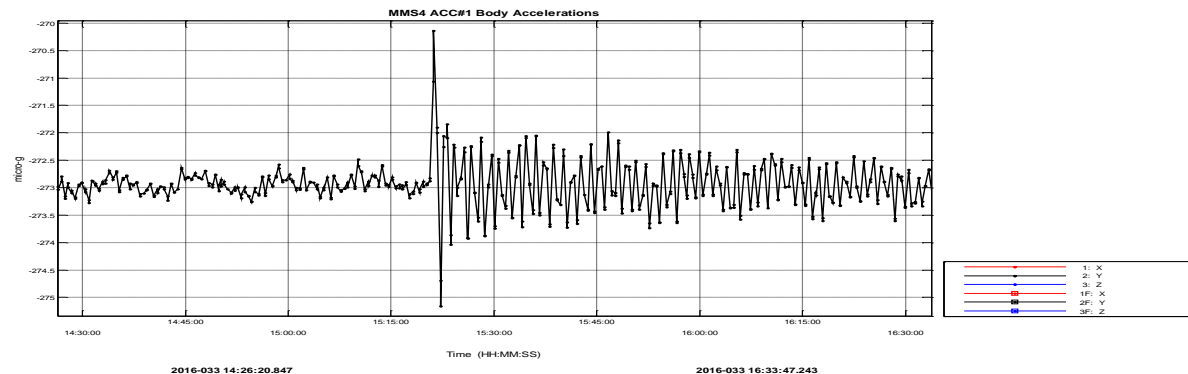
Accelerometer Measurements

X-axis: Initial spike -0.8 micro-g

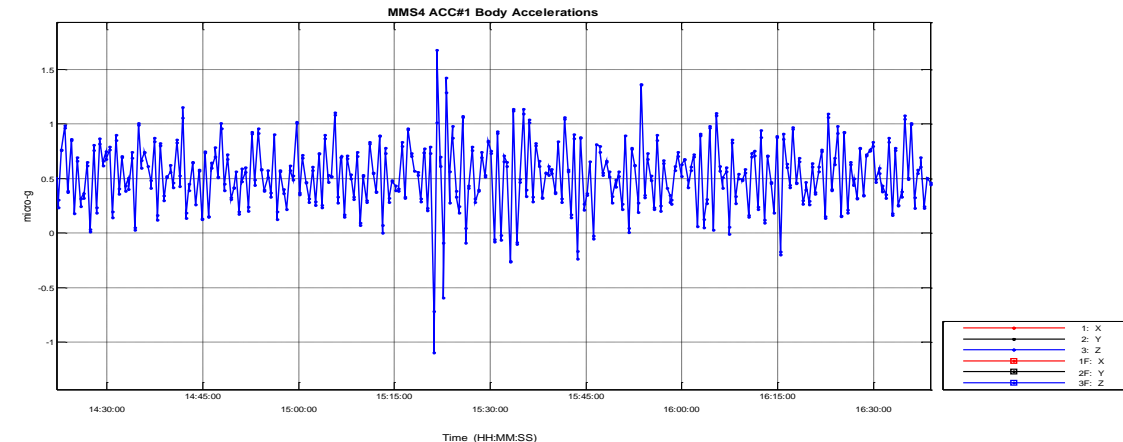
Note: All three axes only sampled every 30 s, so actual first motion may not be observed



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

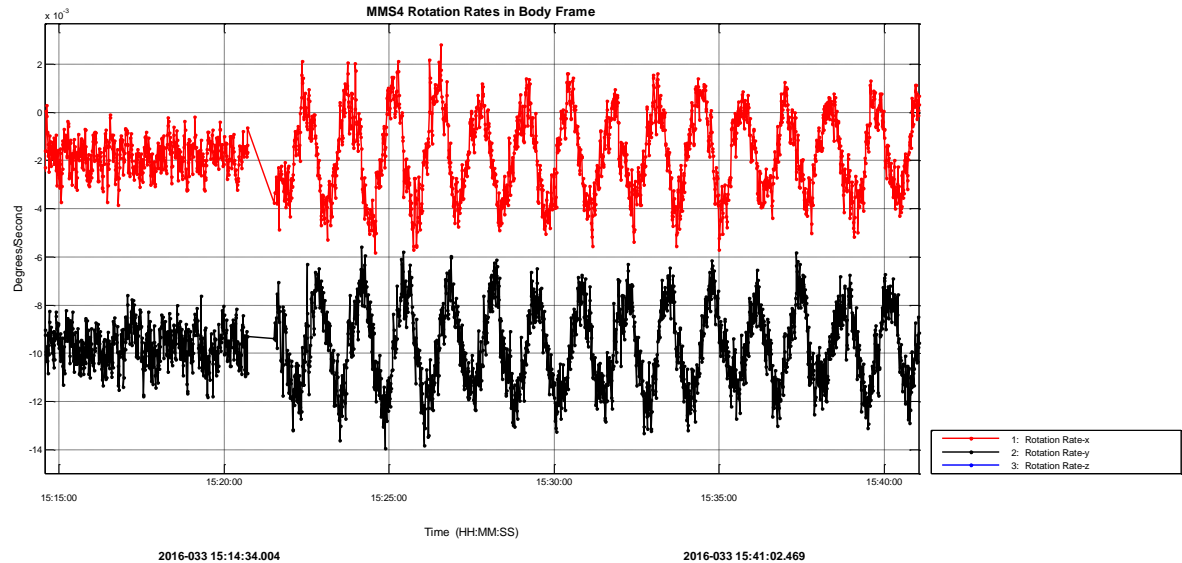
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Rotation Rates, Transverse and Axial

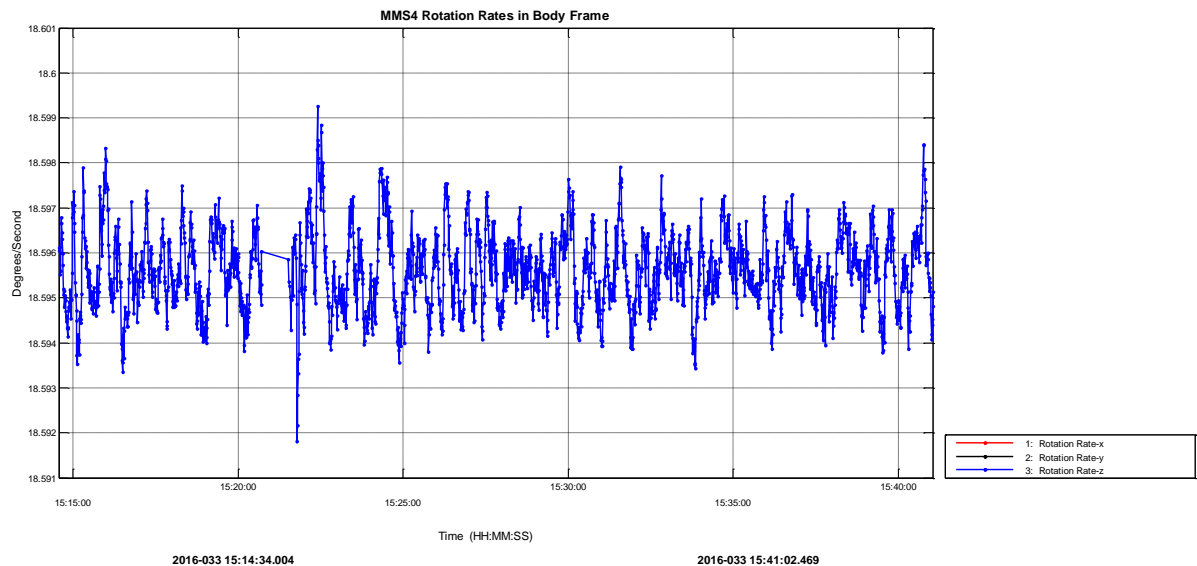


Transverse:
Nutation/boom
vibration evident



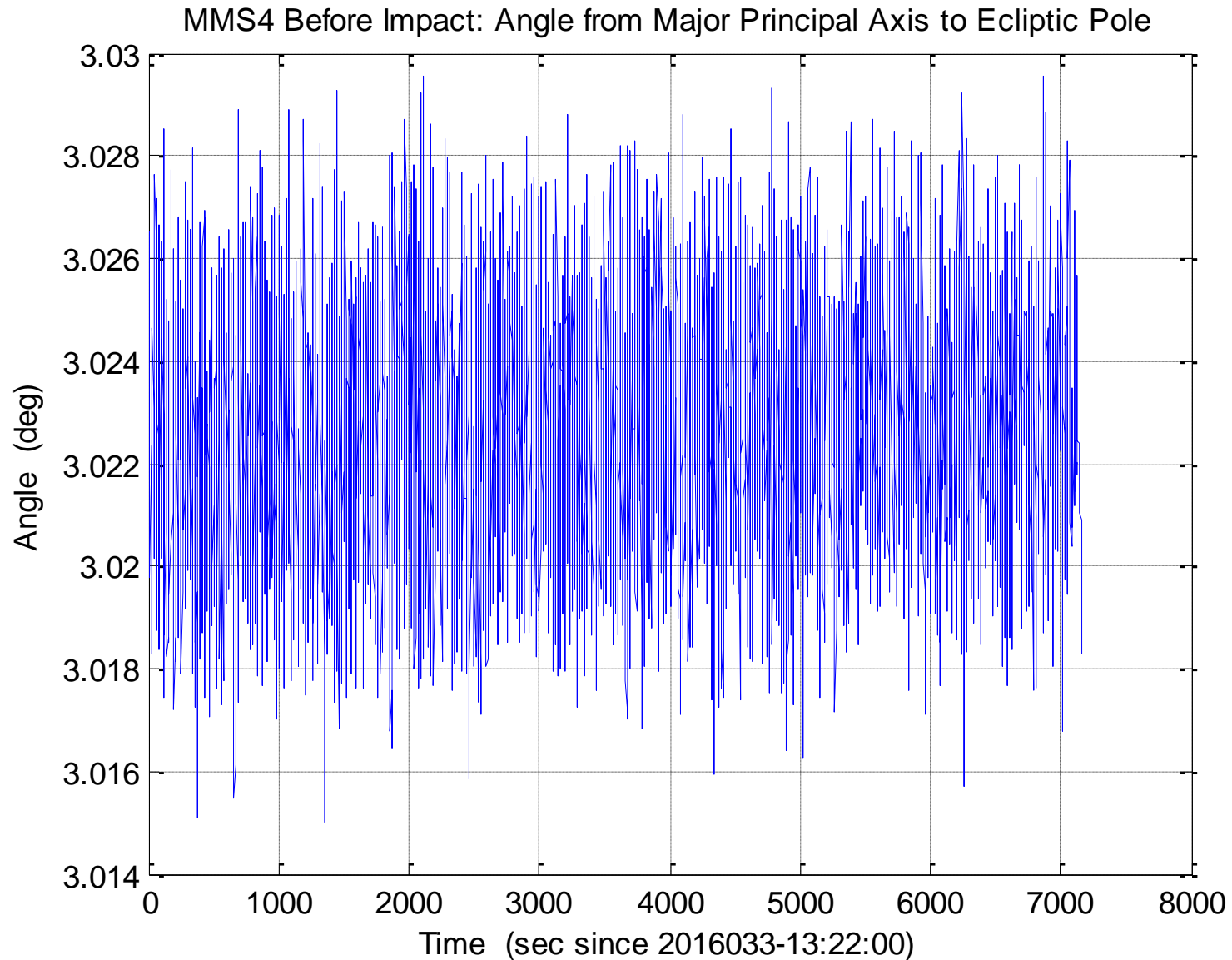
Note brief
dropout resulting
from star
cameras being
blinded/resetting

Axial: No change
in spin rate
evident



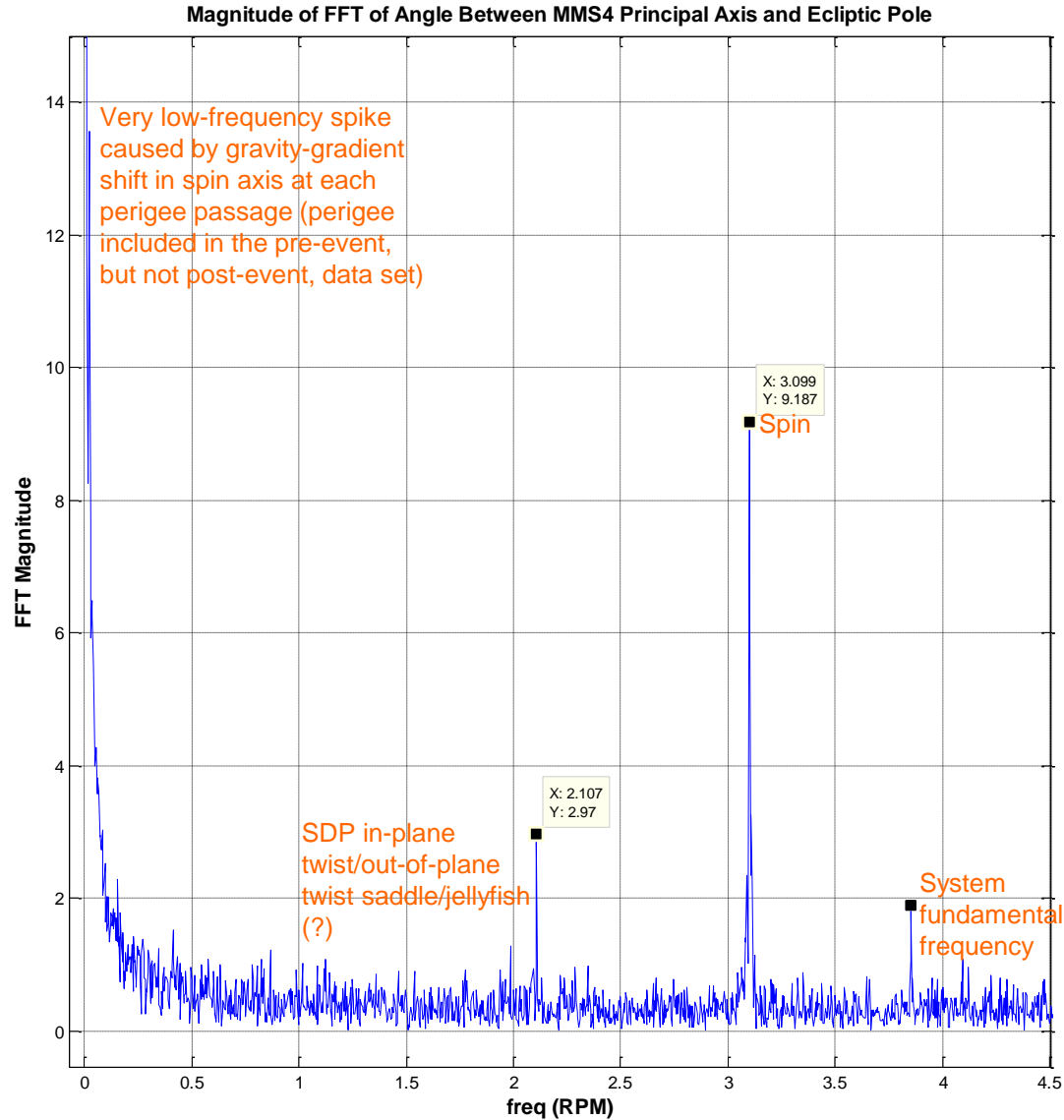


Pointing Angle Before Event





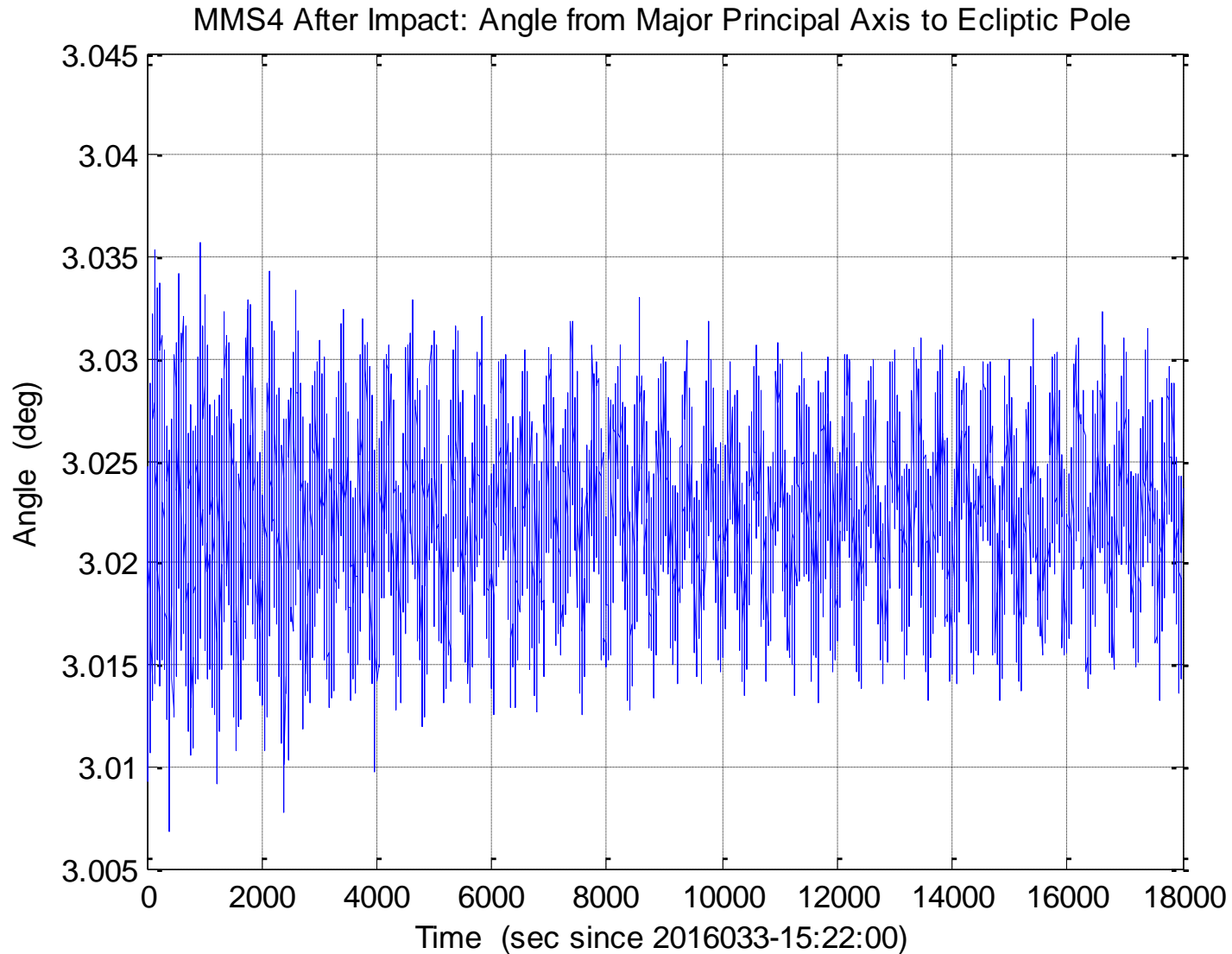
FFT of Pointing Angle Before Event





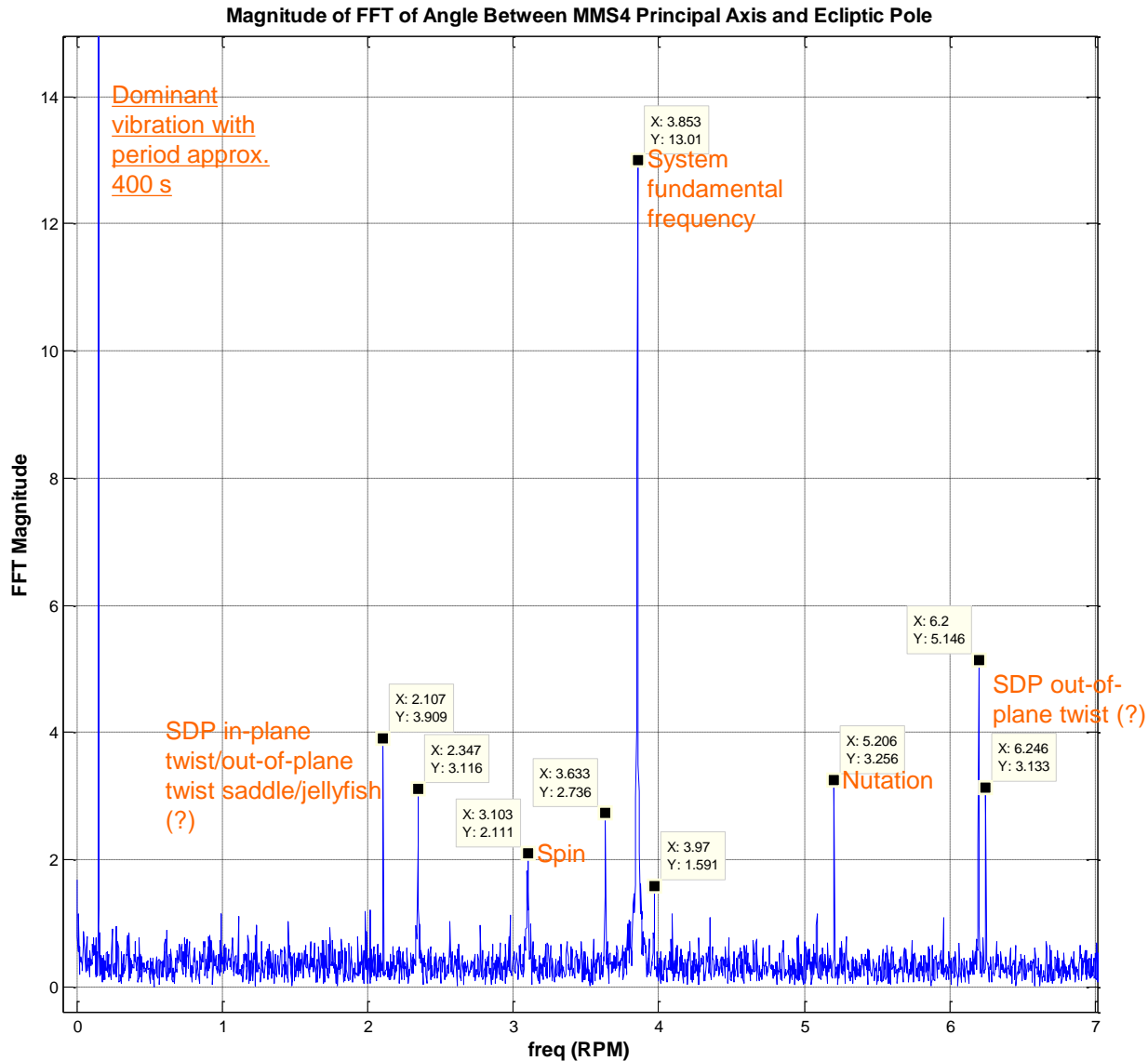
Pointing Angle After Event

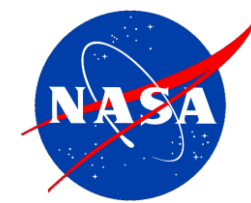
Vibration with
period of ~400 s
dominates
response





FFT of Pointing Angle After Event





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 ($\sim 2 \times 10^{-4}$ - 0.9 mm diameter)
 - Flux tails off quickly: $\sim 10^{-3}$ as high at 1 mm diameter as at 0.1 mm*

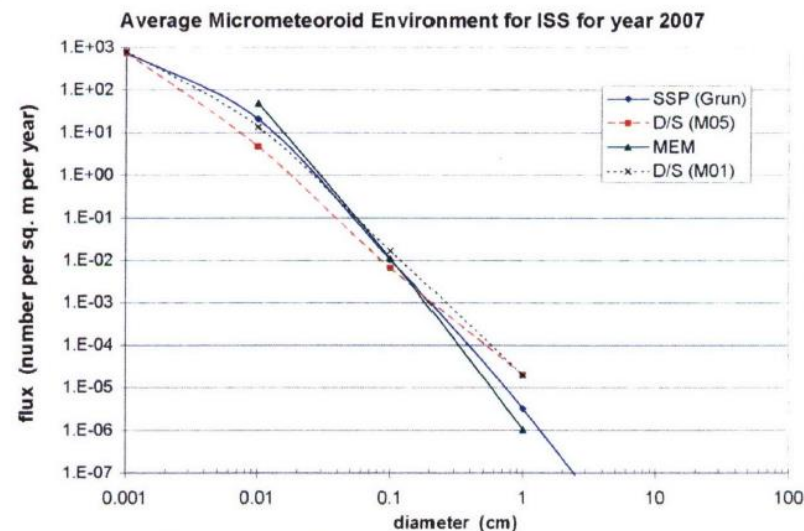
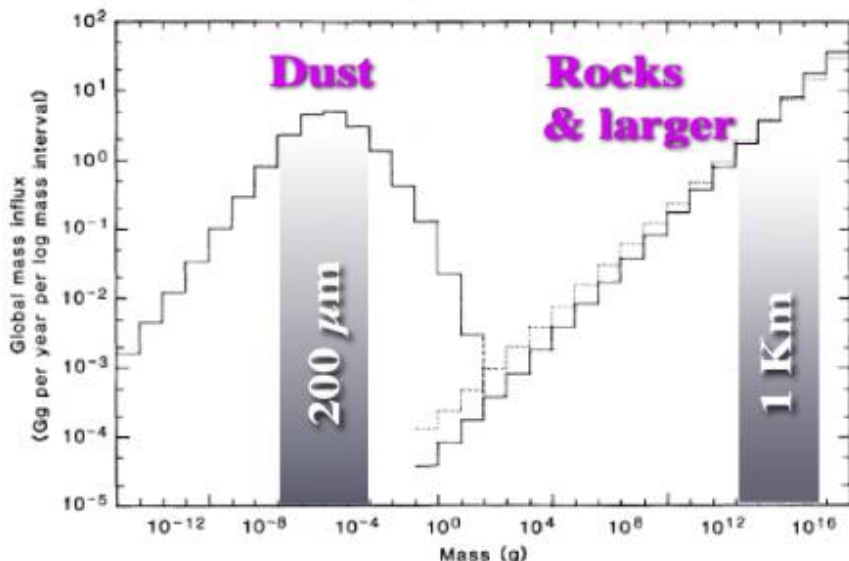


Figure 2. Micrometeoroid particle fluxes from various models.

* 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 ($> \sim 15 \text{ m}^2/\text{kg}$) 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
 - “Long-Term Evolution of Geosynchronous Orbital Debris with High Area-to-Mass Ratios”, Pardini and Anselmo, 2006
- Possible debris source: multi-layer insulation (MLI). MLI degrades in GEO. See Tedlar thin film before, after 3 years simulated GEO*:



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

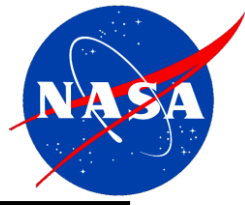


Particle Mass, Kinetic Energy Estimates

- 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 8.48×10^{-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 2.96×10^{-2} gm
 - If from an MLI layer with representative density 40 gm/m², this yields an area of 7.41×10^{-4} m², 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



Backup Material

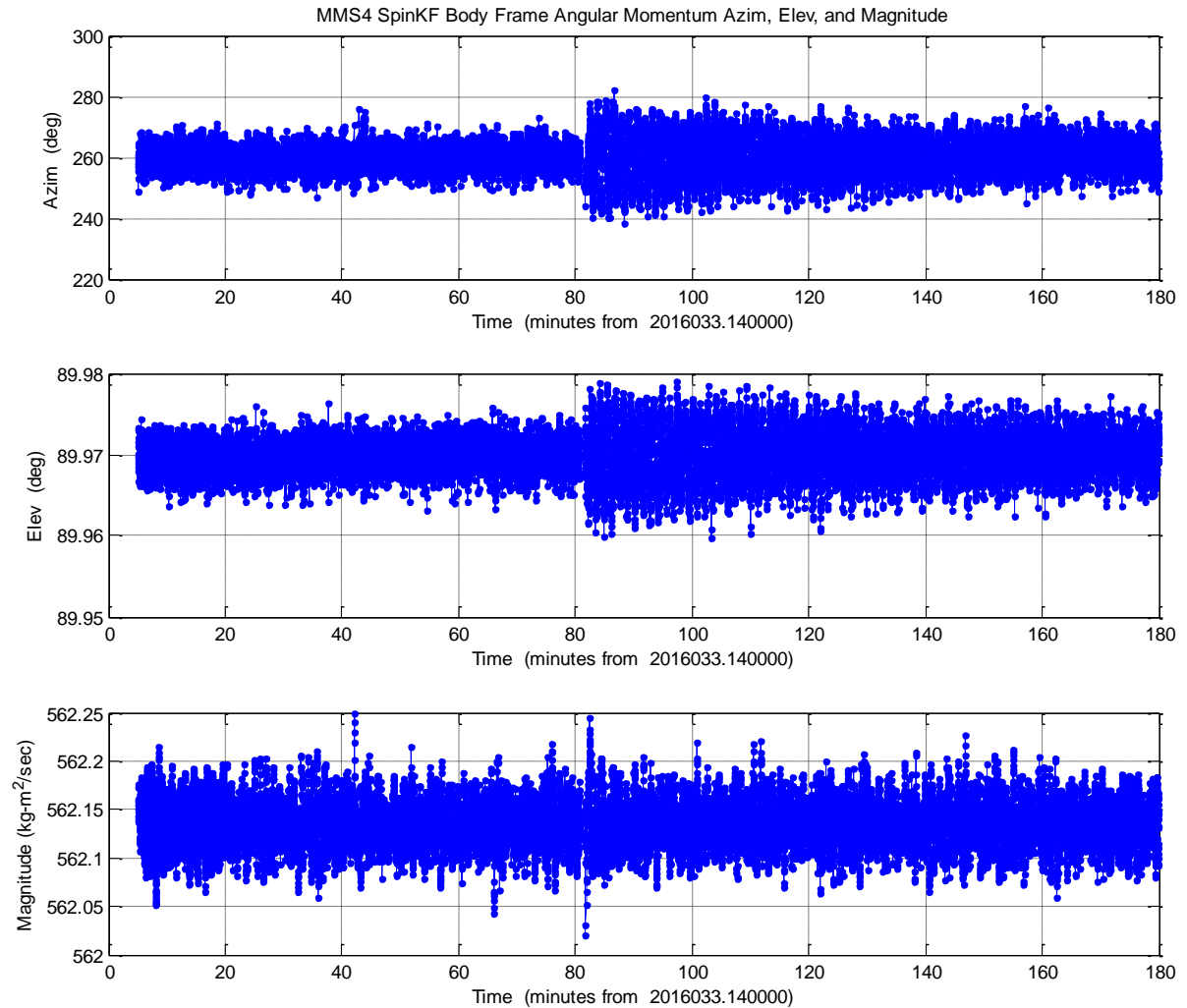




Angular Momentum

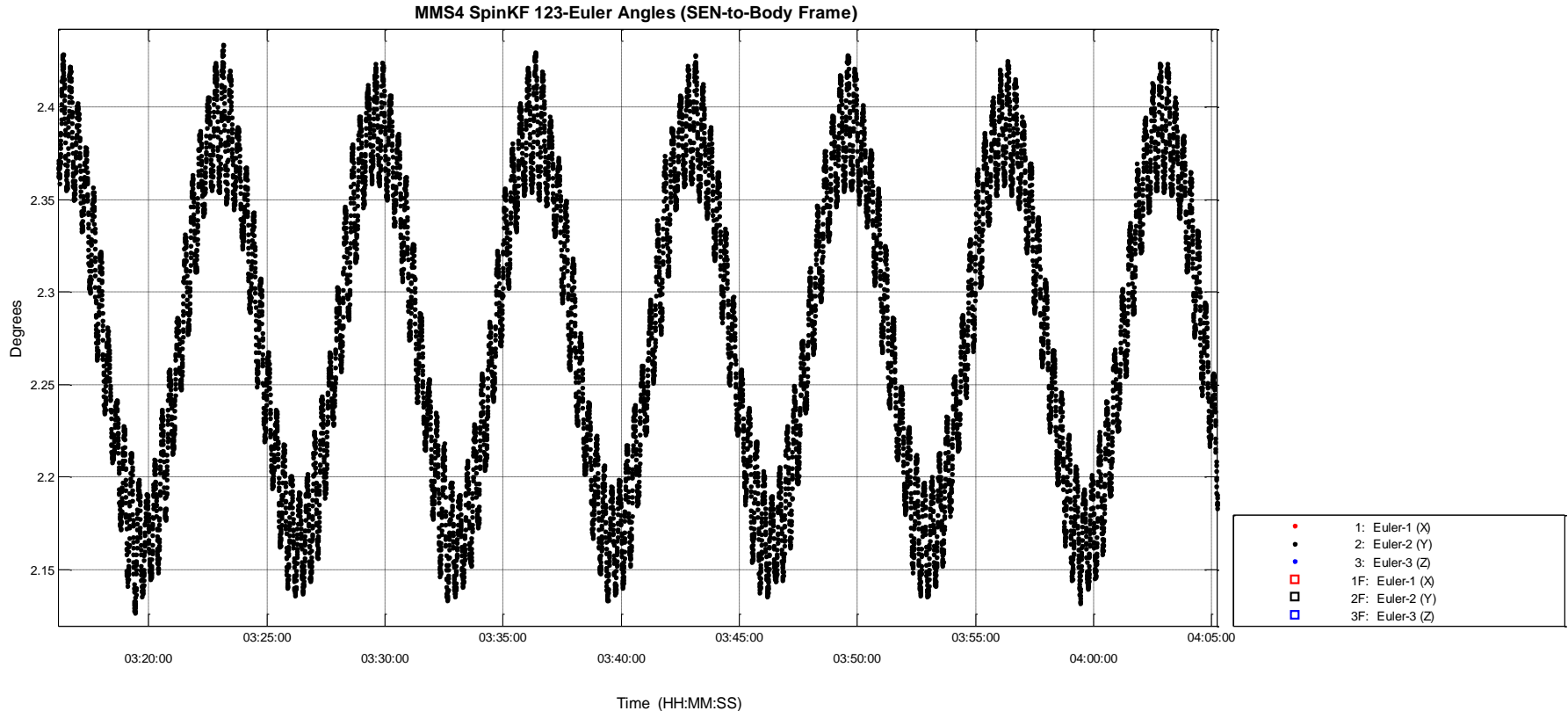
Transverse:
Nutation/boom
vibration evident

Axial: No change in
spin rate evident.
Consistent with
shunt location being
close to spin axis





Pointing Angle After Previous Maneuver



2016-049 03:16:09.201

2016-049 04:05:12.951

- 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