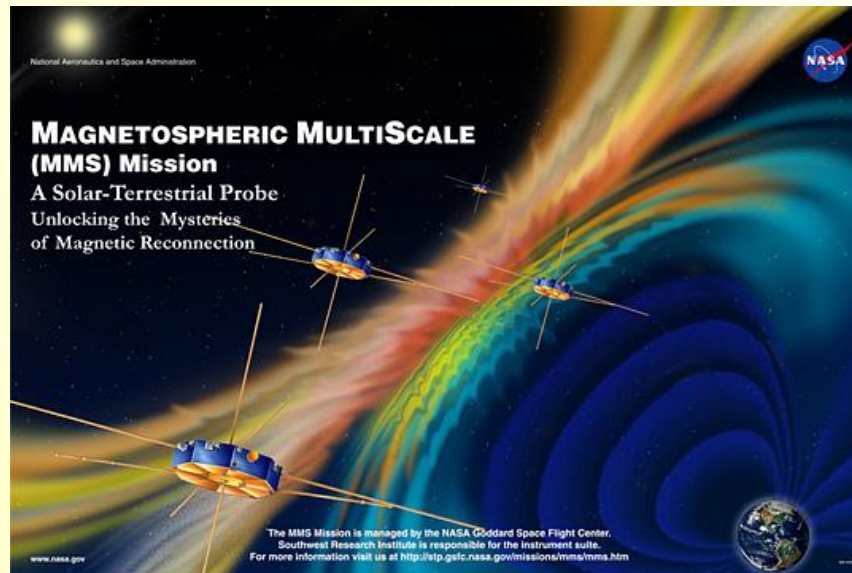


Initial Satellite Formation Flight Results from the Magnetospheric MultiScale Mission

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¹NASA/Goddard Space Flight Center, and ²a.i. solutions, Inc.



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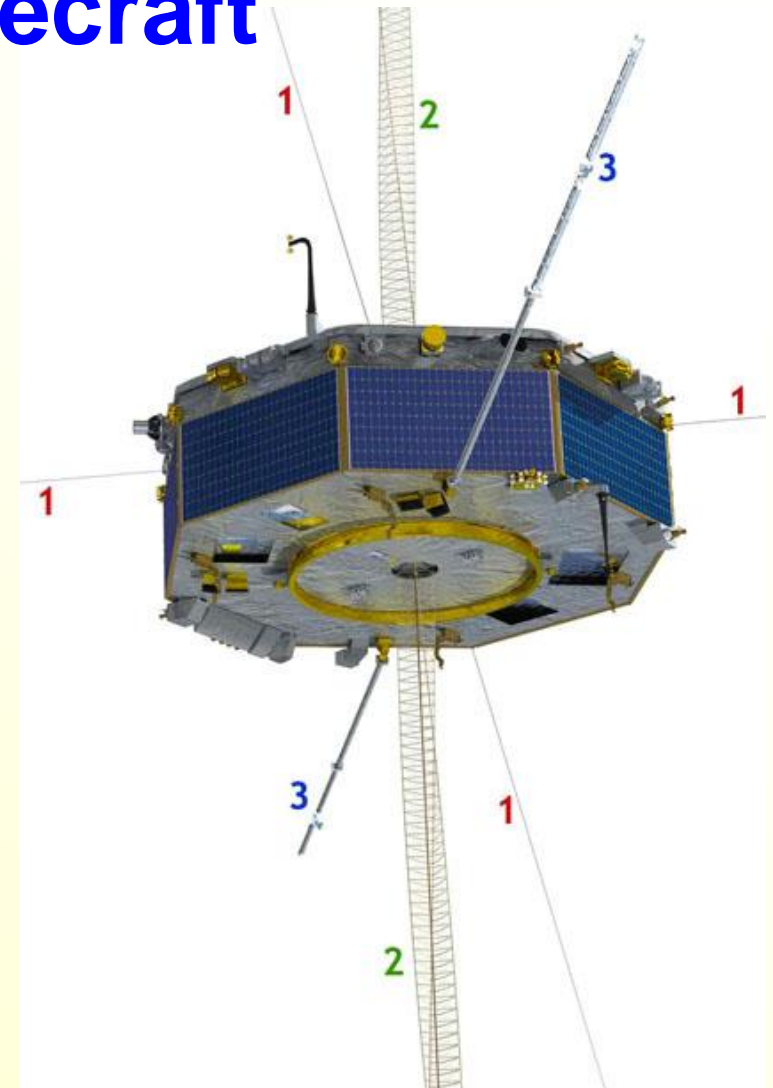
Introduction

- MMS Formation Flying Dynamics
- MMS Onboard Navigation System
- Formation Maneuver Design Process
- Formation Maneuver Execution Process
- Formation Maneuver Results



MMS Spacecraft

- Width: 3.15 m
- Height: 1.23 m
- Weight: ~ 1,290 kg
- SDP-Wire Booms (x4): 60 m
- ADP-Antenna Mast (x2): 14.75 m
- Magnetometer Booms (x2): 5 m



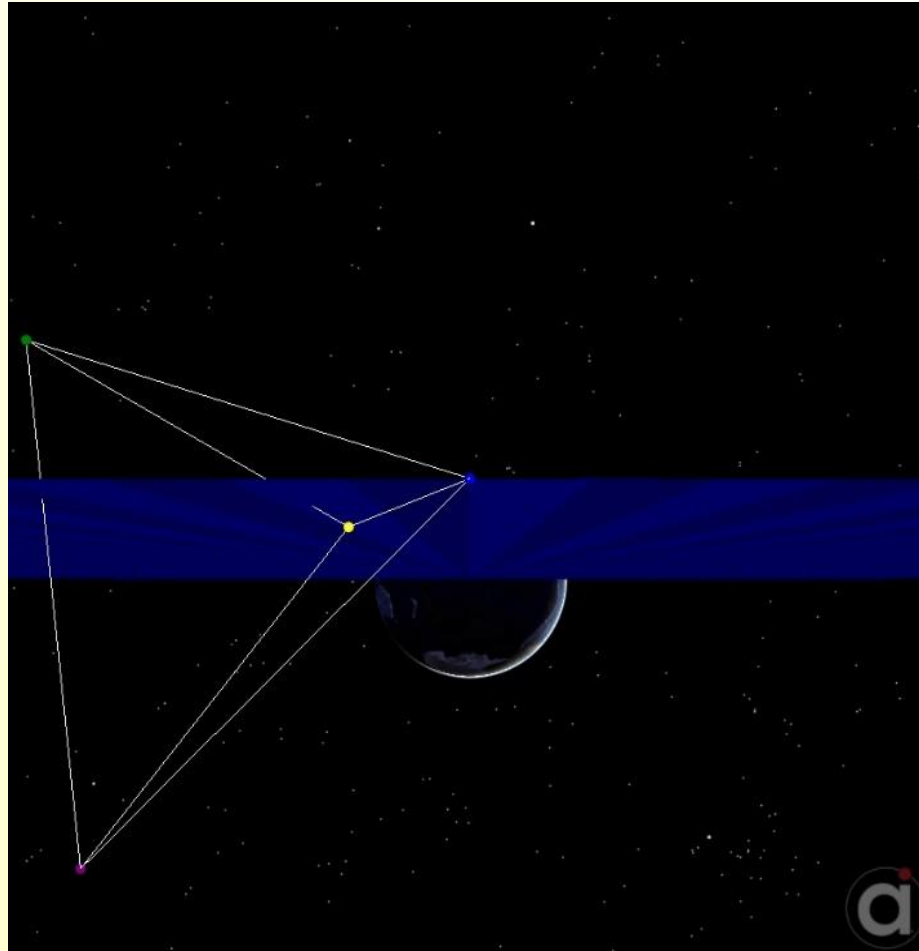
1.SDP-Wire Booms

2.ADP-Antenna Masts

3.Magnetometer Booms

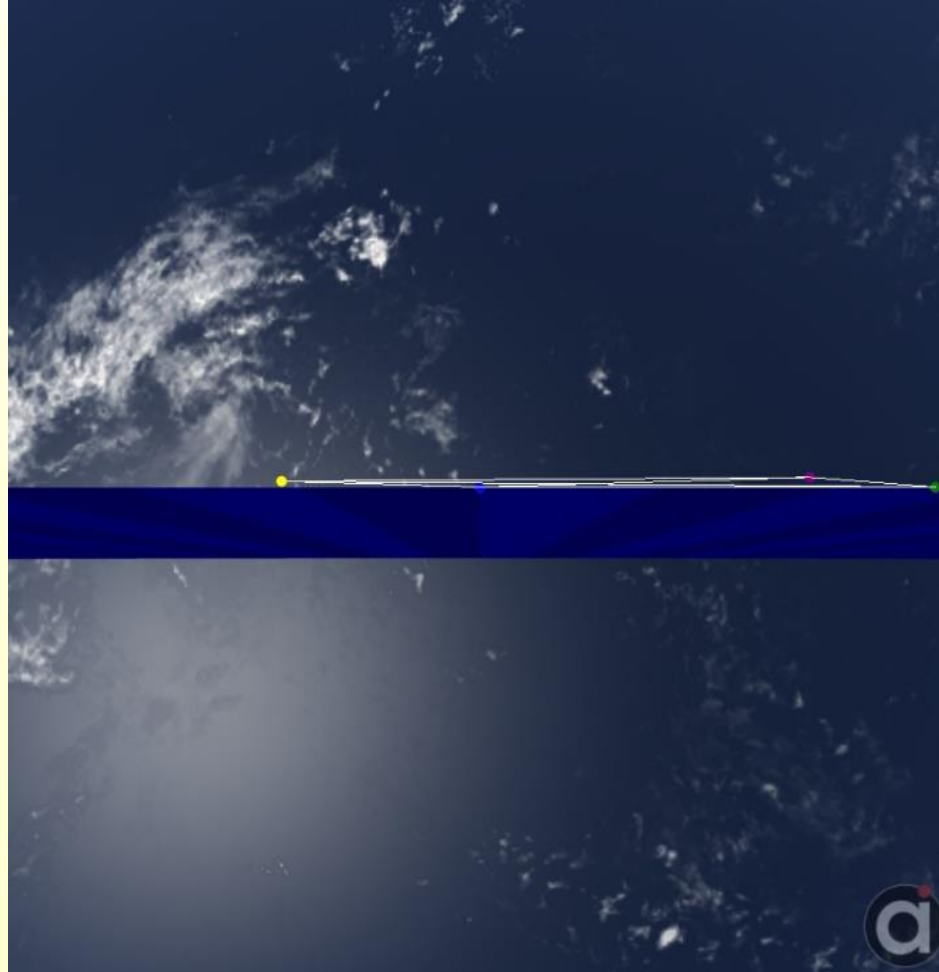


Formation at Apogee





Formation at Perigee



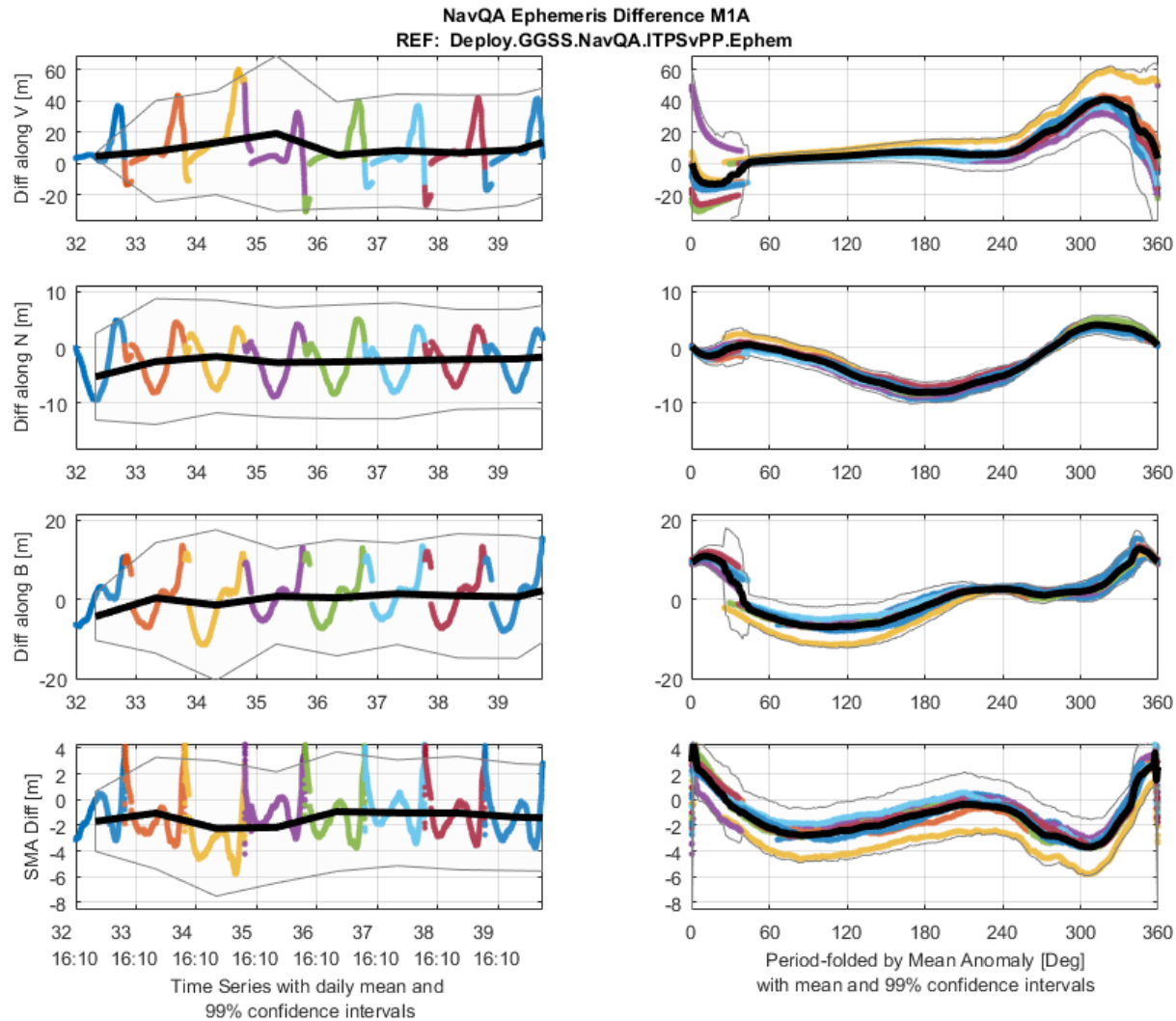


MMS Onboard Nav System: GEONS

- GEONS processes GPS L1 signals in an Extended Kalman Filter (EKF) and uses a high-fidelity dynamics model to estimate the spacecraft's position, velocity, clock bias with respect to GPS time, clock bias rate, and clock bias acceleration.
- GEONS predictive performance and maneuver planning capability were evaluated by comparing definitive data with the predictive solutions generated in FreeFlyer 6.9.1.

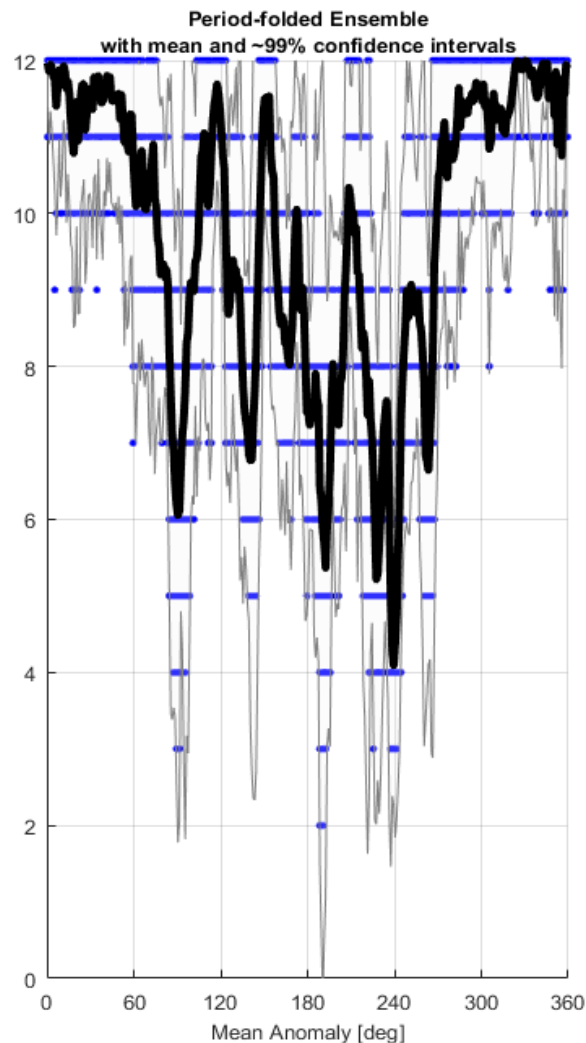
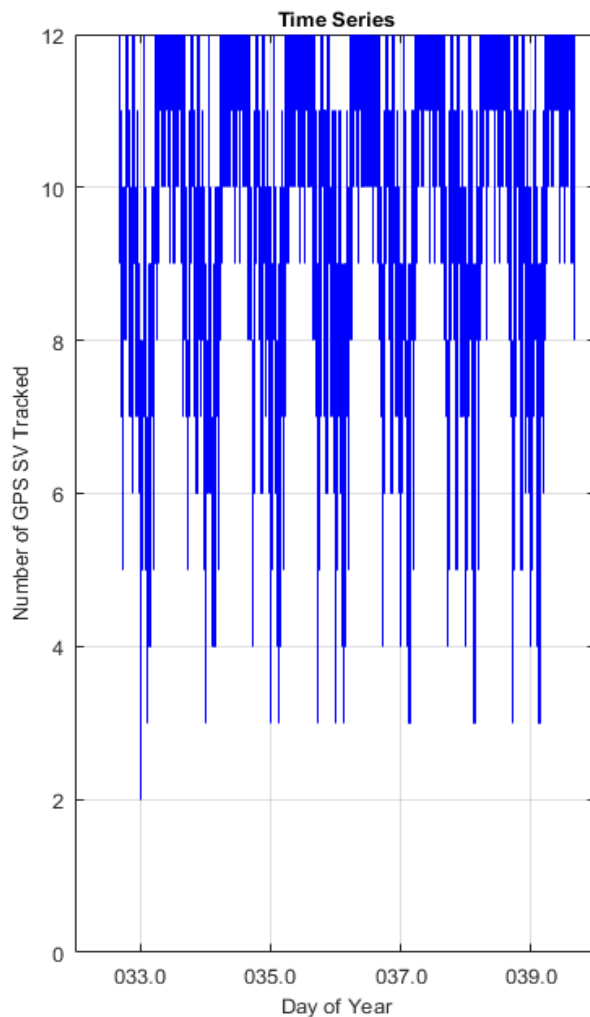


GEONS vs Predicted Solutions Differences





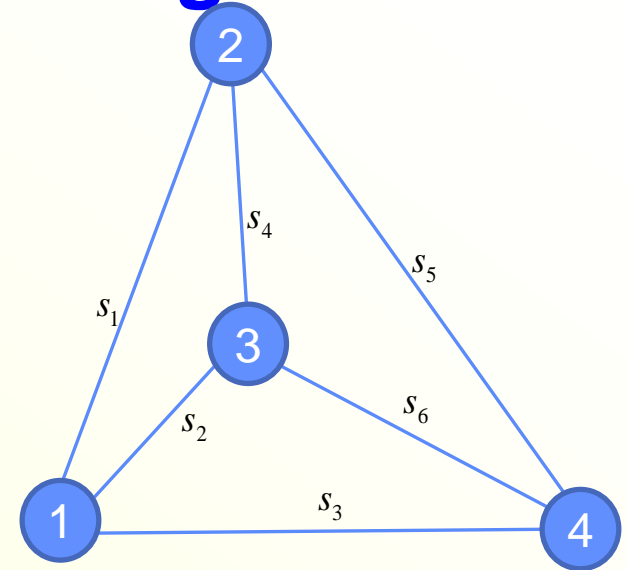
Number of GPS Space Vehicles Tracked





Formation Maneuver Design

- Target formation has shape of a regular tetrahedron in the region-of-interest (ROI) (TA ~160-200 deg)
- Instantaneous quality factor $Q(t) \in [0,1]$ which is a product of two terms
 - $Q_s(t)$ associated with scale size (allows for 'breathing')
 - $Q_v(t)$ measures how close the shape is to a regular tetrahedron
- Science requirement T_Q , the time the formation spends in the ROI with a $Q(t)$ above 0.7
 - $T_Q \in [0,100]$; Current science requirement is to have $T_Q > 80$, on average, for each mission phase



$$Q(t_i) = Q_s(t_i) Q_v(t_i)$$

shape volume

$$T_Q = \frac{100}{N_{ROI}} \sum_{i=1}^{N_{ROI}} M_i \quad \text{where} \quad \begin{cases} M_i = 1 & \text{if } Q(t_i) \geq 0.7 \\ M_i = 0 & \text{if } Q(t_i) < 0.7 \end{cases}$$



Formation Man. Execution Process (1/2)

- Perform preliminary design of maneuvers
- Decide the staggering sequence and reference spacecraft
- Check the results based on daily OD data and the FDA reruns
- Finalize the staggering sequence; submit this to scheduling/operations
- Deliver preliminary DV tables to GEONS team
- Perform preliminary and then final detailed simulation (using the tool CHiFi) to verify expected fuel use and check that the maneuvers do not violate any spacecraft safety constraints (boom bending moments, etc.)
- Evaluate the effects of the maneuvers on SMA values, orbit planes, QF evolution
- Perform Monte Carlo runs to determine safety in the face of maneuver execution errors, as well as QF lifetime



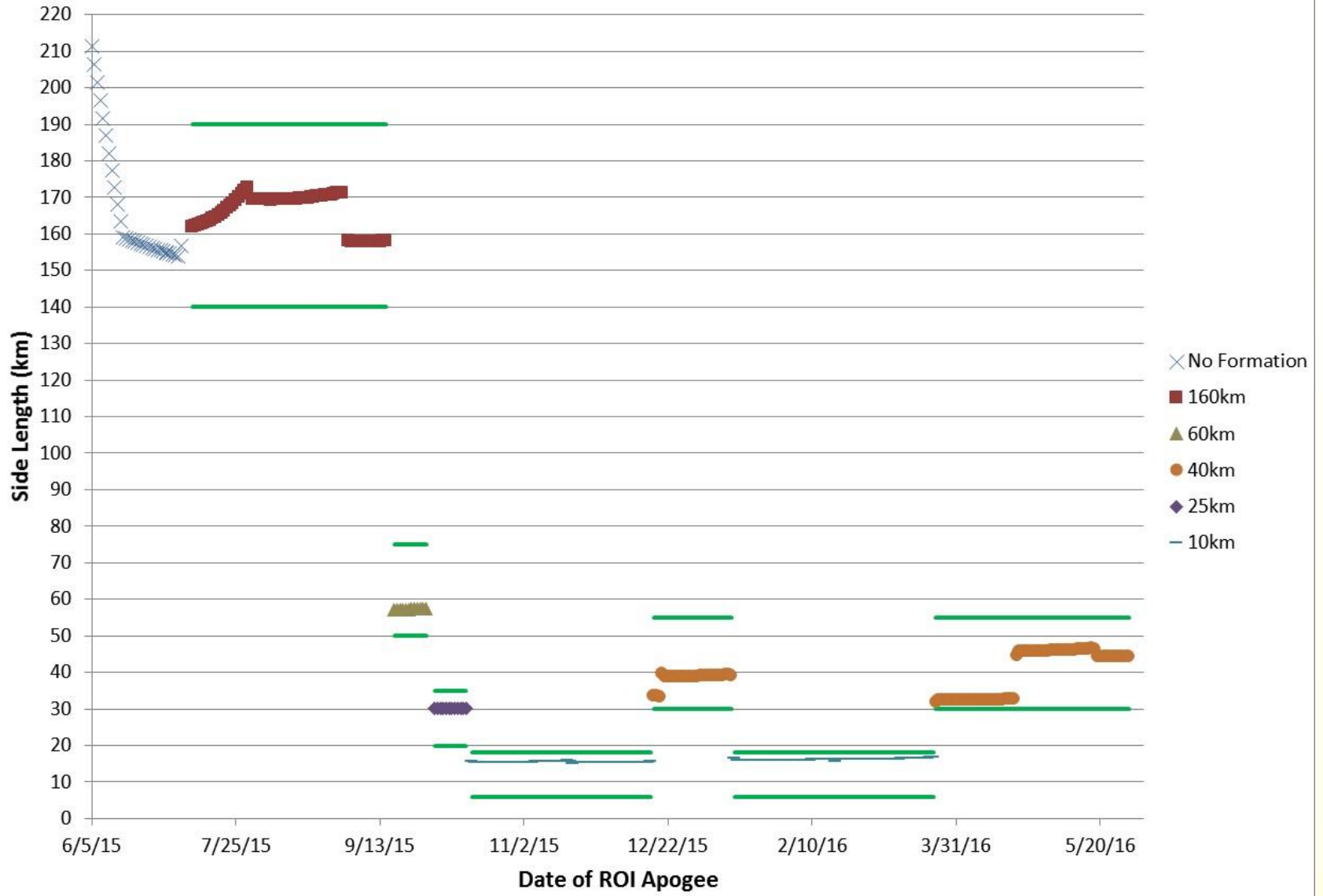
Formation Man. Execution Process (2/2)

- Present results at Command Authorization Meeting (CAM) that is held between the FOT and FDOA teams
- Monitor FM1 burns; reconstruct fuel use and SMA changes from spacecraft data downlinked at end of maneuver pass
- Use the navigation data downlinked at the post-perigee passes to evaluate maneuver errors and determine if tweaking of FM2 is necessary: if so, perform Delta-CAM and upload new maneuver commands
- Monitor FM2 burns; reconstruct fuel use and SMA changes from maneuver pass data
- Use nav data downlinked at the post-perigee passes to evaluate the final formation orbits → initial data for the generation of the next set of maneuvers occurring in 2 or more weeks



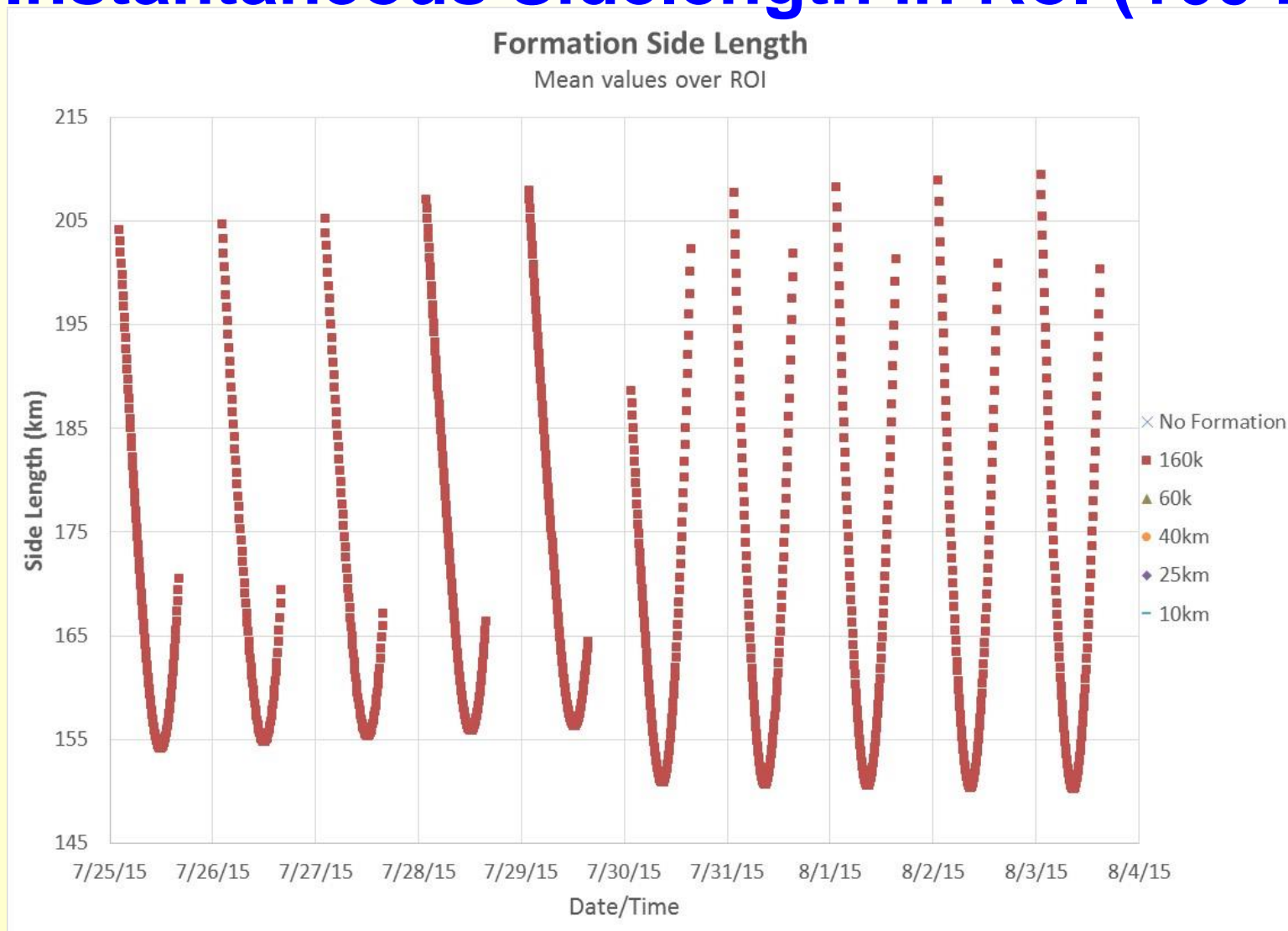
Formation Side Length

Average of Mean values over ROI



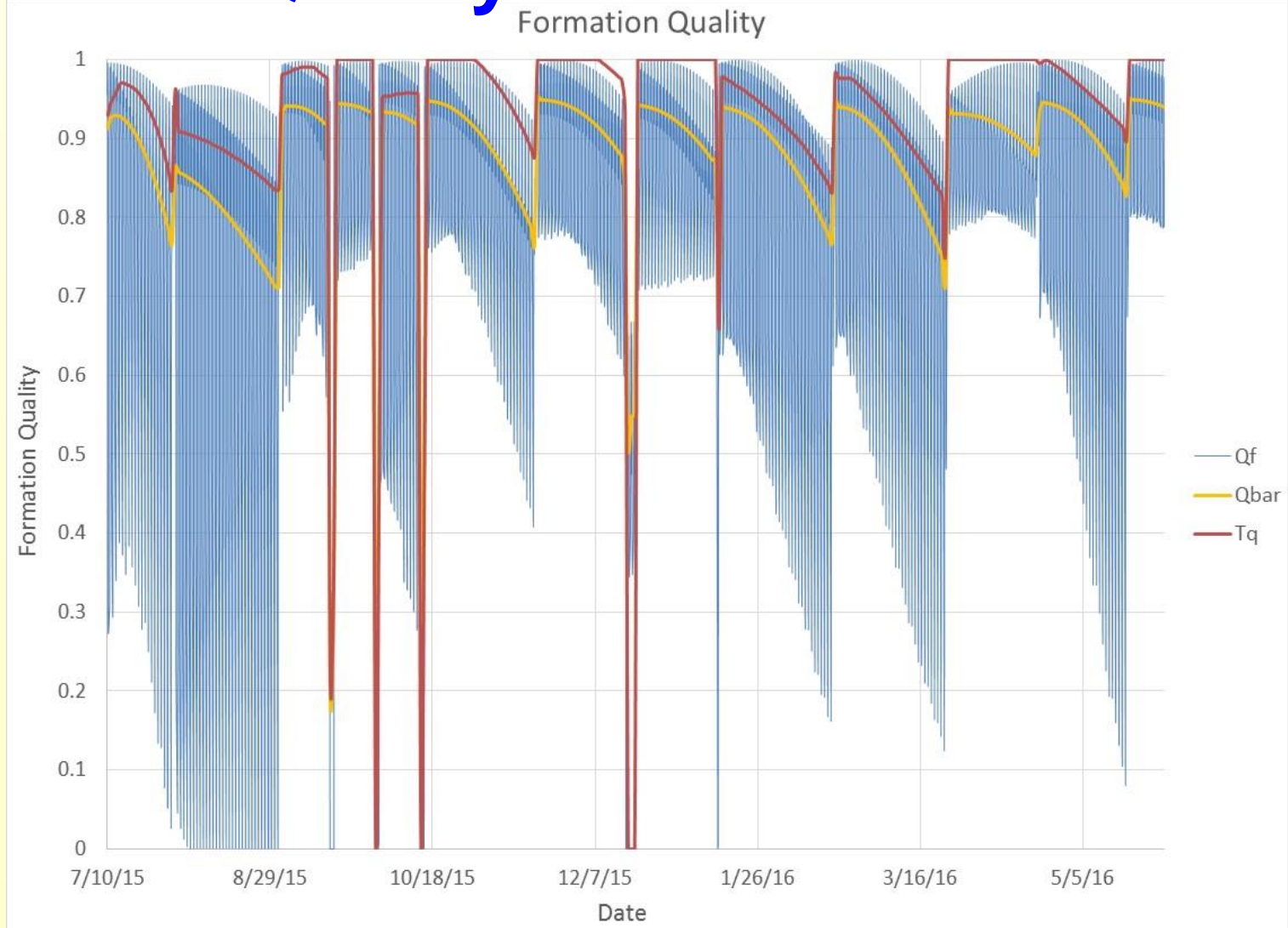


Mean Instantaneous Sidelength in RoI (160 km)



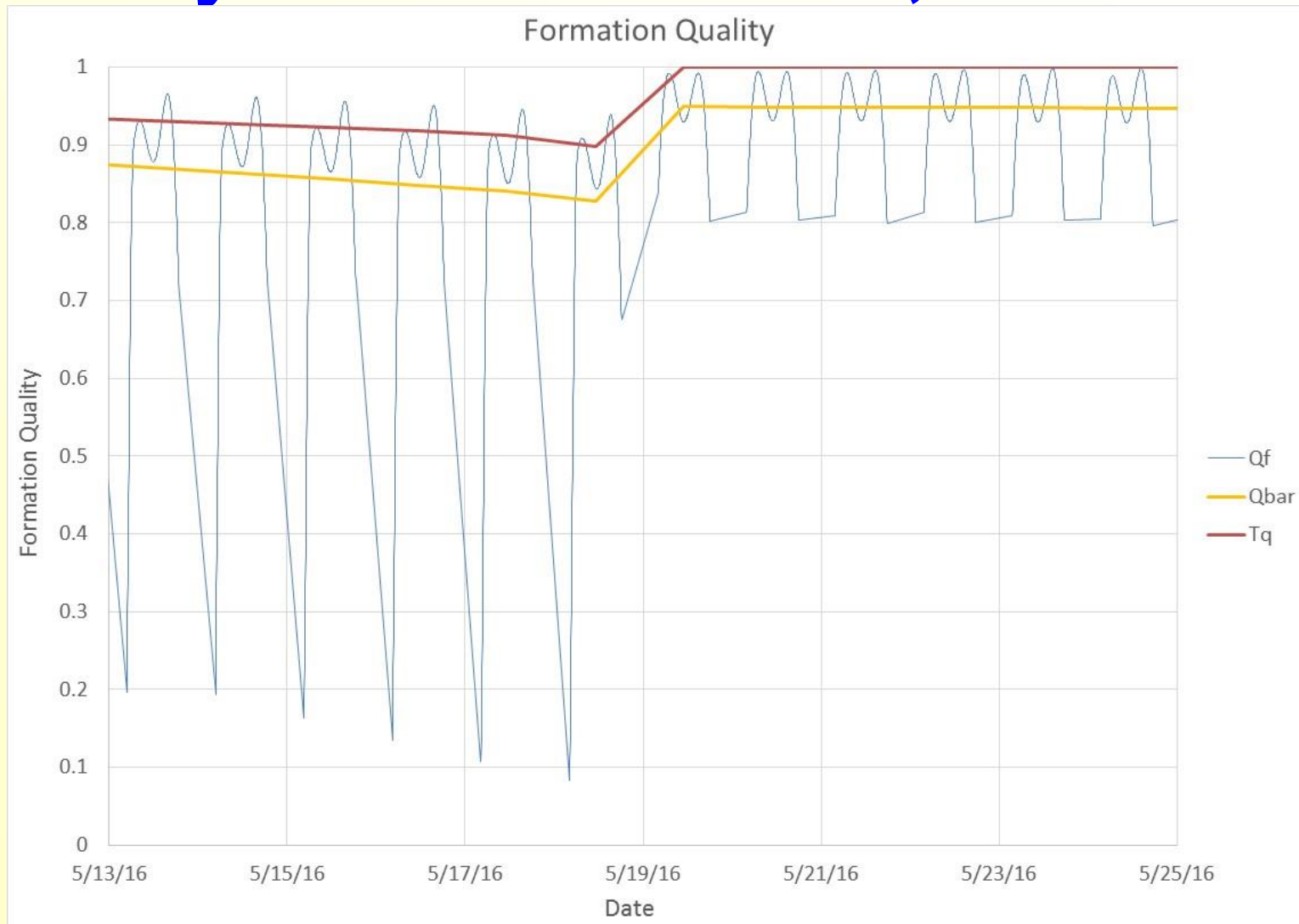


Formation Quality Evolution Over Mission





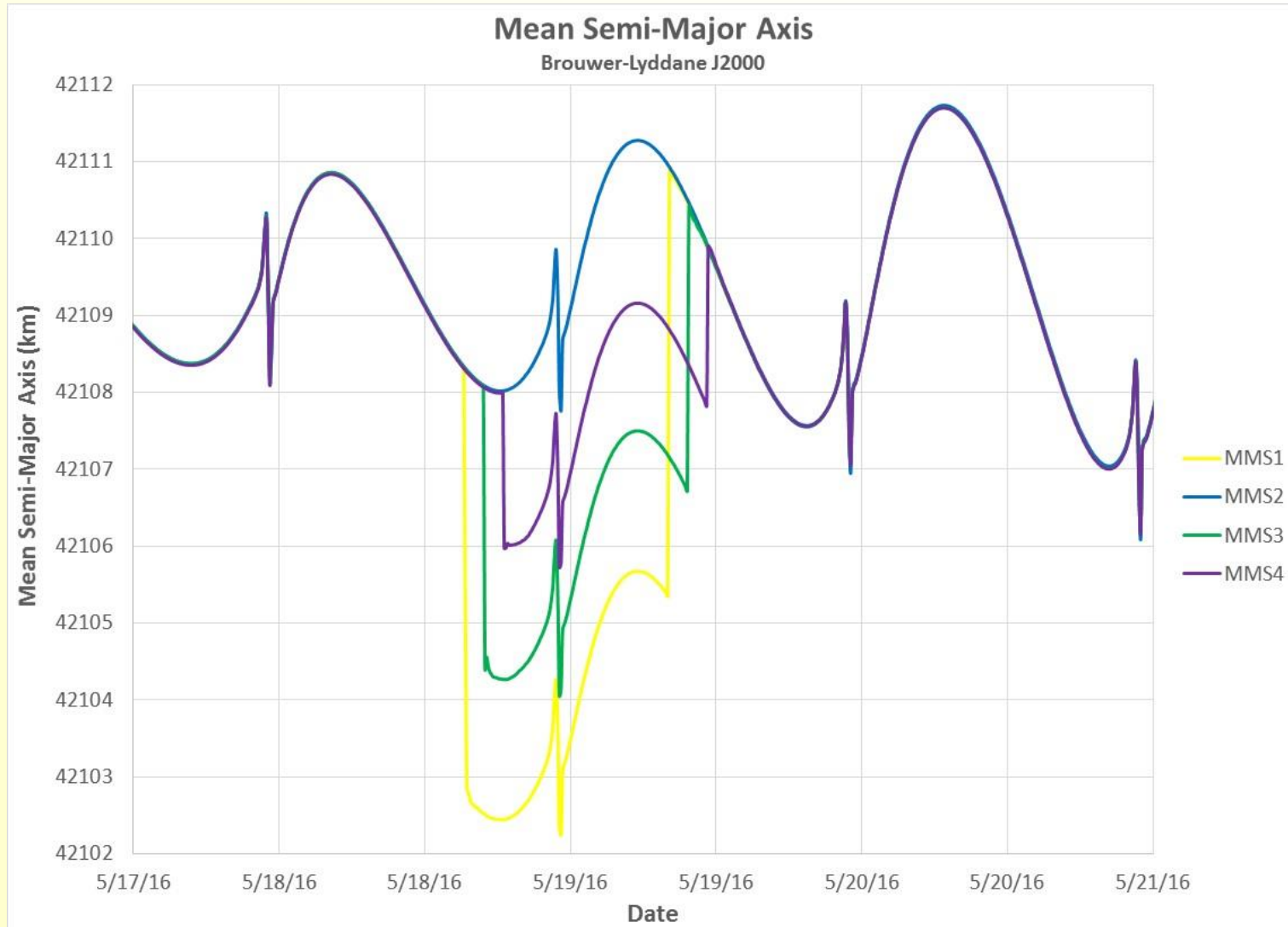
Quality Factor Evolution, Two 40 km





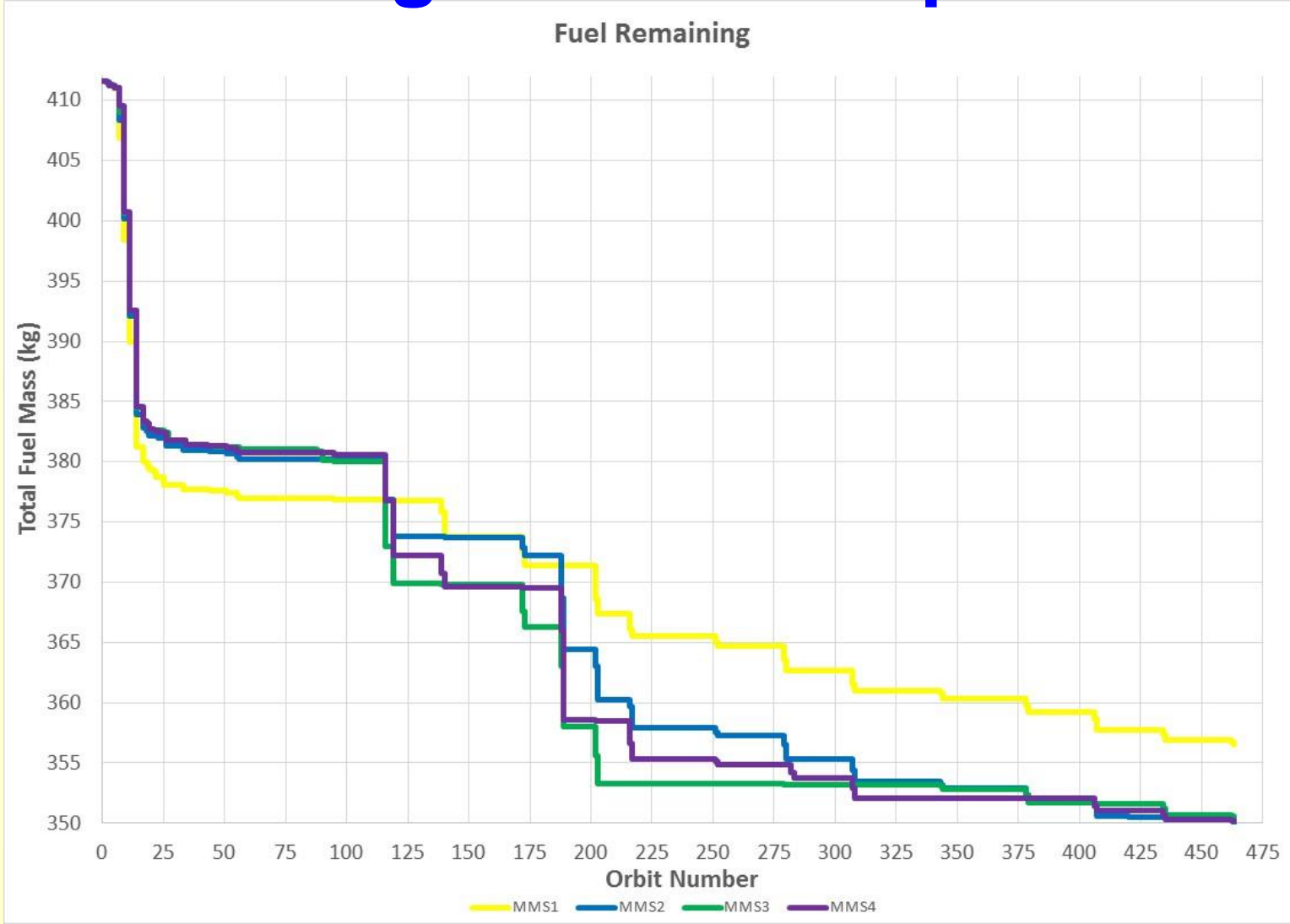


SMA over Set of FM Maneuvers





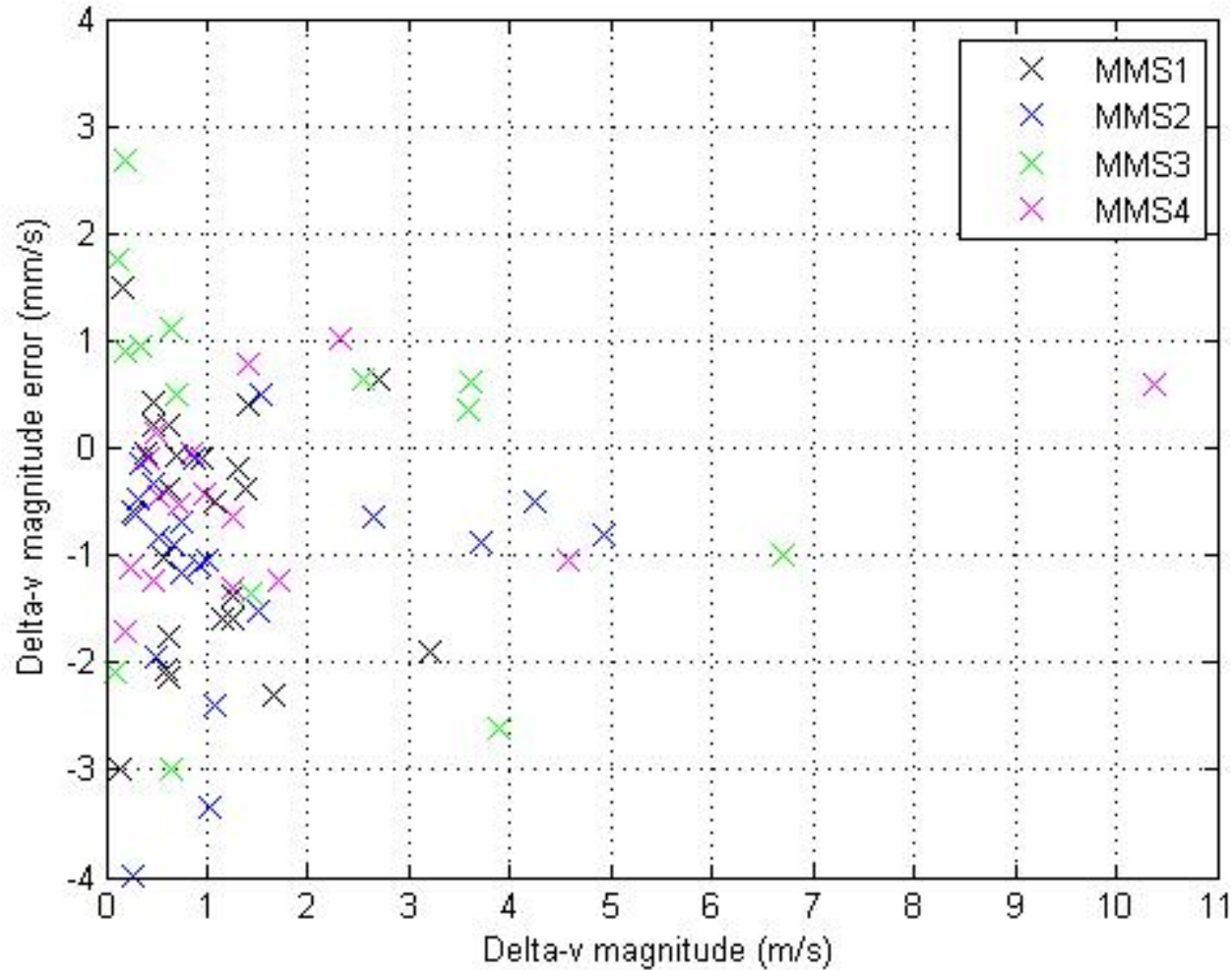
Remaining Fuel Each Spacecraft





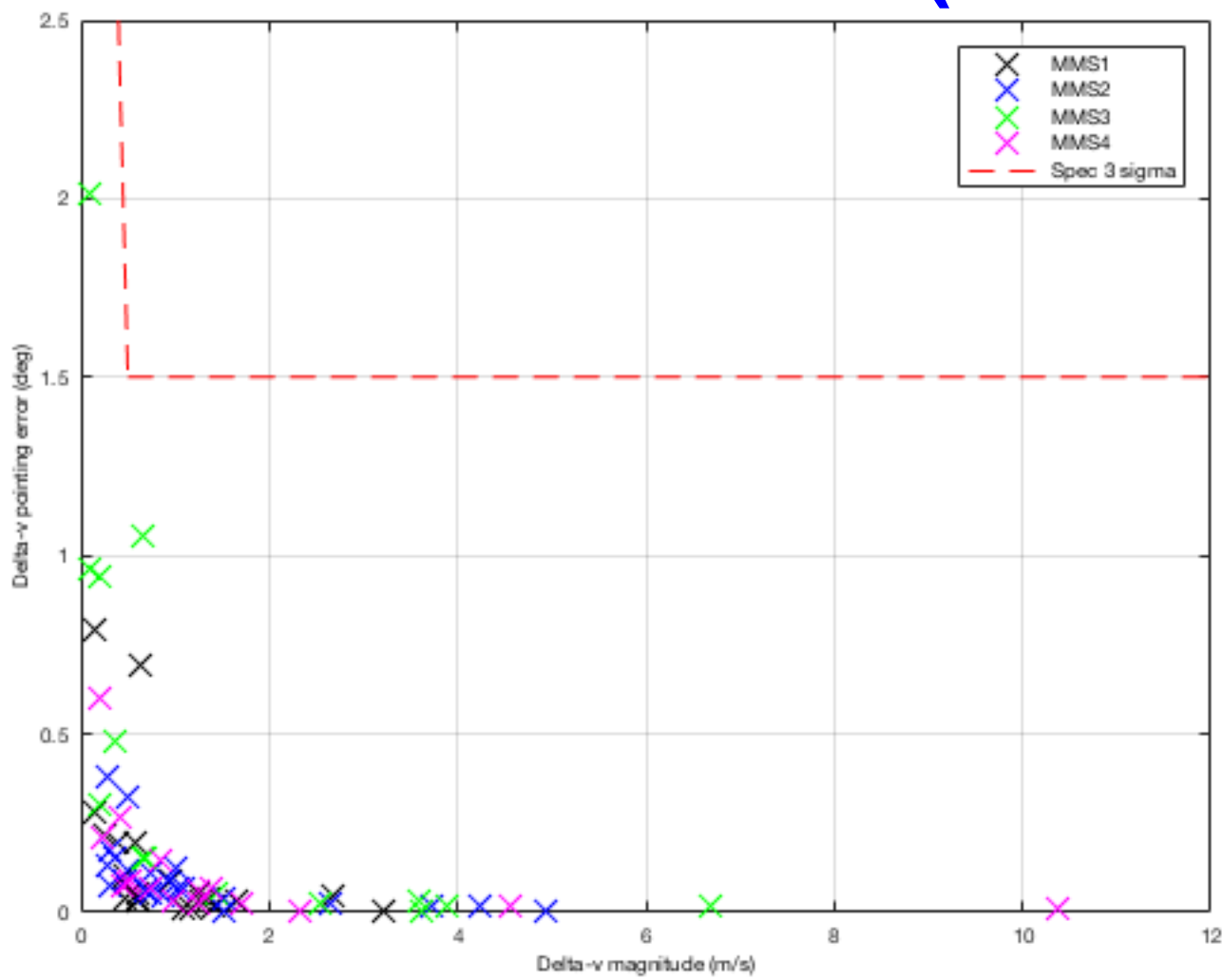


Delta-V Execution Error (Magnitude)





Delta-V Execution Error (Direction)





Conclusions

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- Formation Maneuver Execution Process
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