



UNCLASSIFIED



# Magnetospheric Multiscale Mission Micrometeoroid/Orbital Debris Impacts

Trevor Williams<sup>1</sup>, Joseph Sedlak<sup>2</sup>, Seth Shulman<sup>3</sup>

Spacecraft Anomalies and Failures Workshop 2017

Chantilly, VA

Dec. 12, 2017

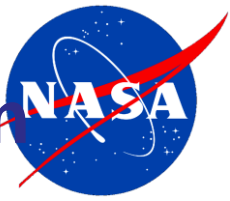
<sup>1</sup> NASA Goddard Space Flight Center; <sup>2</sup> ai Solutions, Inc.; <sup>3</sup> KBRwyle

UNCLASSIFIED

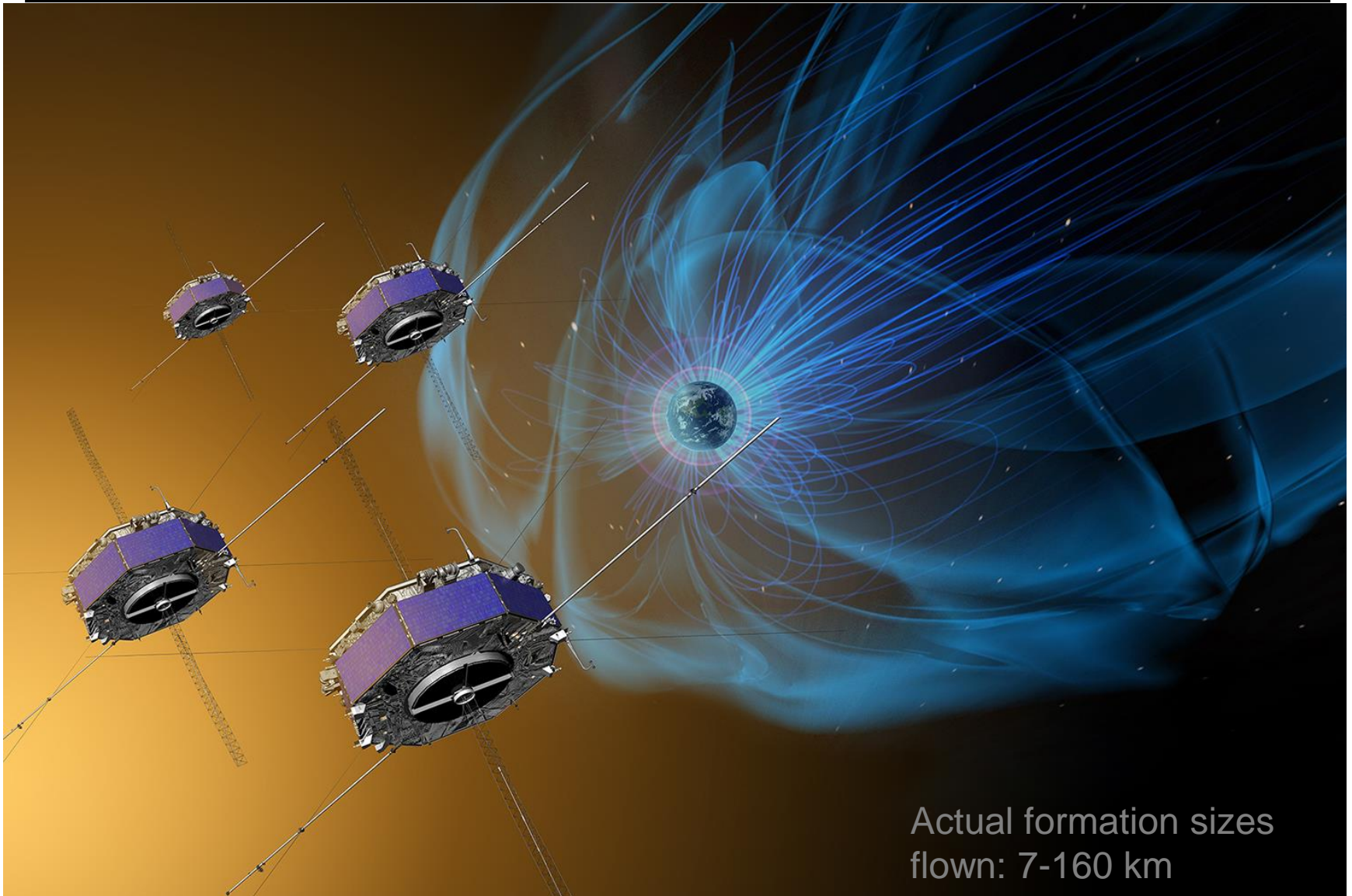


# Summary of Presentation

- The Magnetospheric Multiscale (MMS) mission, launched in Mar. 2015, uses four spacecraft flying in tetrahedral formations of various sizes to collect heliophysics science data on magnetic reconnection
- The MMS mission consisted of several orbital phases:
  - Phase 1 was flown at an apogee radius of 12 Earth radii ( $R_E$ ) and perigee radius of  $1.2 R_E$  (altitude 1,276 km), to study magnetic reconnection on the dayside of the magnetosphere
  - Phase 2a involved 98 maneuvers to raise apogee radius to  $25 R_E$
  - Phase 2b was flown at  $25 R_E$  apogee radius, to study the magnetotail
  - Phase 3 (extended mission) is continuing for now in the Phase 2b orbit
- The MMS spacecraft are highly instrumented (accelerometers, star cameras, Sun sensors, science experiments for plasmas etc.). This presentation will discuss how data from these systems has allowed two micrometeoroid/orbital debris events to be studied:
  - Impact with MMS4 shunt resistor, Feb. 2, 2016
  - Impact with MMS4 wire boom, June 12, 2016

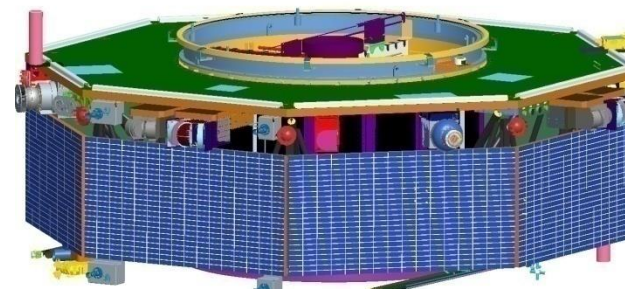
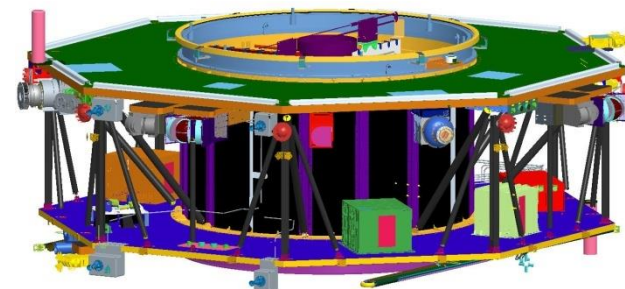
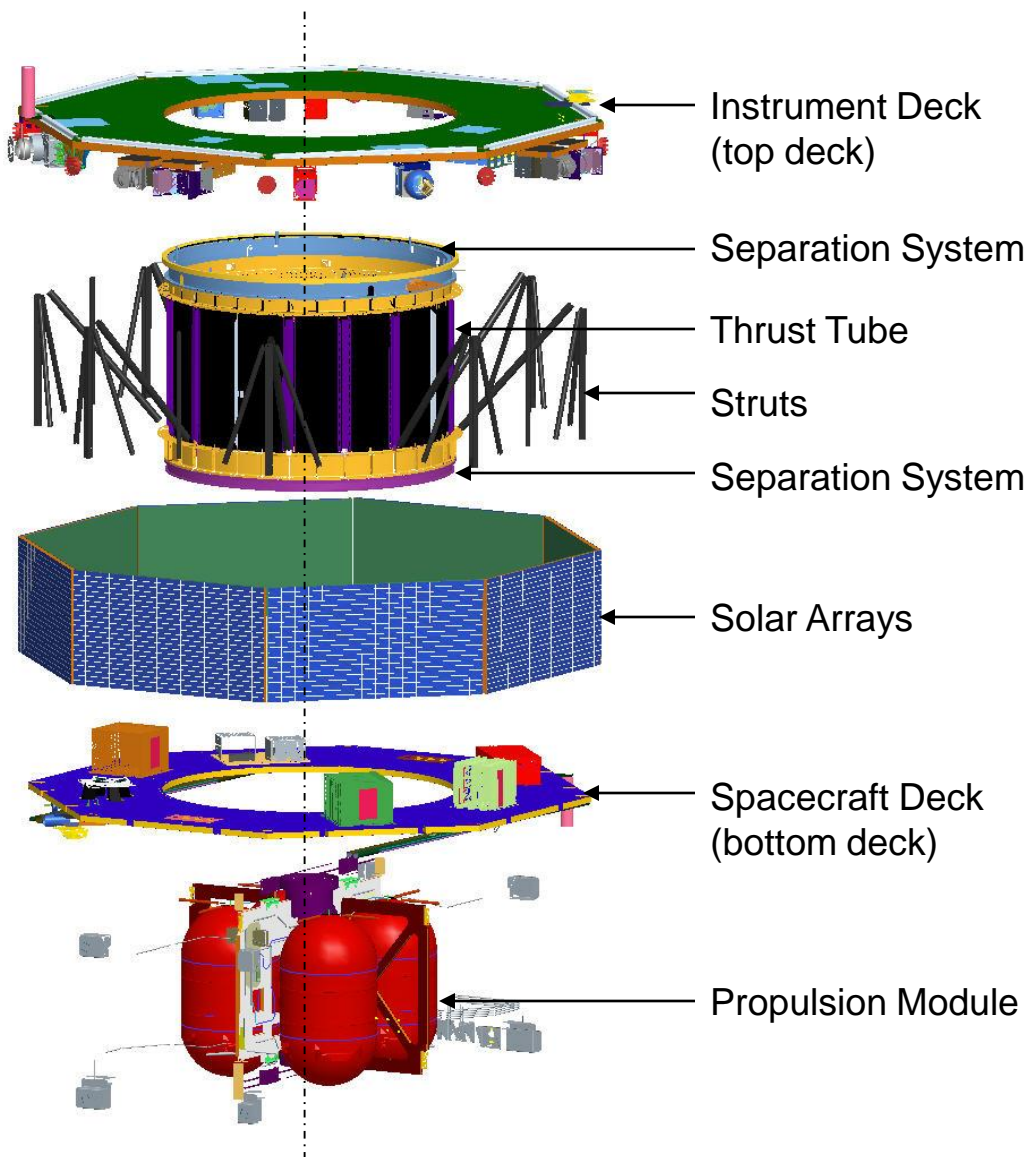


# Magnetospheric Multiscale (MMS) Mission

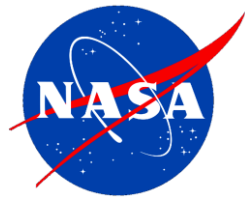


Actual formation sizes  
flown: 7-160 km

# Observatory Layout



Dry mass average 938 kg  
 Initial fuel mass 412 kg  
 Diameter ~ 3 m; height ~ 1 m  
 Four 60 m wire booms, stiffened  
 by 3.05 RPM spin



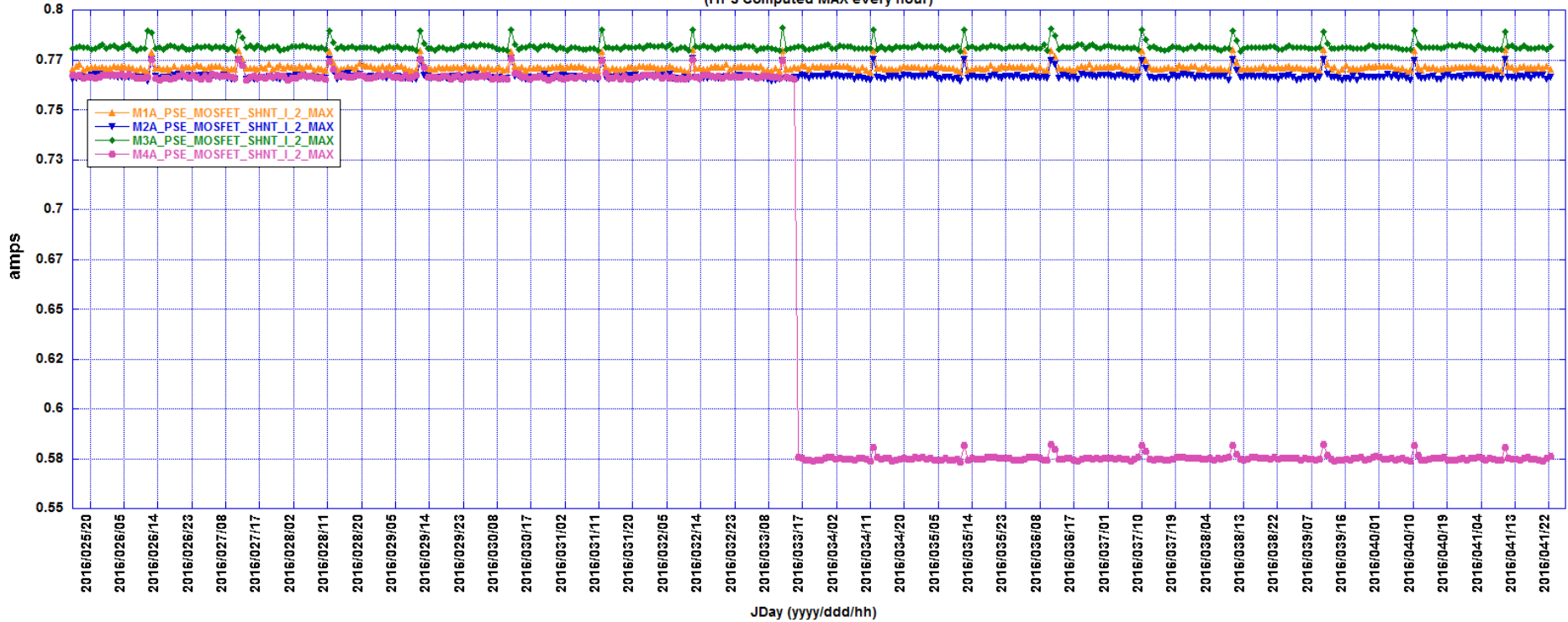
# MMS4 Shunt Resistor Impact Event

- MMS passes any excess electrical energy produced by the solar arrays through five shunt circuits, each with four resistors
- These resistors are mounted behind four radiator panels (Optical Solar Reflectors [OSRs]) attached to the lower face of the spacecraft. This allows dissipation of the excess energy to space as radiated heat
- Data from MMS4 for Feb. 2, 2016 showed a decrease in one shunt circuit current. This indicates an increase in total shunt resistance. The observed change would be consistent with the total loss of one shunt resistor out of the four in parallel on this circuit
- Initial suspicion: cause was internal to the spacecraft, e.g. a workmanship issue with the resistor. However, data from various onboard systems indicated that a dynamic event occurred simultaneously with the change in resistance
- Spacecraft have in the past experienced such dynamic events as the result of the failure of a battery cell. However, telemetry did not indicate any problems with the MMS4 power system
- Conclusion: event was caused by a micrometeoroid/orbital debris impact, as will now be detailed



# MMS4 Shunt Resistor Data, Feb. 2, 2016

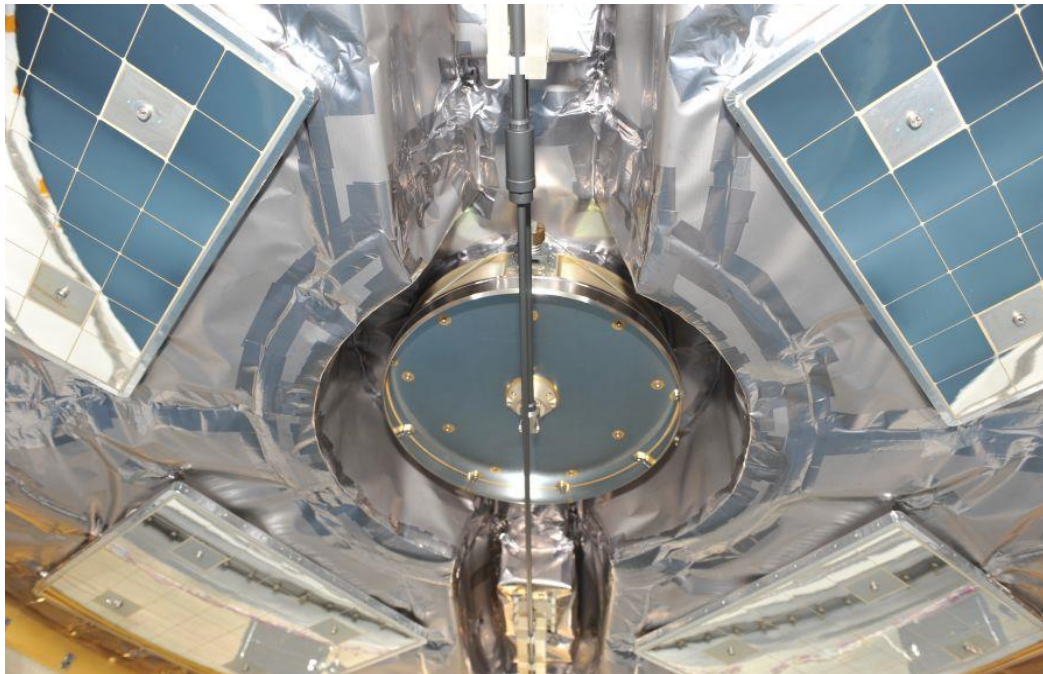
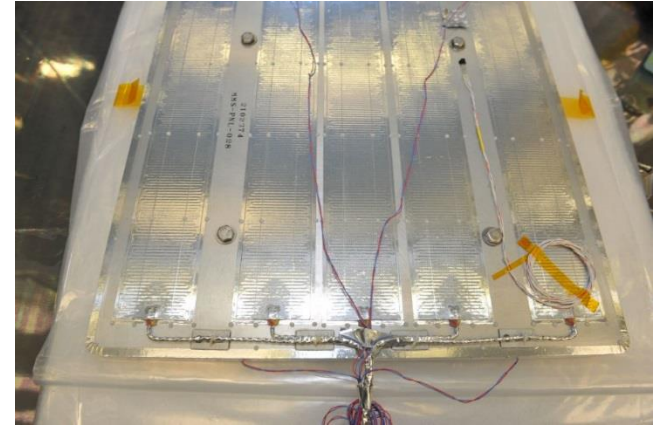
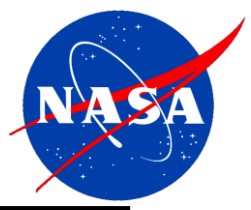
MMS-4: EPS - MOSFET Shunt Current Max Drop  
(ITPS Computed MAX every hour)





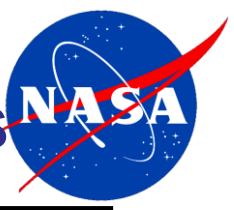
UNCLASSIFIED

# Shunt Resistors and Radiator Panels

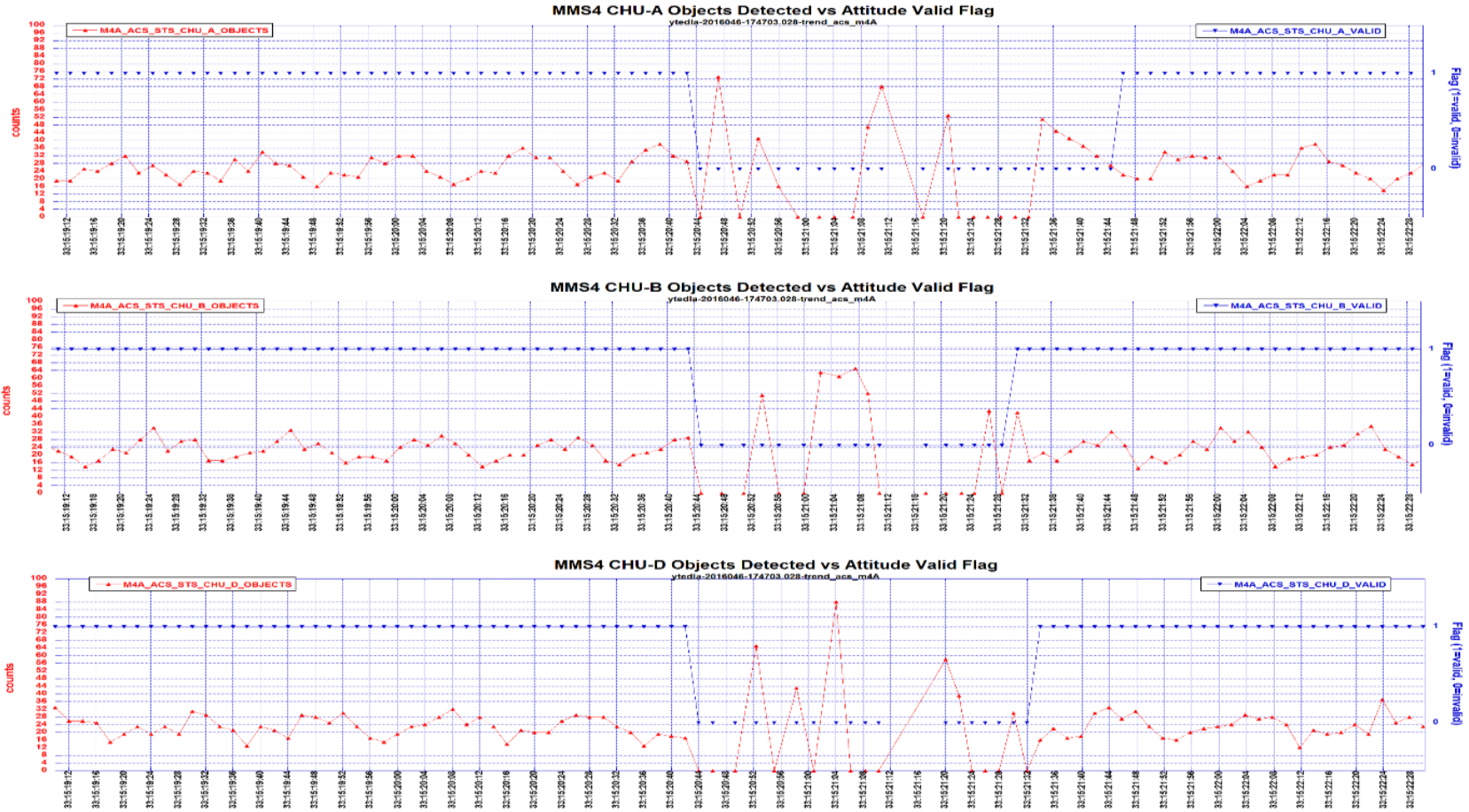




UNCLASSIFIED



# External Event Evidence 1: Star Cameras



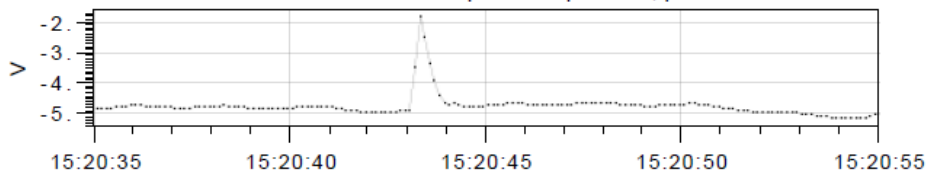




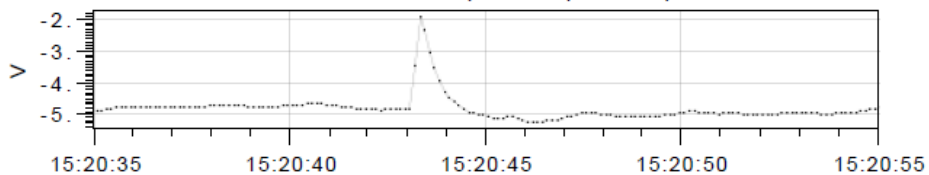
# External Event Evidence 2: Plasma



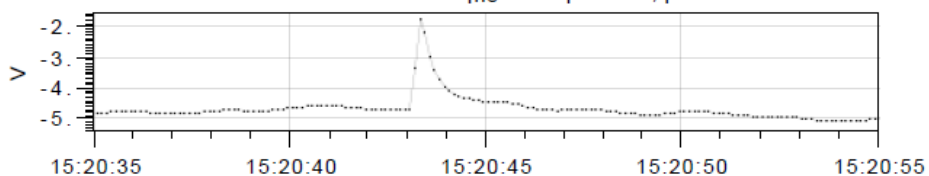
MMS4/EDP Probe to spacecraft potential, probe 1



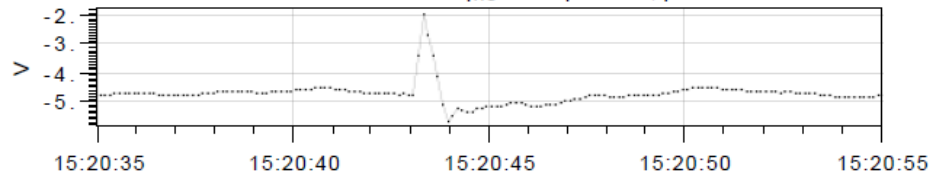
MMS4/EDP Probe to spacecraft potential, probe 2



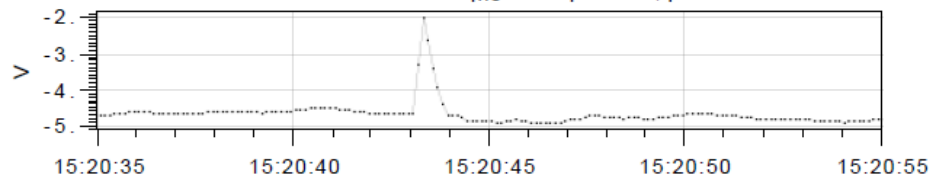
MMS4/EDP Probe to spacecraft potential, probe 3



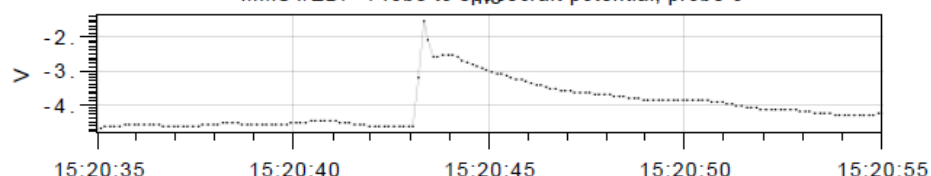
MMS4/EDP Probe to spacecraft potential, probe 4

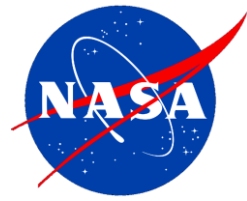


MMS4/EDP Probe to spacecraft potential, probe 5



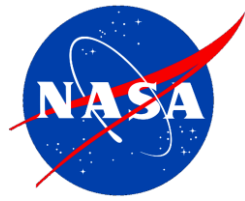
MMS4/EDP Probe to spacecraft potential, probe 6





# Summary of MMS4 Impact Event 1

- MMS4 relevant data observations (most already seen):
  - Failure of one shunt resistor
  - Accelerometers detected spacecraft disturbance
  - Star cameras “blinded” by non-star objects; reset by fault detection
  - Science instruments detected plasma around spacecraft
  - Also: small change in spin axis direction; increase in nutation, etc.
- 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
  - 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



# 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

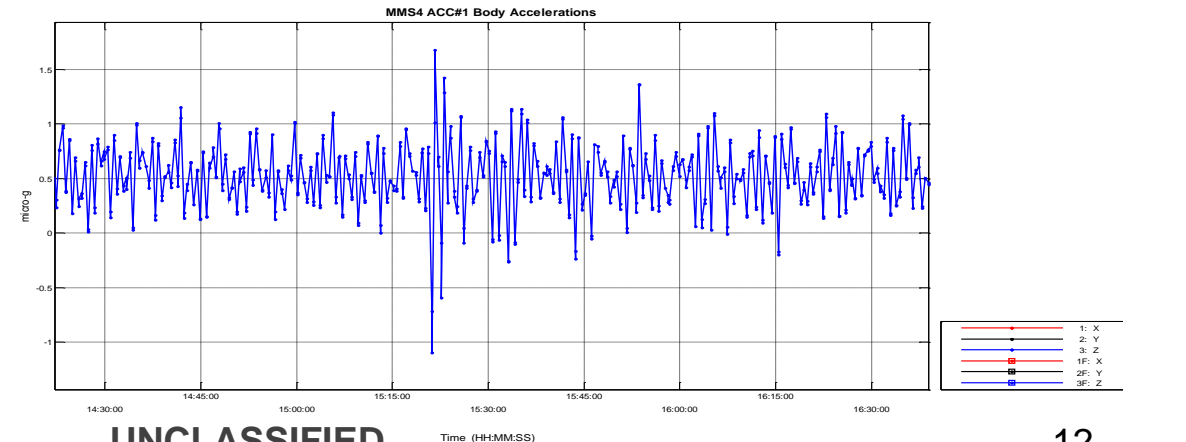
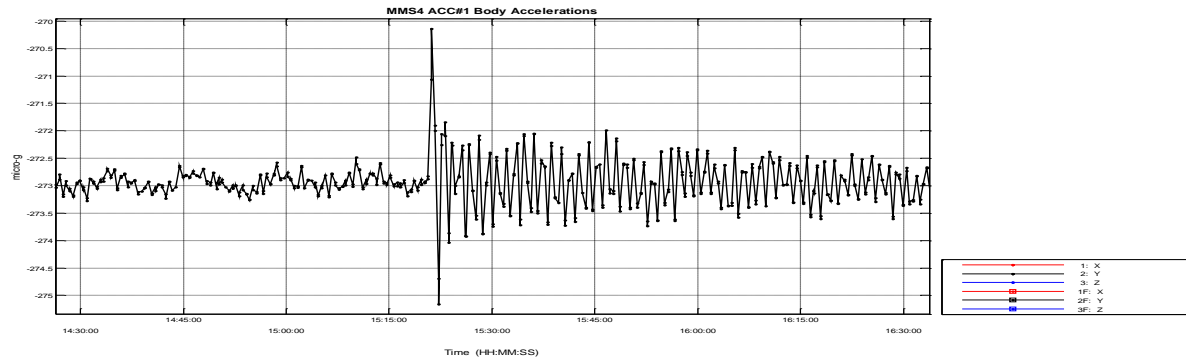
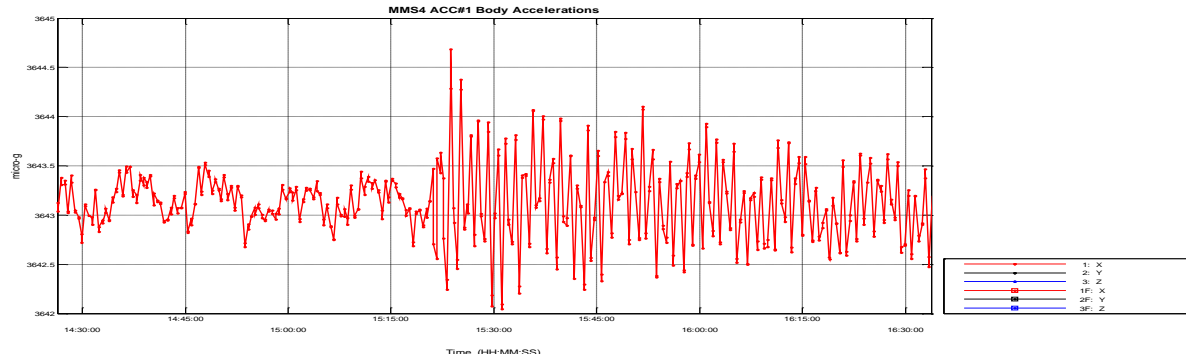
Note: All three axes only sampled every 30 s, so actual first motion may not be observed

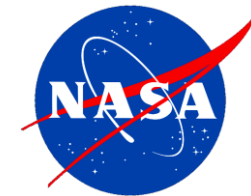
Y-axis: Initial spike 2.8 micro-g

Z-axis: Initial spike -1.7 micro-g

Resulting relative velocity direction estimate: 30.3 deg below spin plane

Dec. 12, 2017





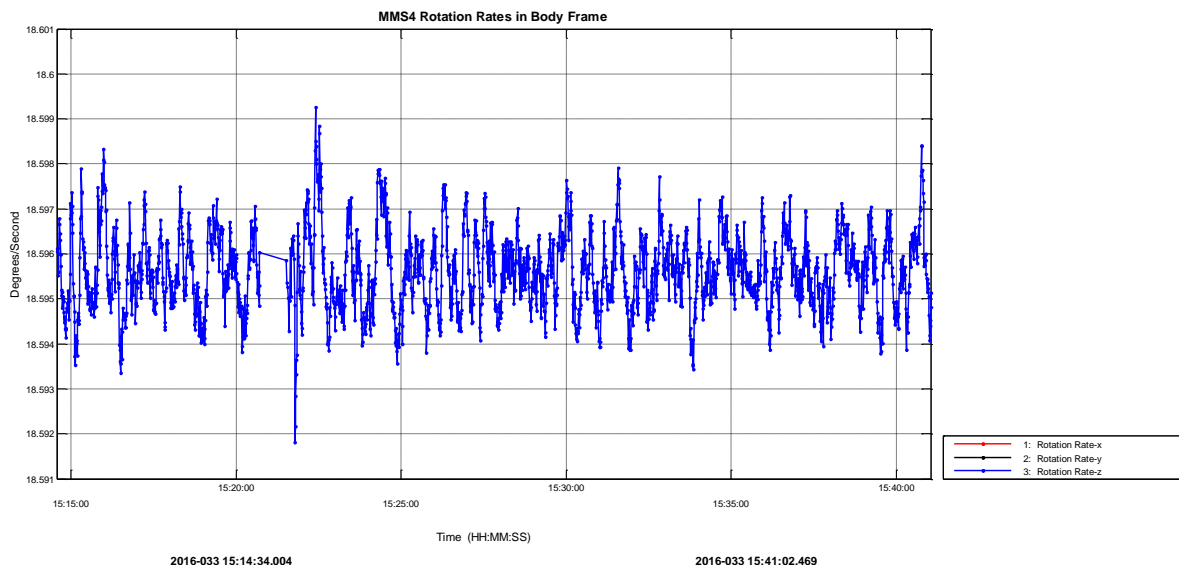
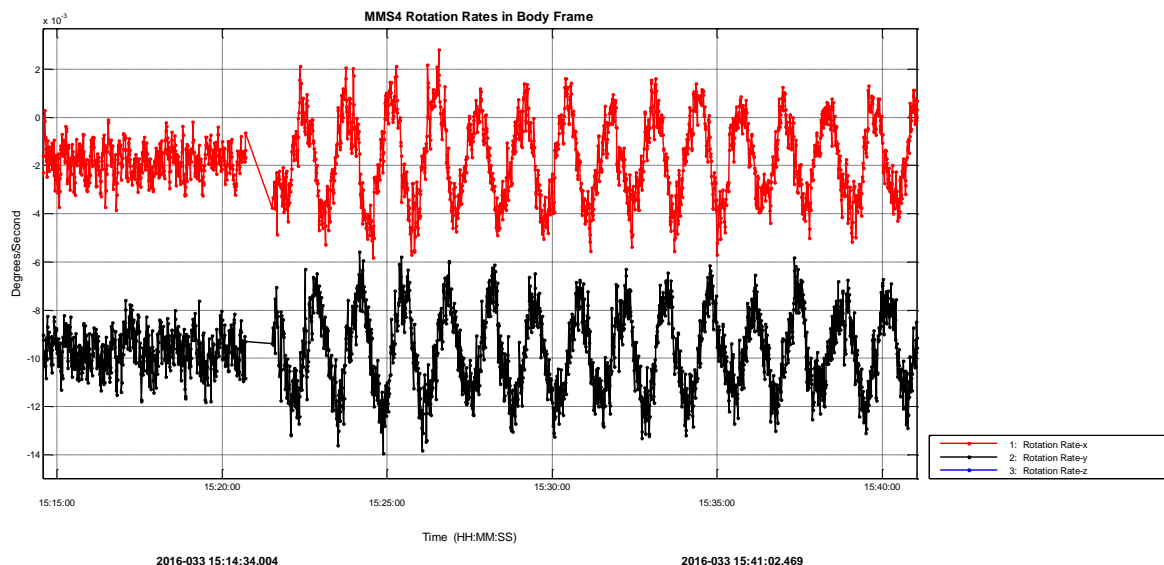
# Rotation Rates, Transverse and Axial



*Transverse:*  
Nutation/boom  
vibration evident

Note brief  
dropout resulting  
from star  
cameras being  
blinded/resetting

*Axial:* No change  
in spin rate  
evident

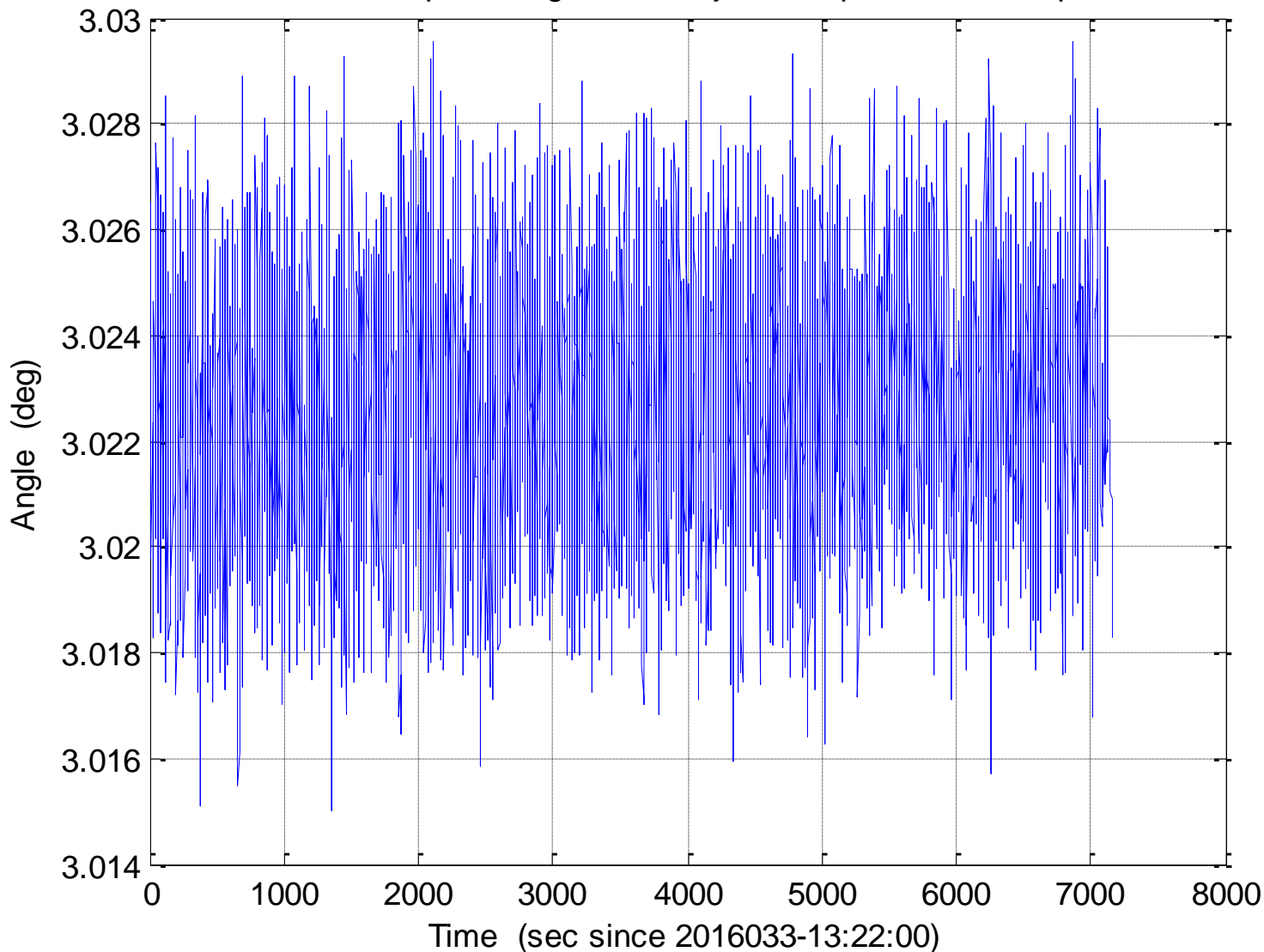




# Pointing Angle Before Event



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

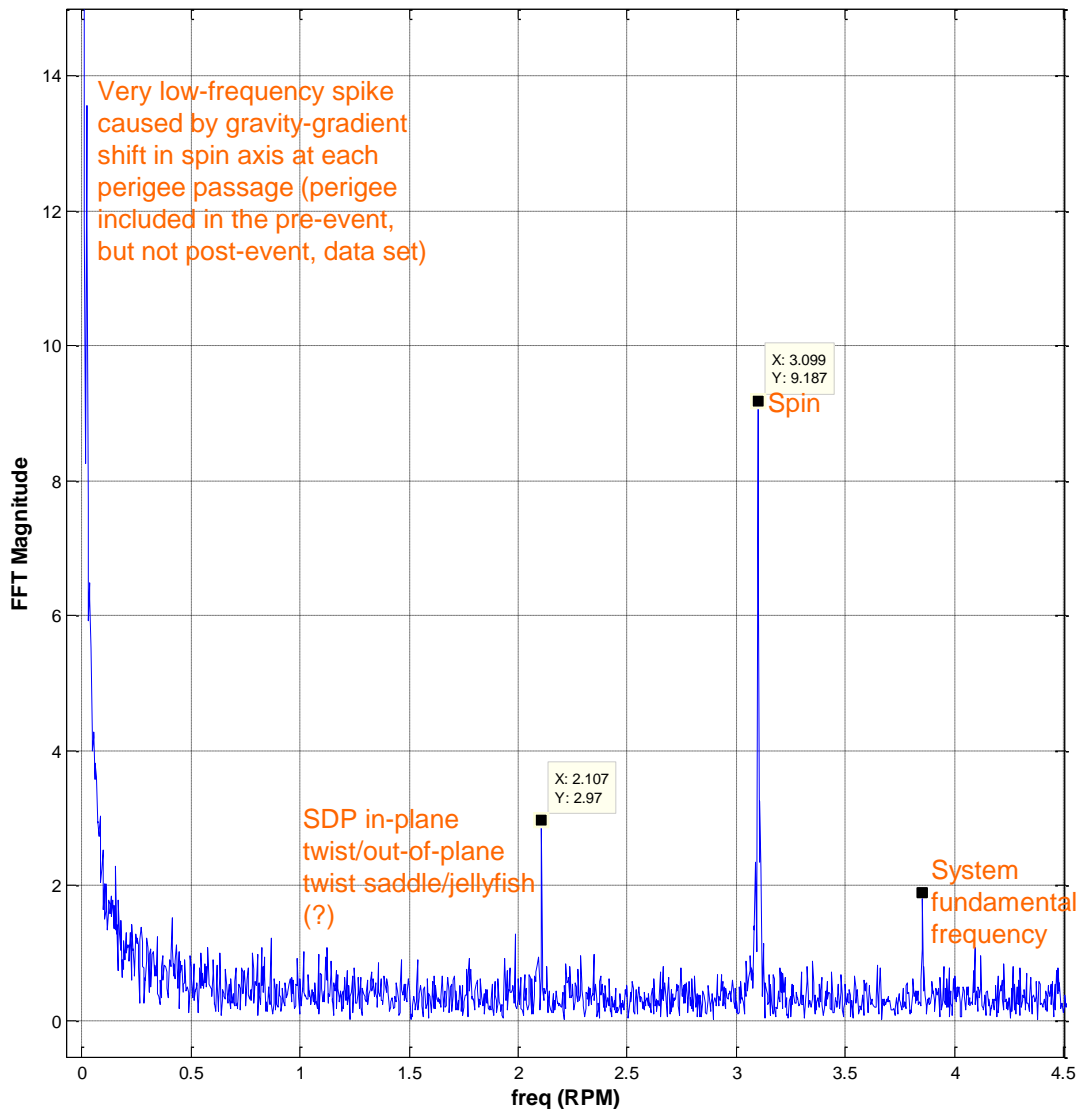




# FFT of Pointing Angle Before Event



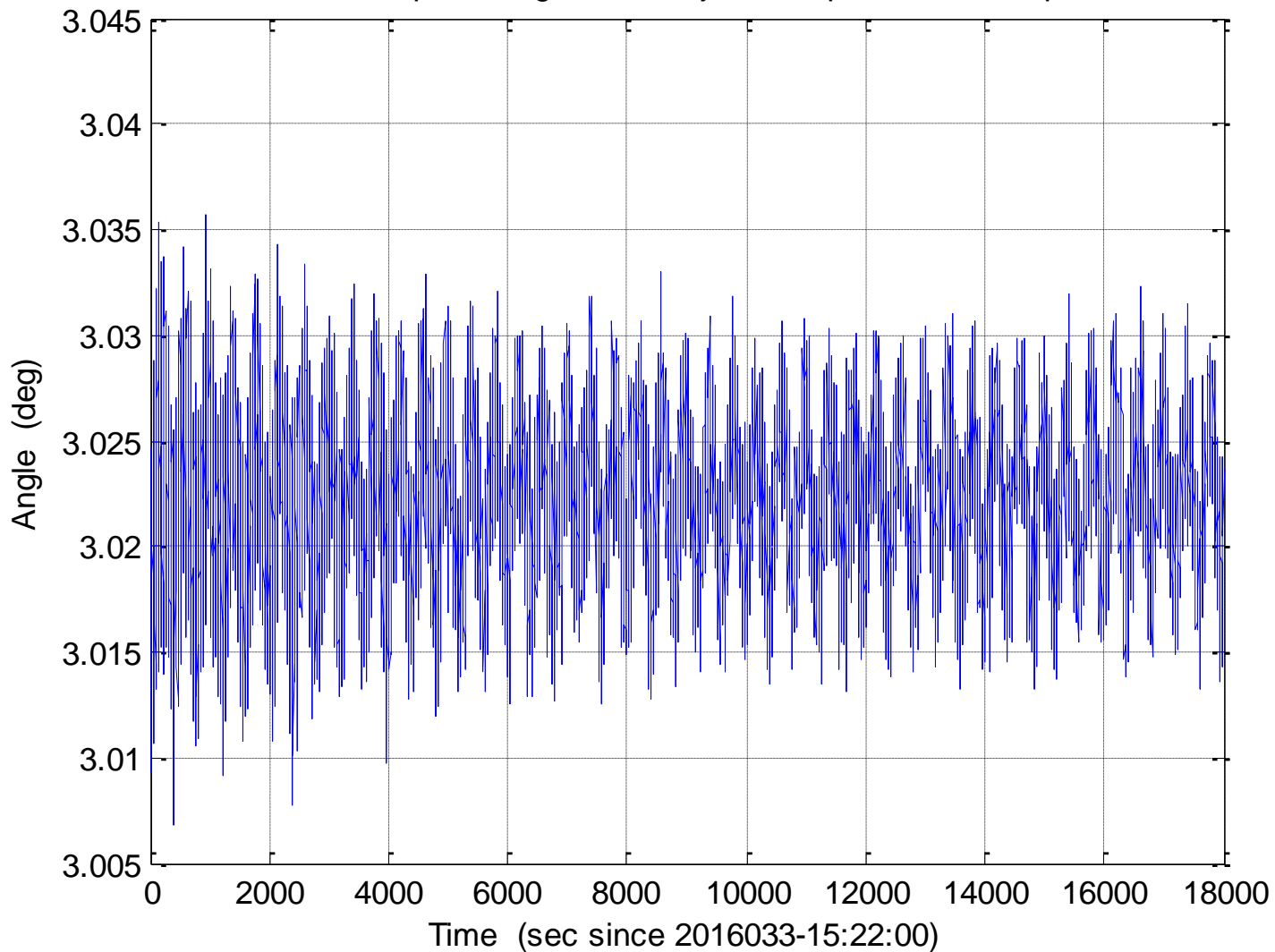
Magnitude of FFT of Angle Between MMS4 Principal Axis and Ecliptic Pole





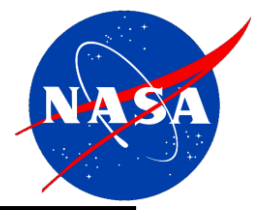
# Pointing Angle After Event

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

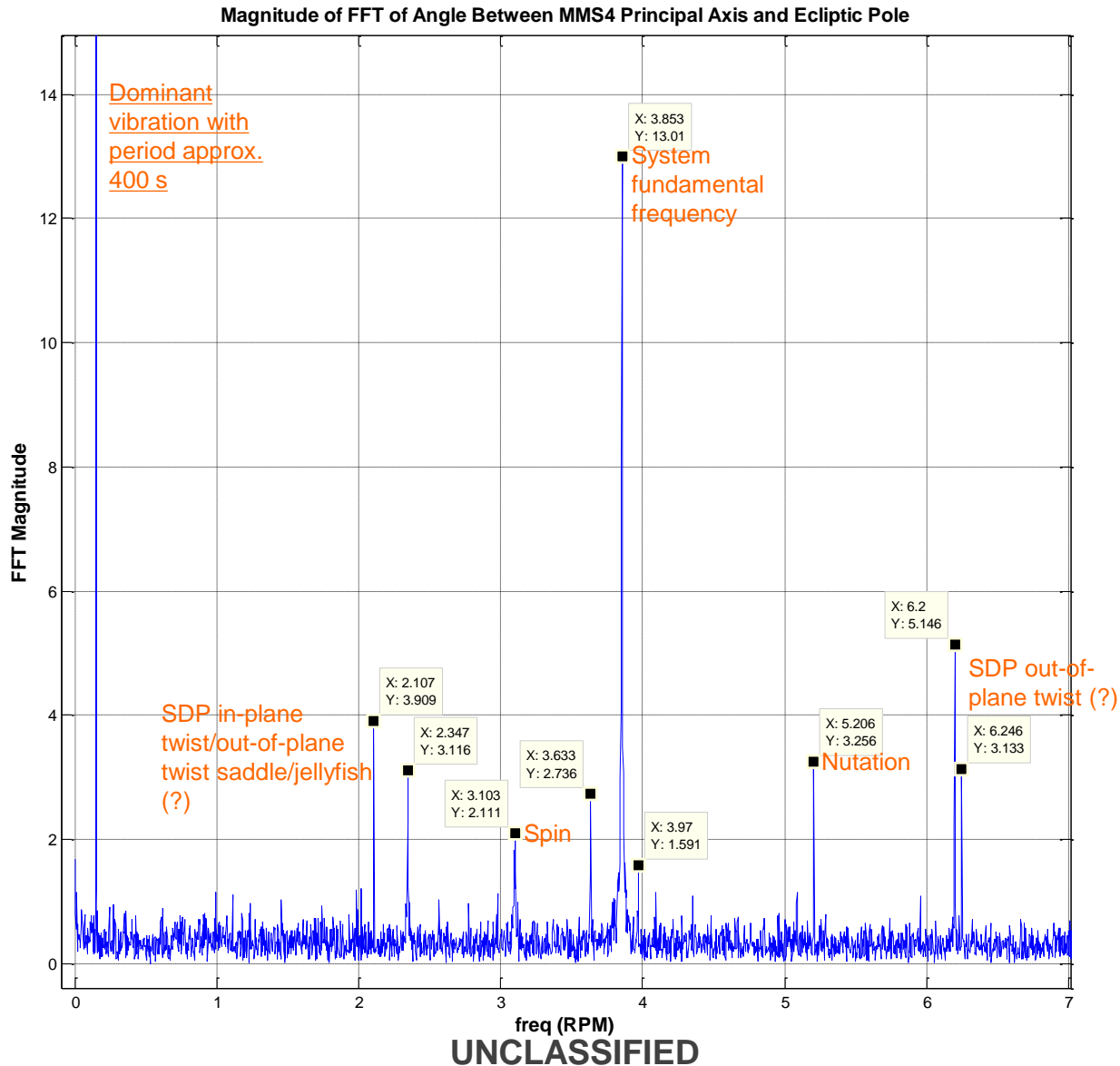


Vibration with  
period of ~400 s  
dominates  
response





# 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\*

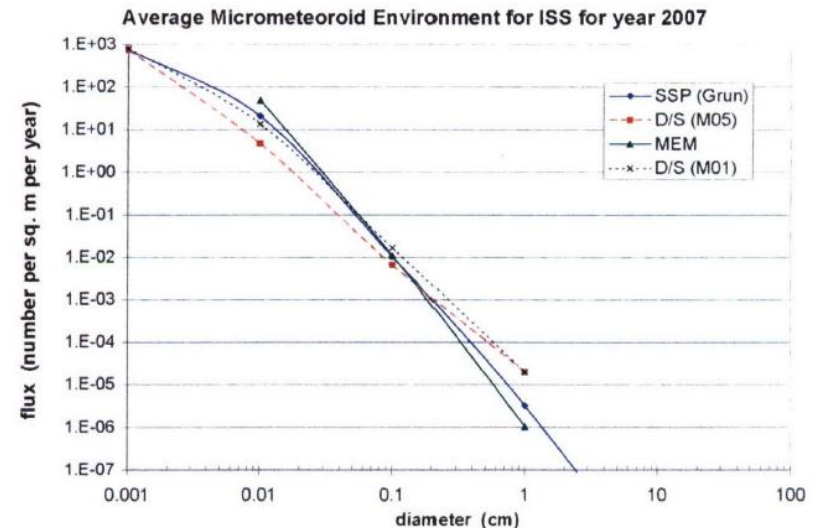
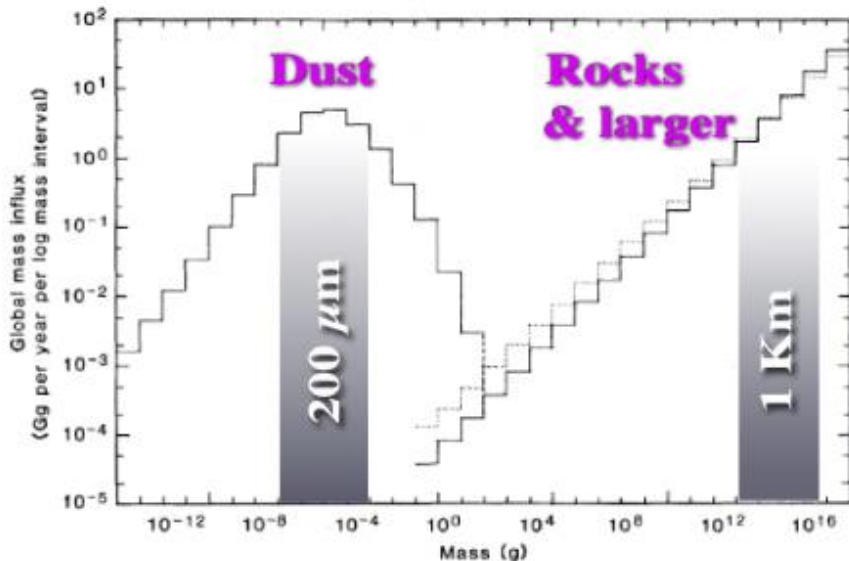


Figure 2. Micrometeoroid particle fluxes from various models.

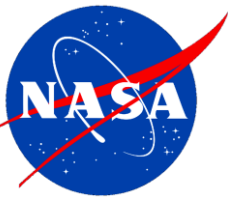
\* Fig. 2, "Micrometeoroid and Orbital Debris Environments for the International Space Station", Peterson and Lynch, 2008

## 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\*:

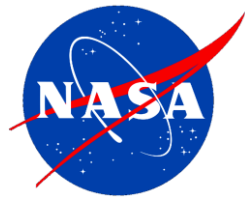


- Representative MLI layer density  $40 \text{ gm/m}^2$ ; area/mass  $25 \text{ m}^2/\text{kg}$



# Particle Mass, Kinetic Energy Estimates

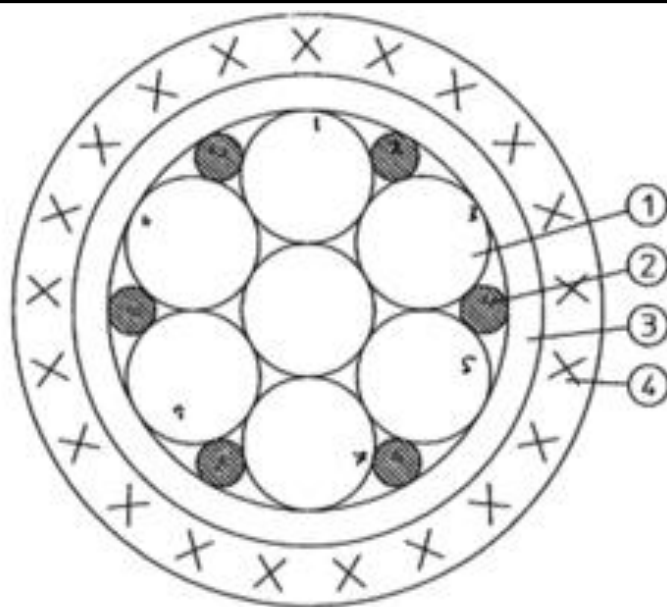
- Linear momentum of impactor must produce observed change in spin axis direction of 0.00157 deg
- Mass, KE estimates differ for the two candidate particle sources, as a result of the different relative speeds between particle and MMS4
- Micrometeoroid:
  - “Typical” relative speed 15 km/s (very wide variation is possible)
  - Resulting estimated particle mass  $8.48 \times 10^{-3}$  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  $\sim 4.292$  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<sup>2</sup>, this yields an area of  $7.41 \times 10^{-4}$  m<sup>2</sup>, 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, either of these candidate sources is possible



# MMS4 Wire Boom Impact Event

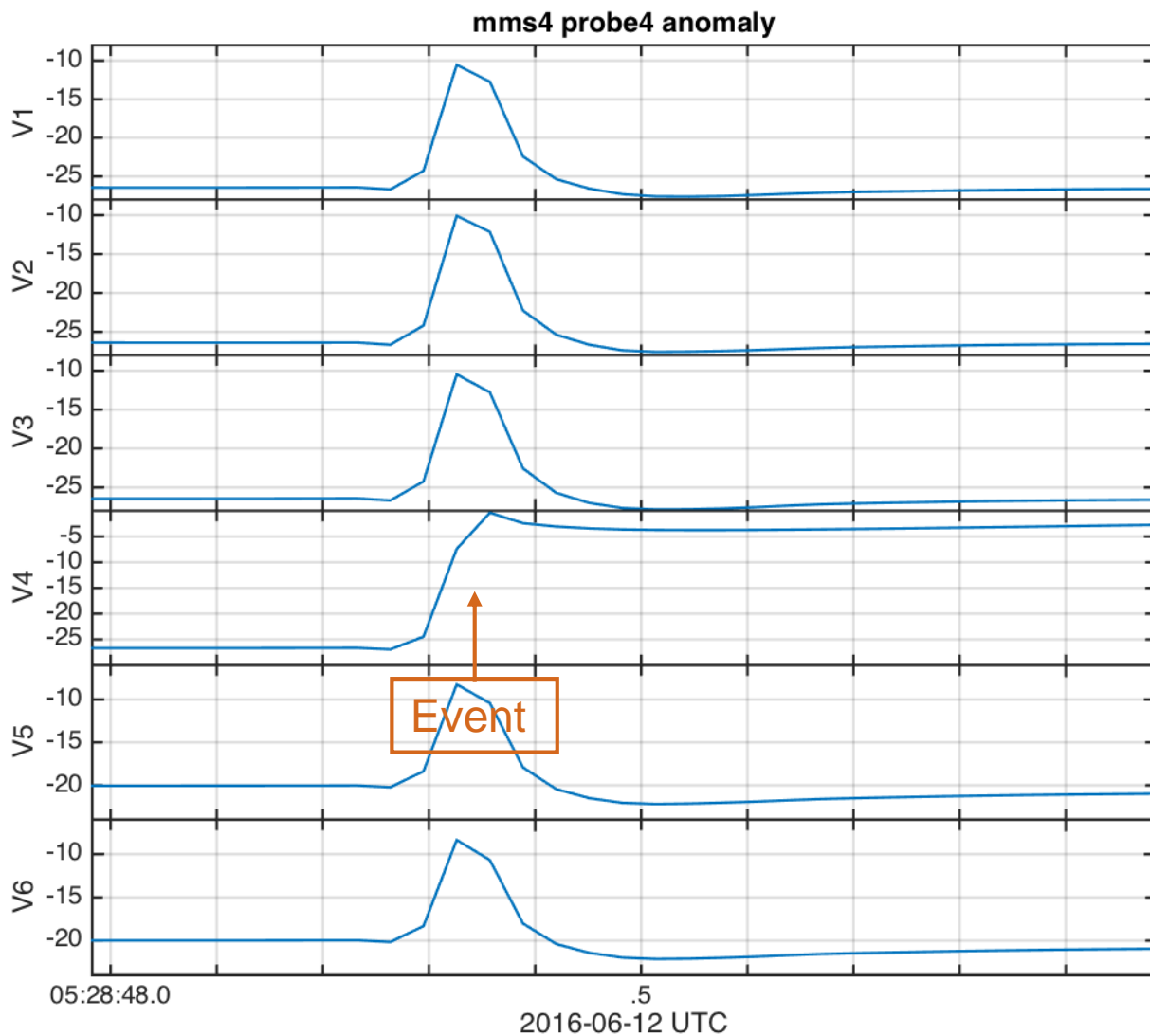
- Various particles and fields science spacecraft, like MMS spinners equipped with long wire booms, have experienced tip mass losses: e.g. THEMIS-B, IMAGE
- These events, which are generally not catastrophic to the spacecraft, could potentially have been caused by instrument design or workmanship issues. However, they have been found to be correlated with passage through meteor showers. They are therefore now thought to be caused by micrometeoroid impacts
- MMS4 (again) experienced an event of this type on June 12, 2016 at 05:28:48.3 UTC. Evidence:
  - Disruption of data from Spin-plane Double Probe (SDP) 4, the electric field sensor at the end of one of the four 60-m long wire booms. Data from the other three SDPs, and the two Axial Double Probes (ADPs), experienced transients at the same time but then recovered
  - Small transient in spin rate as derived from Digital Sun Sensor (DSS)
- Subsequent data was degraded, but showed that the tip mass was not lost. Rather, one or more of the 7 SDP4 wires was severed
- The dynamic effects were too small to analyze as was done for the shunt resistor case: e.g. event not evident in accelerometer data. Presumably because central body was not impacted directly

# SDP Wire Boom: 7 Signal Wires





# SDP and ADP Fields Data at Event



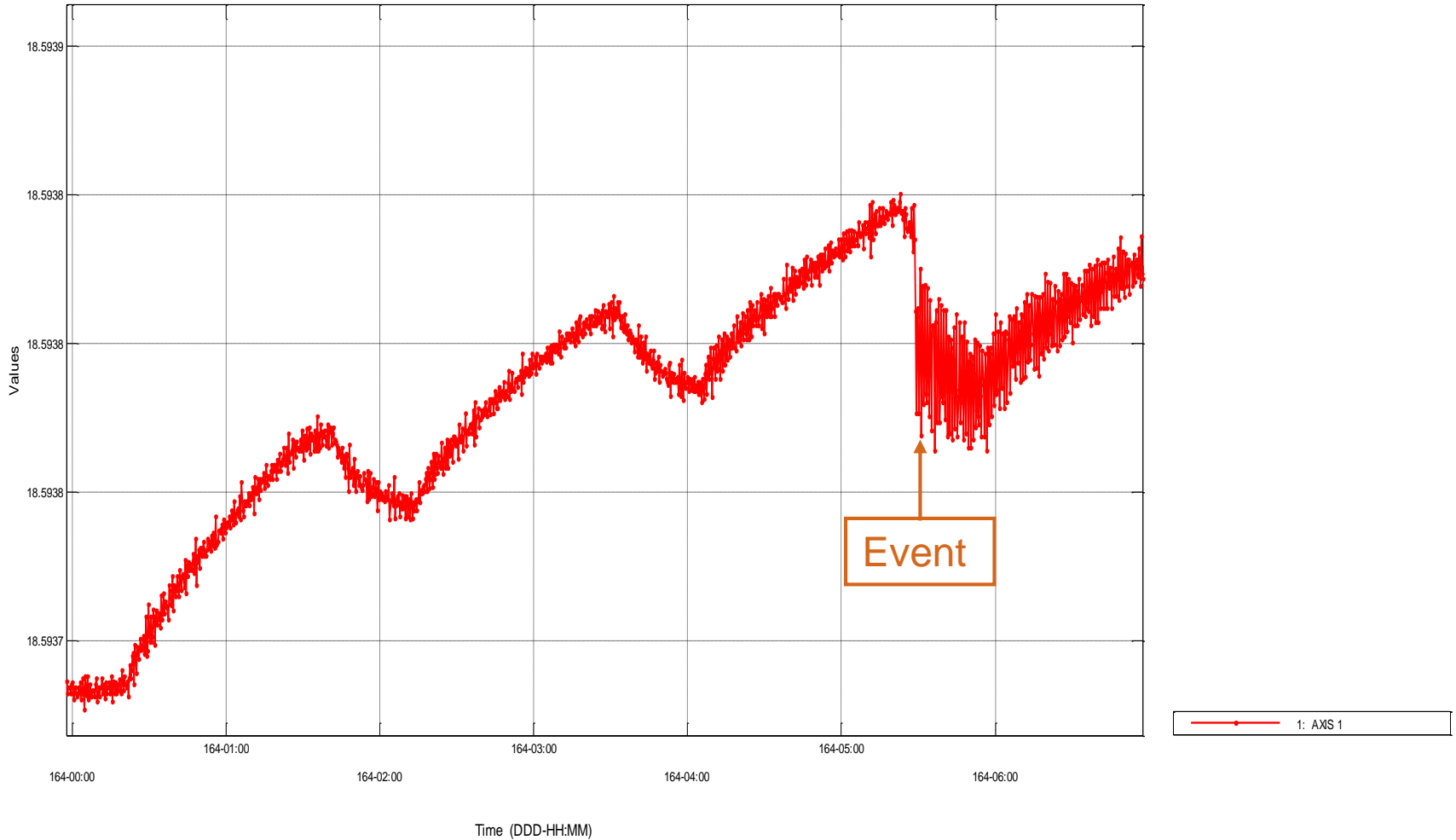


UNCLASSIFIED



# DSS-Derived Spin Rate at Event

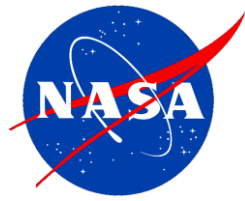
MMS4 Spin Rate from DSS Sun Pulse Times



2016-163 23:57:47.106

2016-164 06:57:24.900





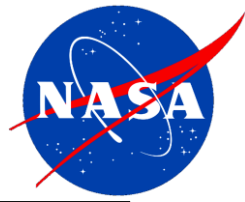
# Conclusions

- The four MMS spacecraft fly on highly eccentric orbits, passing from somewhat above low-Earth orbit to well above the geosynchronous ring
- These spacecraft are highly instrumented. In particular, they have accelerometers that are always collecting data
- There have been two confirmed impacts from micrometeoroid/orbital debris in the nearly three years that MMS has been on orbit. Both of these led to only minor damage to the spacecraft, and essentially no loss in functionality
- In addition, extensive accelerometer data has been collected throughout the mission. This will, as time permits, be analyzed to determine statistics for the smaller impacts that have presumably occurred in the various orbital regimes that MMS passes through
- The spacecraft have Orbital Debris Shields (ODSs) on their upper and lower faces, with the sides protected by an extensive thrust tube structure. There is therefore little likelihood of severe damage from any future impacts

UNCLASSIFIED

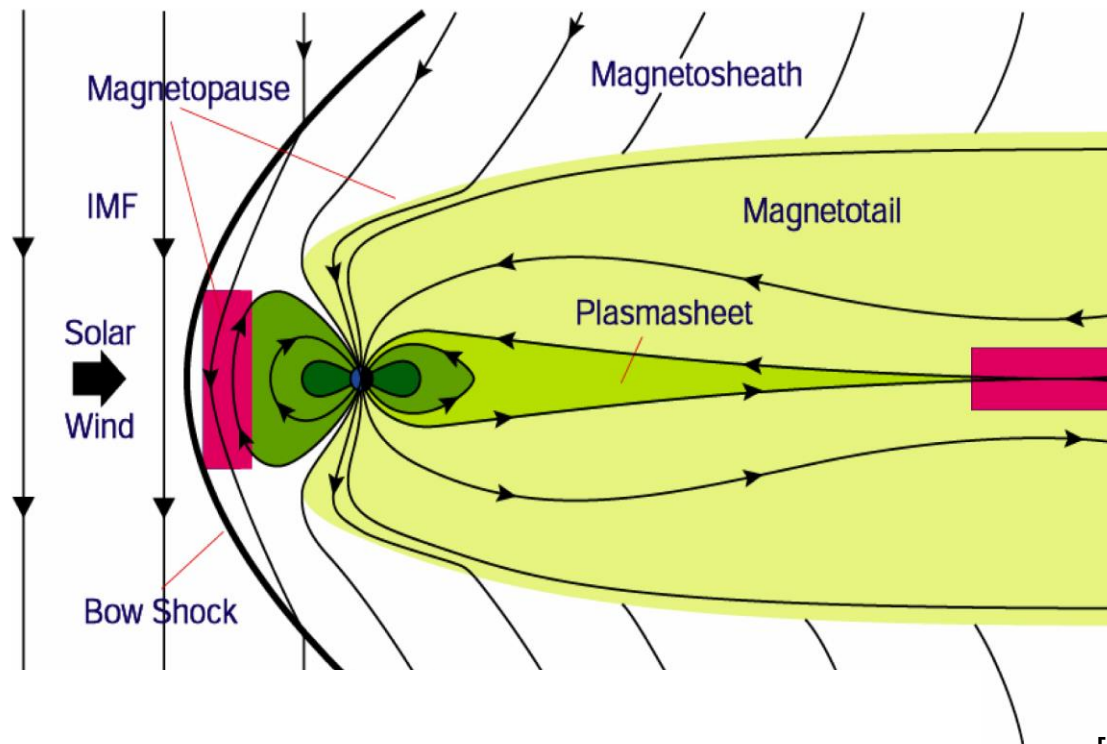
# Backup Material

---



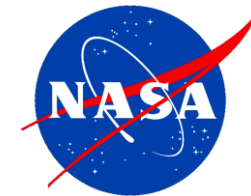
# The “Magnetospheric Laboratory”

*Collisionless reconnection “laboratory”*



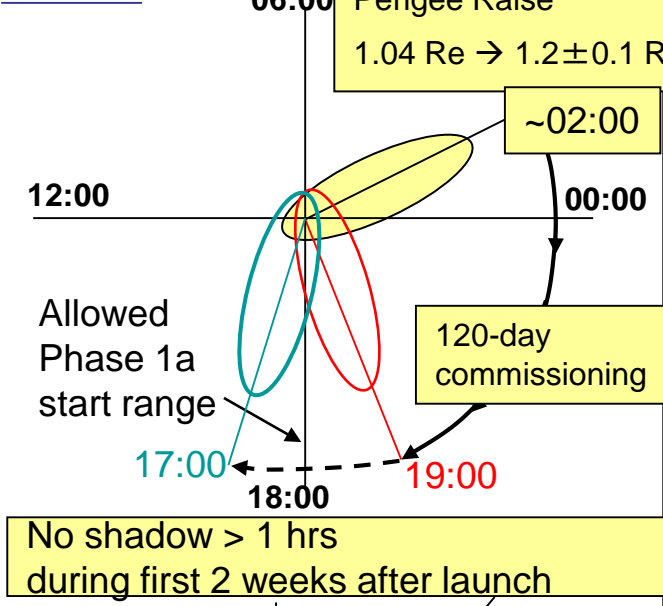
[Nakamura, 2006]

- Most easily accessible place in space where in-situ observation of both plasma and fields can be performed to probe the energy release and magnetic reconfiguration process of reconnection

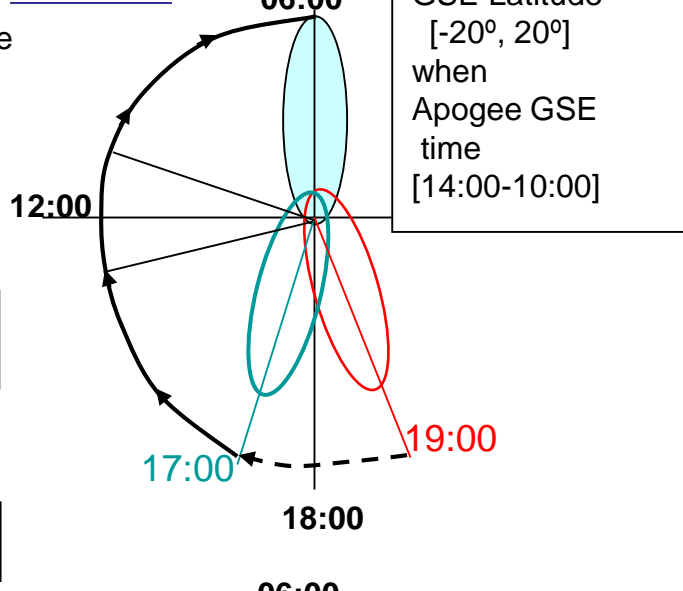


# MMS Mission Orbit Phases

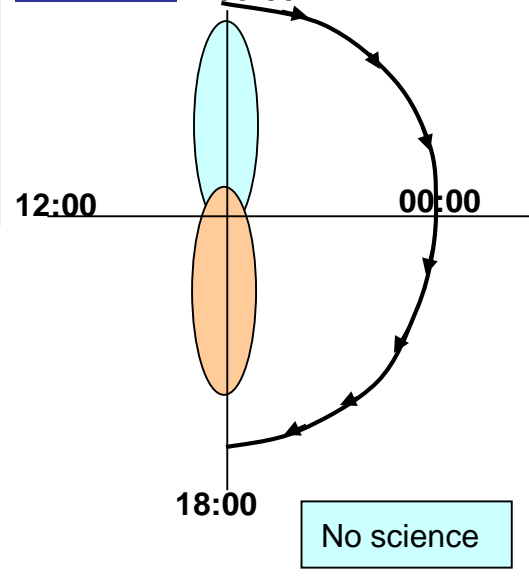
## Phase 0



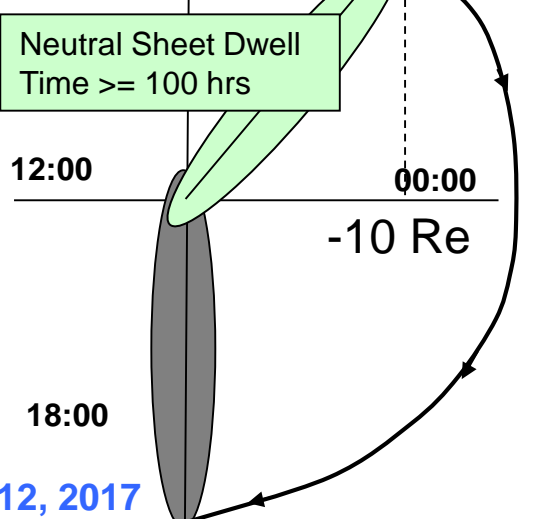
## Phase 1a



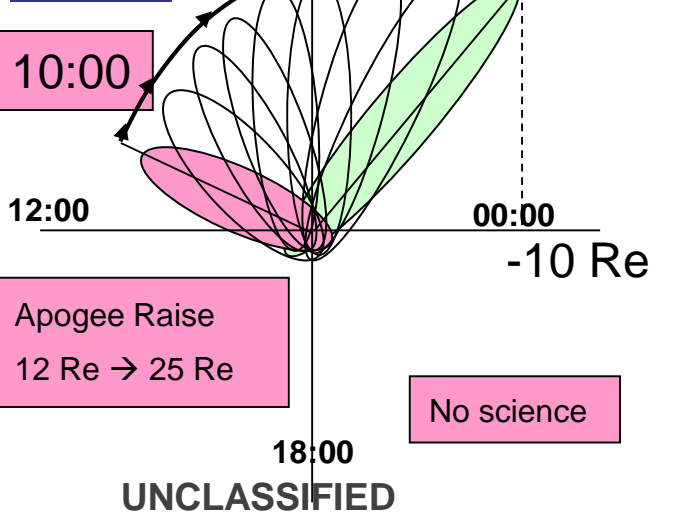
## Phase 1x



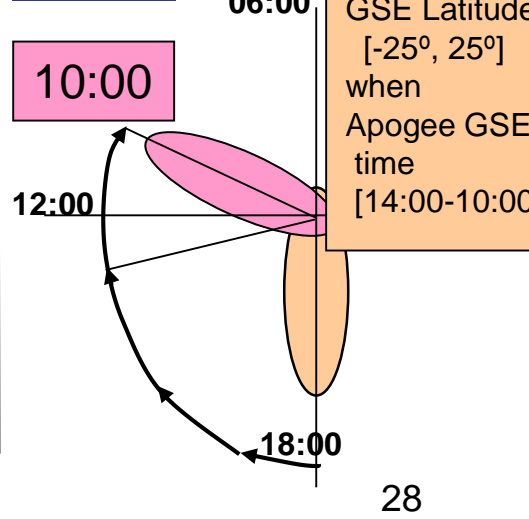
## Phase 2b



## Phase 2a



## Phase 1b



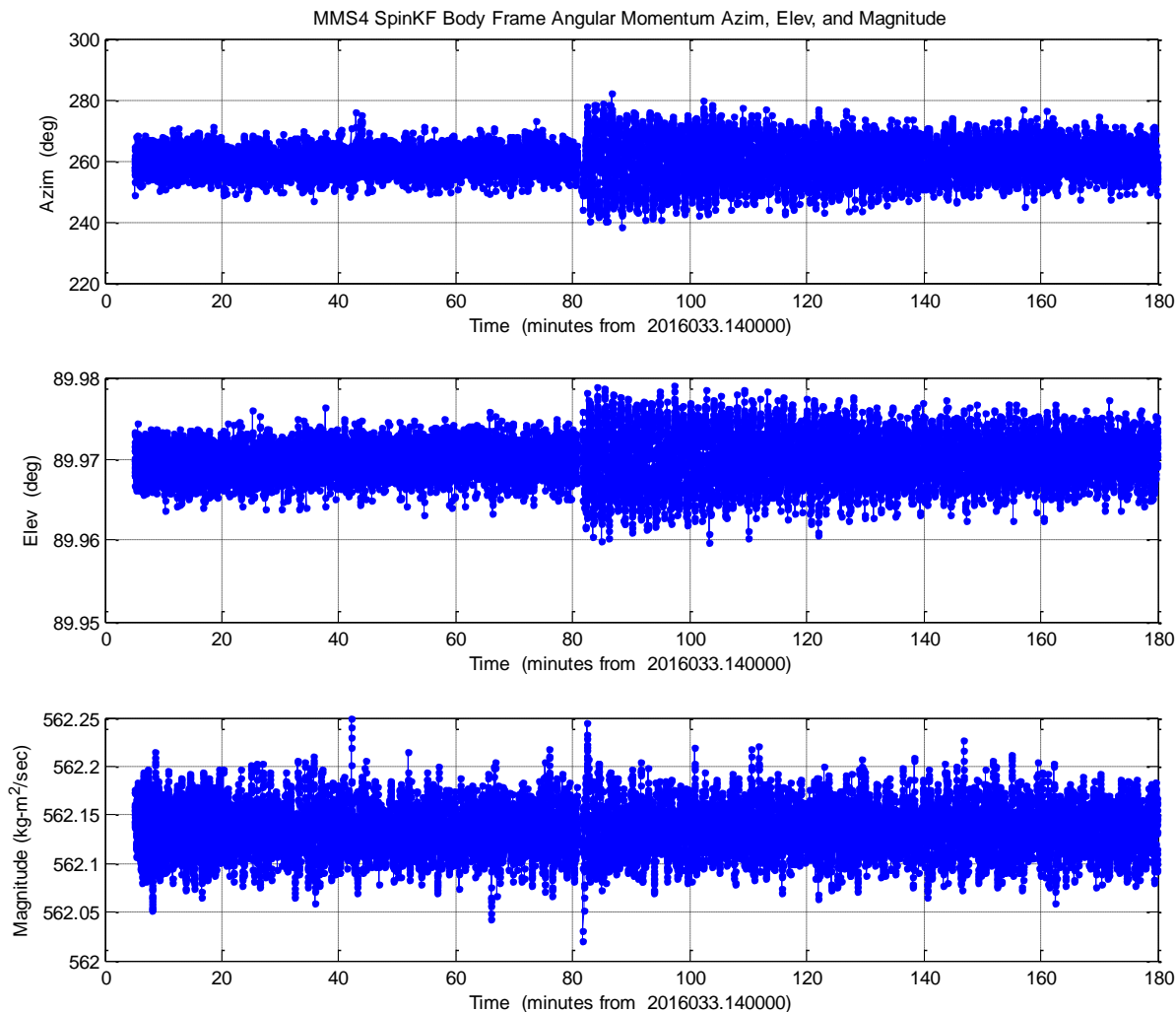


# Angular Momentum, Shunt Event



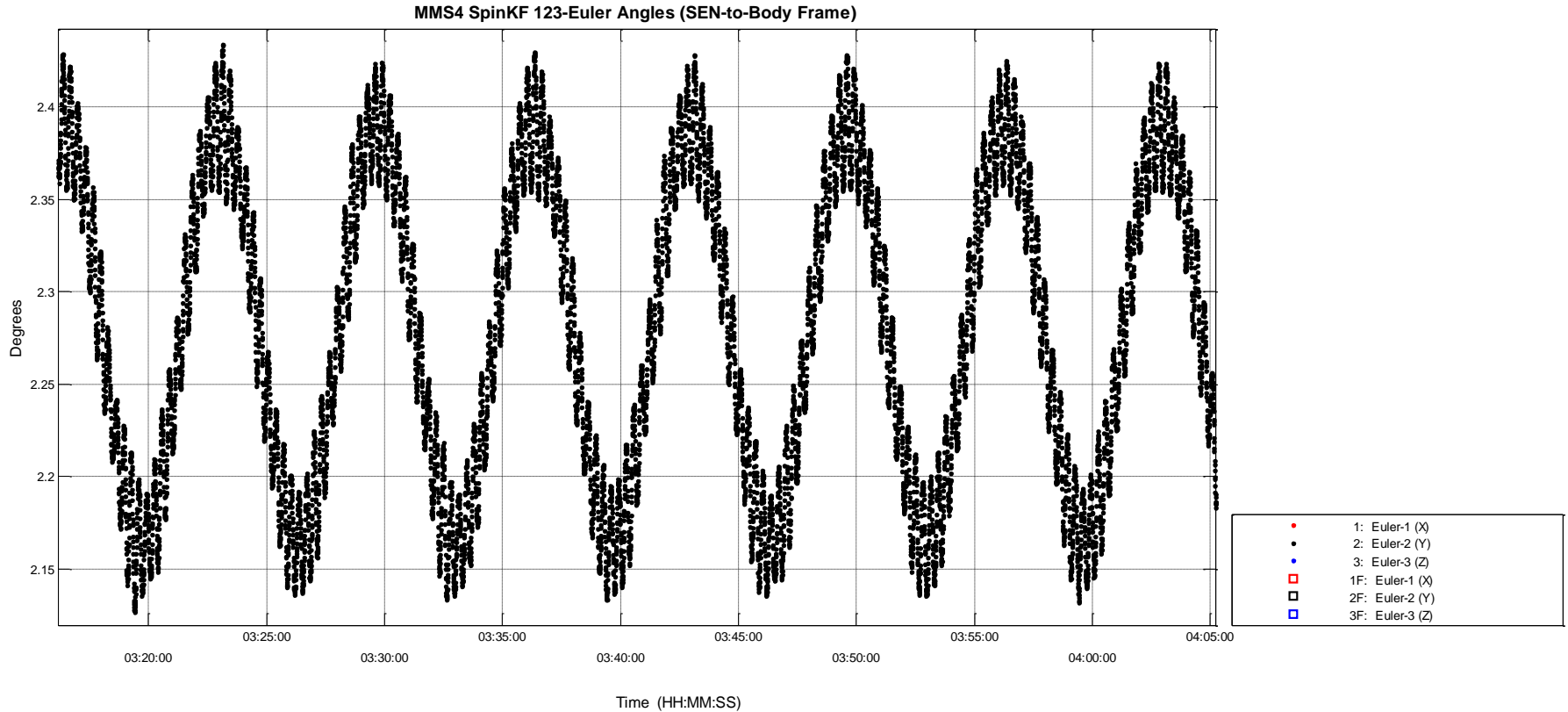
*Transverse:*  
Nutation/boom  
vibration evident

*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