Formation Flying Dynamics and Control for the MMS Mission: Flight Experience

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Summary

- The Magnetospheric Multiscale (MMS) mission is flying four spacecraft in formation in highly eccentric orbits to study magnetic reconnection

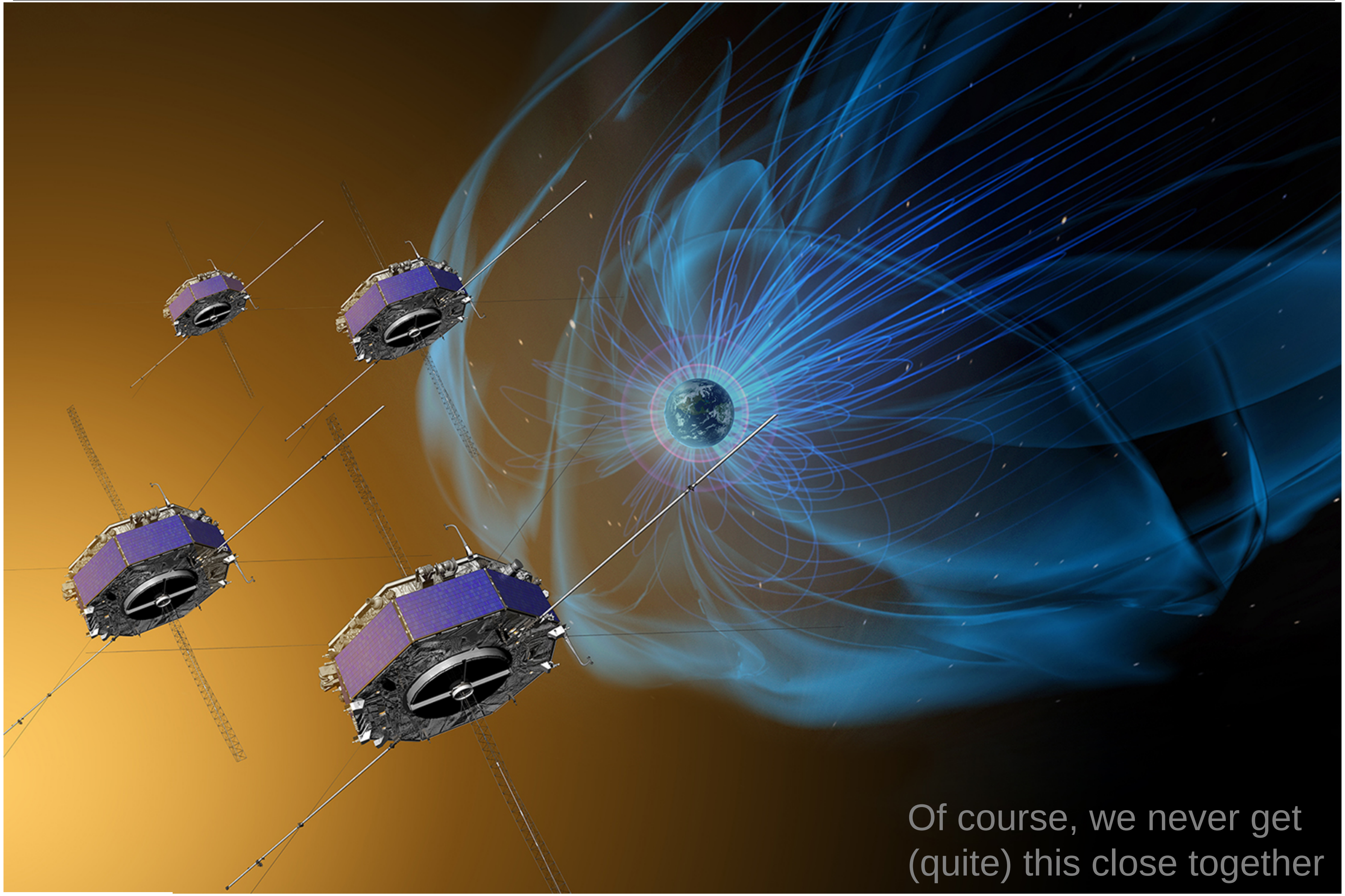
- Reconnection is a key but poorly understood interaction between the solar wind and the magnetosphere of the Earth. It is key to coronal mass ejections (CMEs), “space weather“, pulsars, fusion reactor instabilities, ...

- MMS1-4 launched together in Mar. 2015 into an orbit with apogee radius 12 Earth radii (R_E), to study the magnetopause. Apogee was then raised in Spring 2017 to 25 R_E (in 98 maneuvers!) to study the magnetotail. Fuel remains for decades of formation flying operations

- Four spacecraft allows temporal and spatial changes to be distinguished. They have flown in tetrahedral formations of 7 to 160 km around apogee. Formation maneuvers are needed about every 6 weeks; >450 total so far

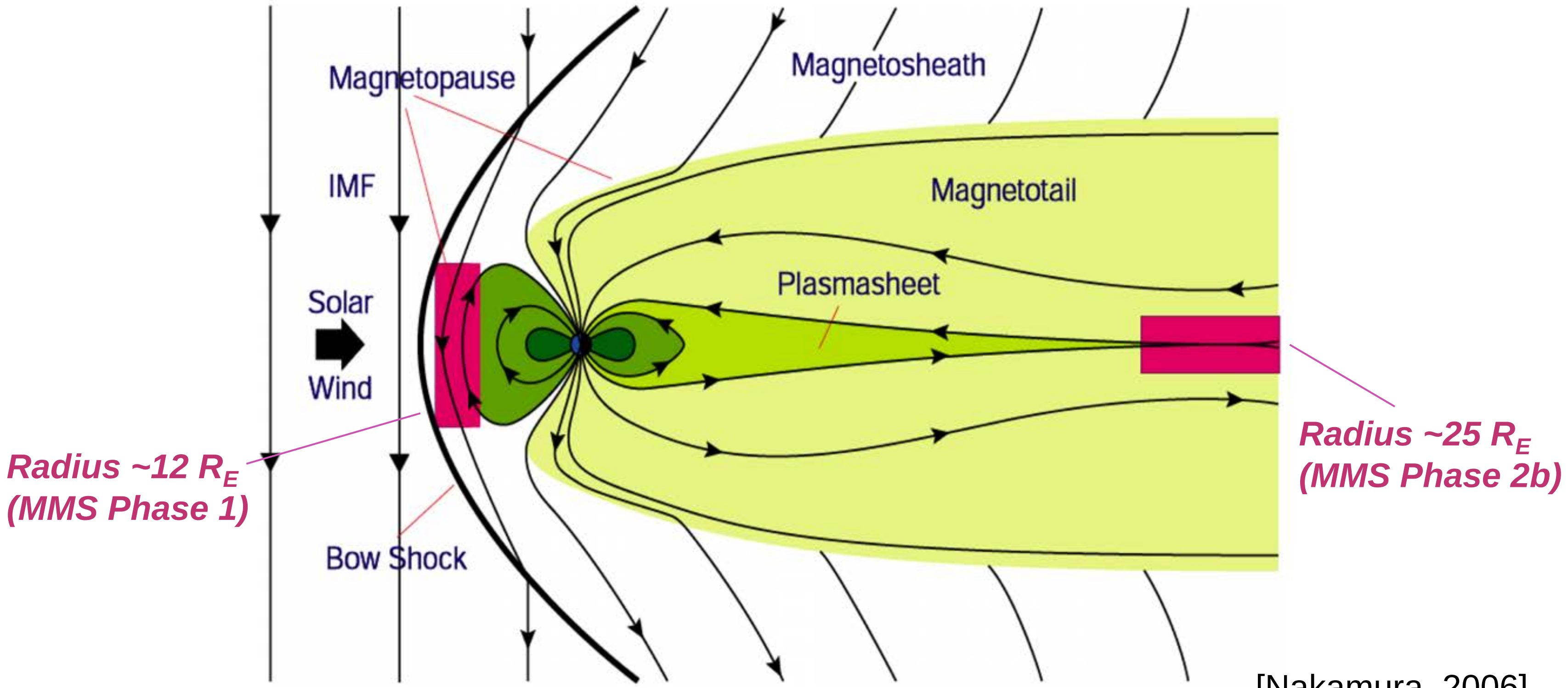
- Maneuvers are designed on the ground, uplinked and then performed autonomously by the spacecraft: the ground just monitors. Additional autonomy could help lower costs for future smallsat formation missions

Magnetospheric Multiscale (MMS) Mission



The "Magnetospheric Laboratory"

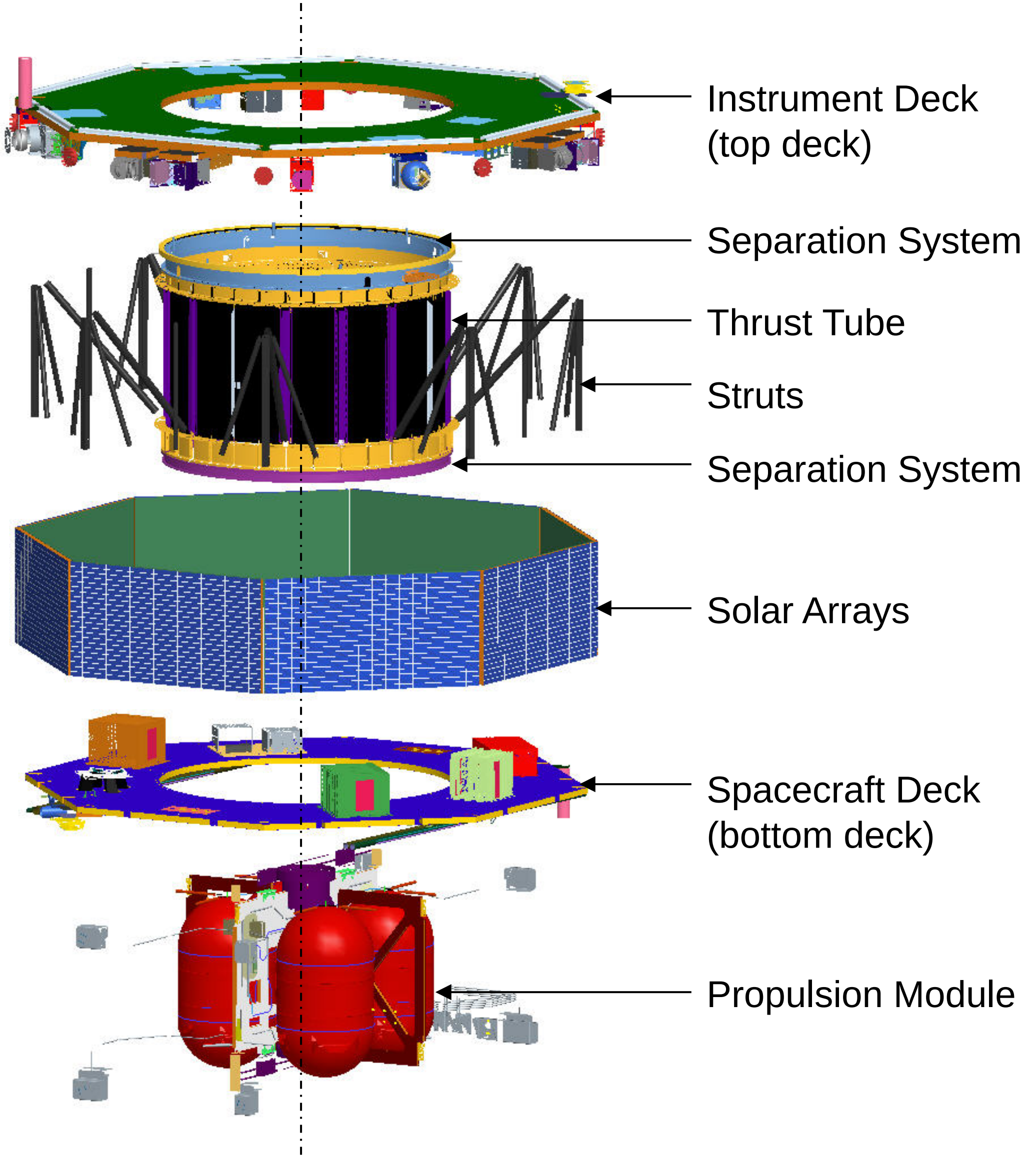
Collisionless reconnection "laboratory"

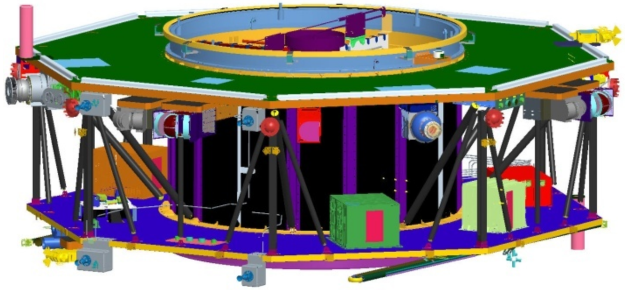


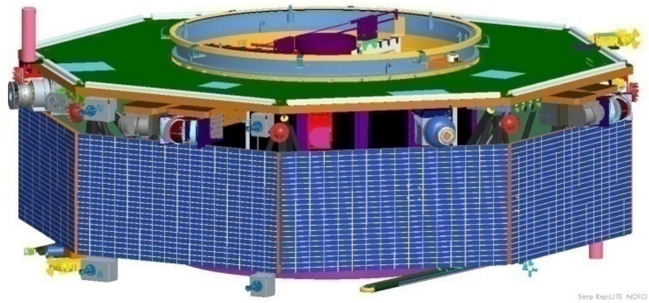
[Nakamura, 2006]

- 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

Observatory Layout

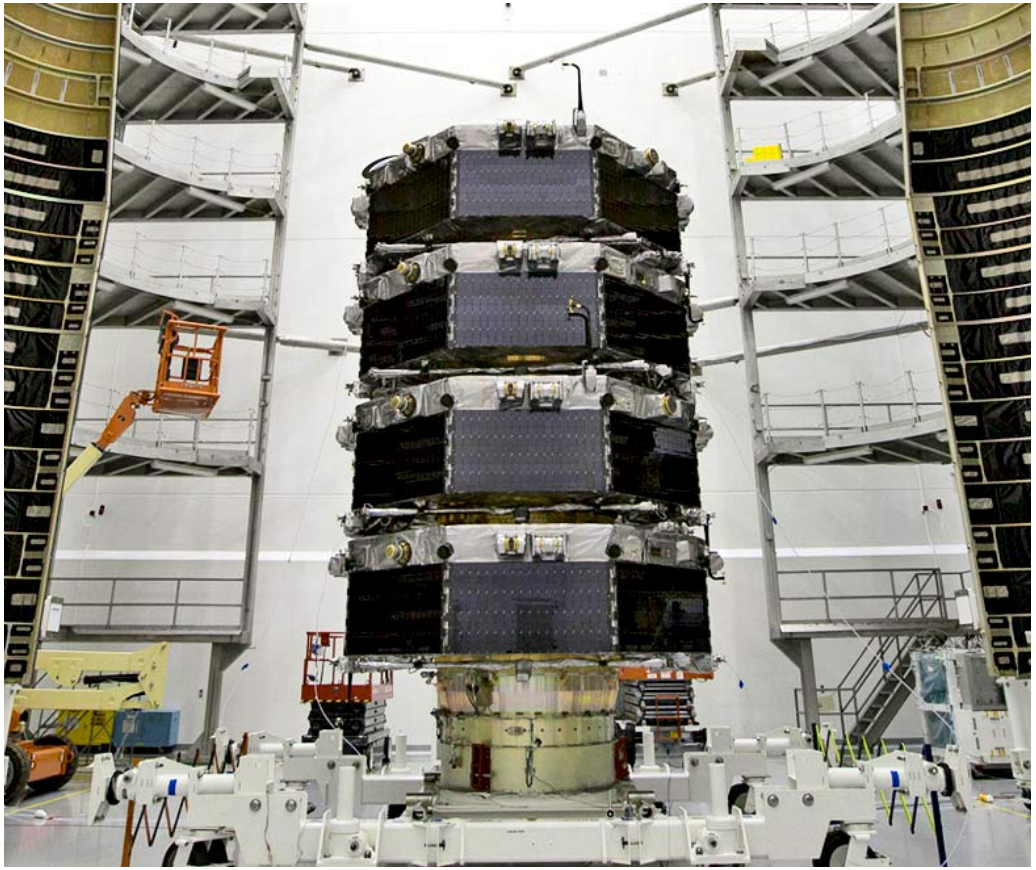






Dry mass ~938 kg
Initial fuel mass 412 kg
Diameter ~ 3 m; height ~ 1 m
Four 60 m wire booms, stiffened by 3.05 RPM spin

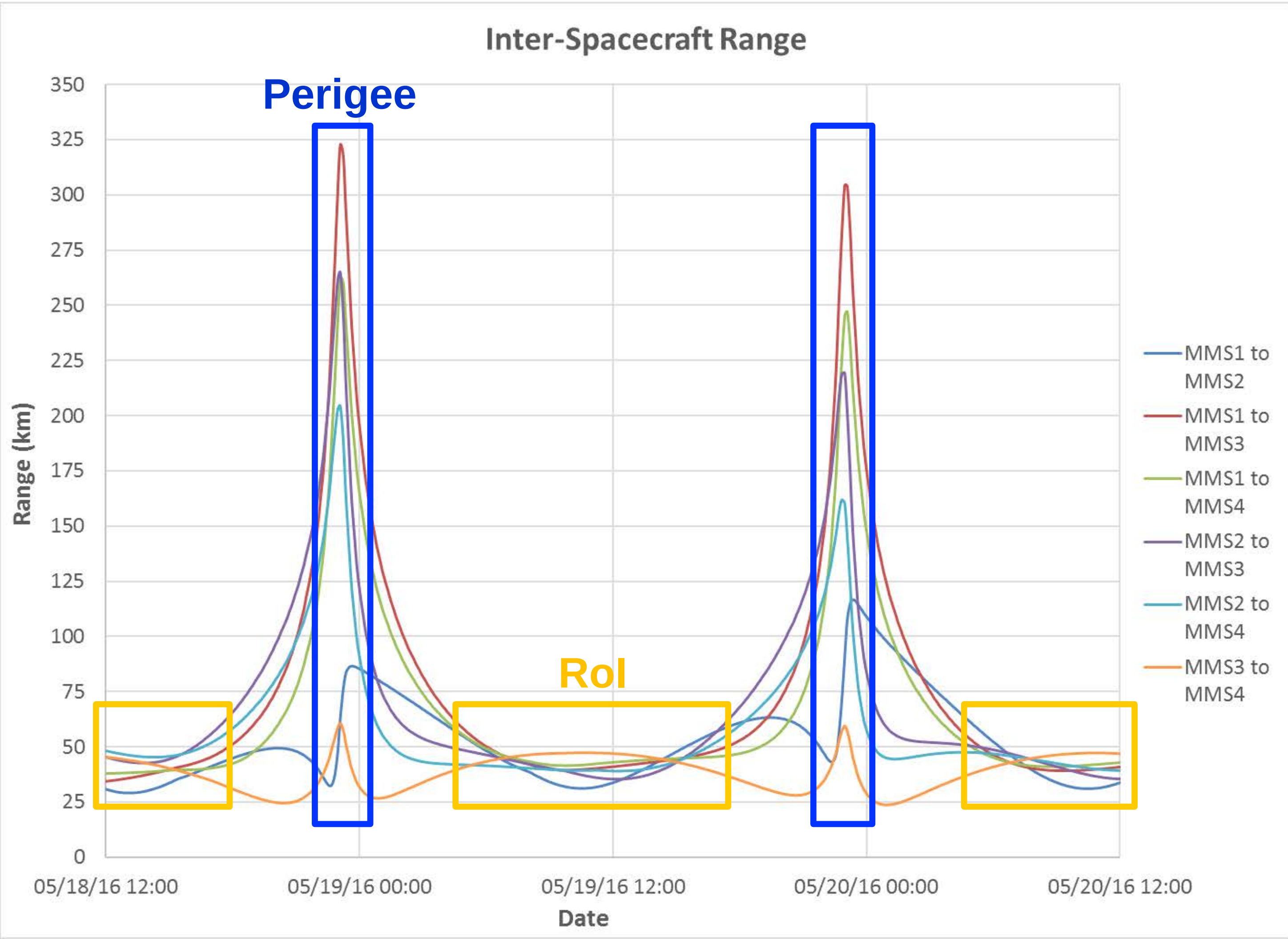
MMS Stack and Launch



- Launched in this stack, then released one by one
- MMS1-4 are essentially identical, but not precisely so: they are “hand made”. Each has its own personality…

Formation Flight in Very Eccentric Orbits

- For science, the MMSs should form an approx. regular tetra-hedron in the *Region of Interest (RoI)* around apogee
- As they fall towards perigee though, the MMSs speed up, pulling much farther apart. The tetrahedron turns into a needle, with left and right, top and bottom having swapped over

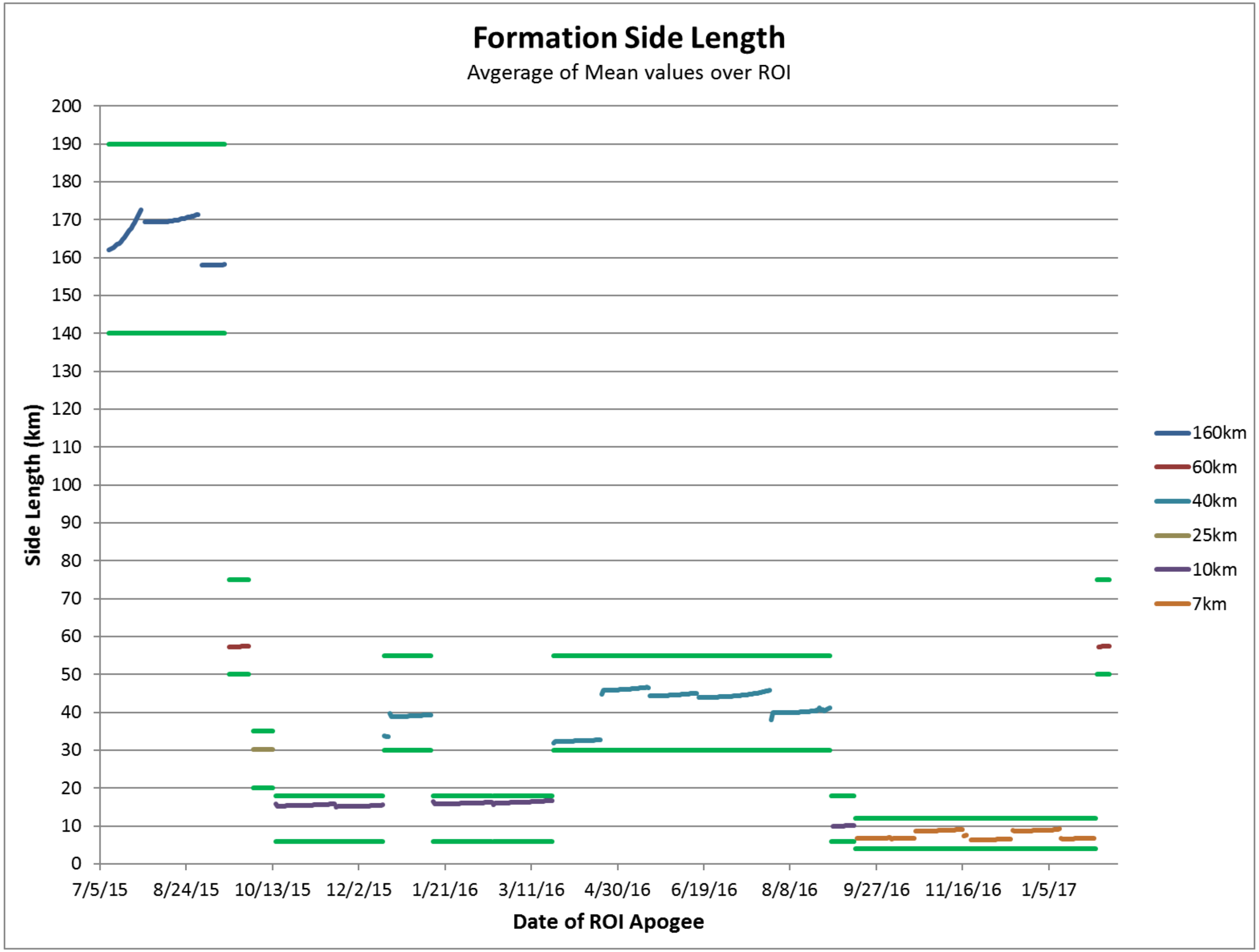


Formation Maneuver Design Process

- Periodically, maneuvers are needed to reset the formation. Reasons:
  - Execution errors in previous maneuvers cause MMSs to drift out of position
  - Scientists desire a new formation size
- One of the spacecraft is chosen as reference, and does not maneuver
- The remaining three MMS perform two burns each; rendezvous pairs:
  - Burn 1 targets the desired location in the new formation at the time of Burn 2
  - Burn 2 then sets up the velocity vector so that spacecraft stays in formation
- The Formation Design Algorithm (FDA) designs each maneuver by performing numerical optimization of the *Quality Factor* (a measure of how close a formation is to a regular tetrahedron around apogee) while:
  - Matching semi-major axes (keeps orbital periods equal: MMSs stay together)
  - Keeping inter-satellite ranges above a specified limit over the entire orbit (aim is to prevent close approaches/collisions at any point)
- The FDA uses orbit solutions produced autonomously by the on-board GEONS navigation system: uses weak-signal GPS to work even high up

Formation Sizes Flown

- Green: bounds on the various formation sizes
- Also shown: actual sizes of formations
- Pre-launch agreed min was 10 km. Based on flight data though, the scientists wanted to go closer; 7 km was feasible



2017 Apogee-Raise Campaign

- This took us from the initial 12 R_E apogee radius needed for studying dayside reconnection to the 25 R_E needed for the magnetotail. Total of 98 apogee-raise (AR) burns, including slews etc., over about 3 months
- AR were the main deterministic maneuvers: used almost 40% of all fuel
- The AR burns occur in an arc of around ±90 deg centered on perigee: any longer, and the burn becomes inefficient ("gravity losses": orbital speed is lower at points higher up the flanks, so the increase in semi-major axis produced by a given DV is less)
- The low MMS acceleration (4 lbf thrusters, ~1100 kg spacecraft: "0 to 60 MPH in about an hour") then means that each MMS used 8 AR DV burns
- Since only one spacecraft can be in communications contact (with a TDRS comsat) at a time, only one spacecraft burned on each perigee passage. This led to the "snake" sequence in which the MMSs burn orbit by orbit, first in order and then again in reverse order, pulling far apart midway through the sequence and then rejoining at the end

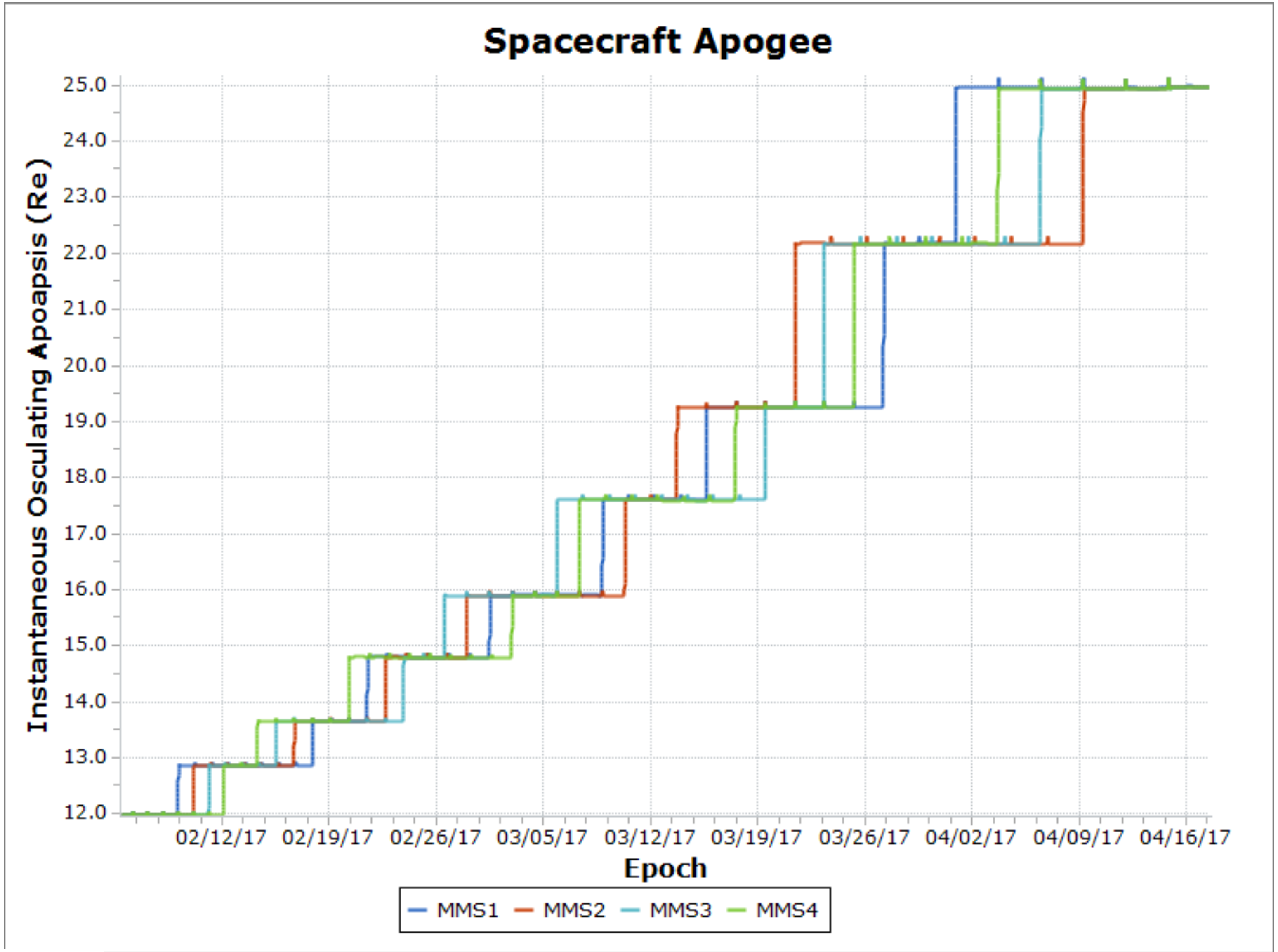
AR Burn Times/Shifts, Feb. 2017:
Happy Days (and Nights, and Weekends…)

Sun	Mon	Tues	Wed	Thurs	Fri	Sat
			1 FR1	2 FR2	3	**4**
5	6	7	8	9 AR1	10 AR2	**11** **AR3**
12 **AR4**	13	14 AR5	15	16 AR6	17 AR7	**18** **AR8**
19	20 AR9	21 AR10	22	23 AR11	24 AR12	**25**
26 **AR13**	27	28 AR14				

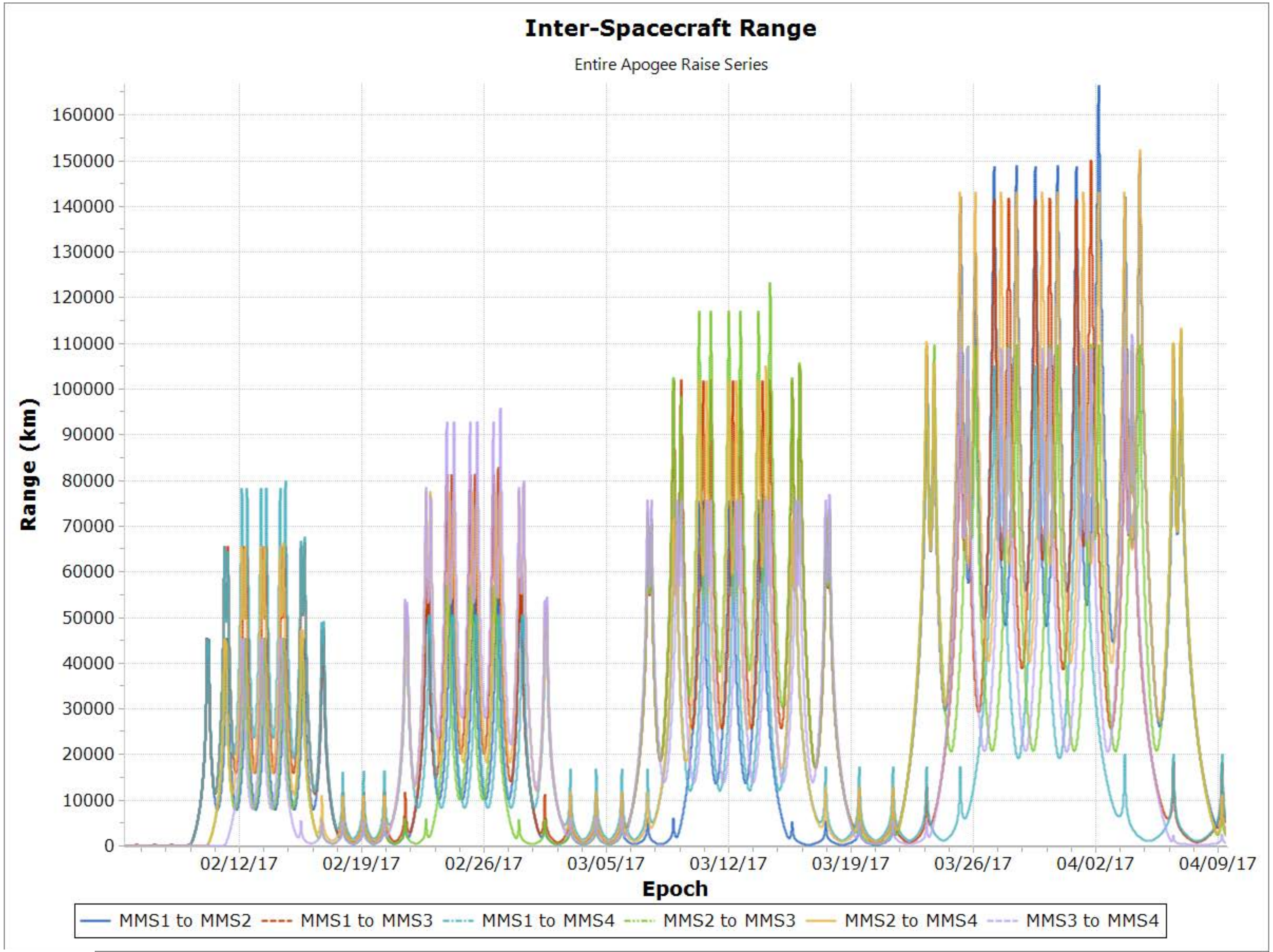
Black: Maneuver on day shift
Blue: Maneuver on night shift
Dates are UTC

Plain: Maneuver on weekday
Bold: Maneuver on weekend
Burns are autonomous; just monitored from the ground

Apogee Radii, AR Campaign



Inter-Satellite Ranges, AR Campaign

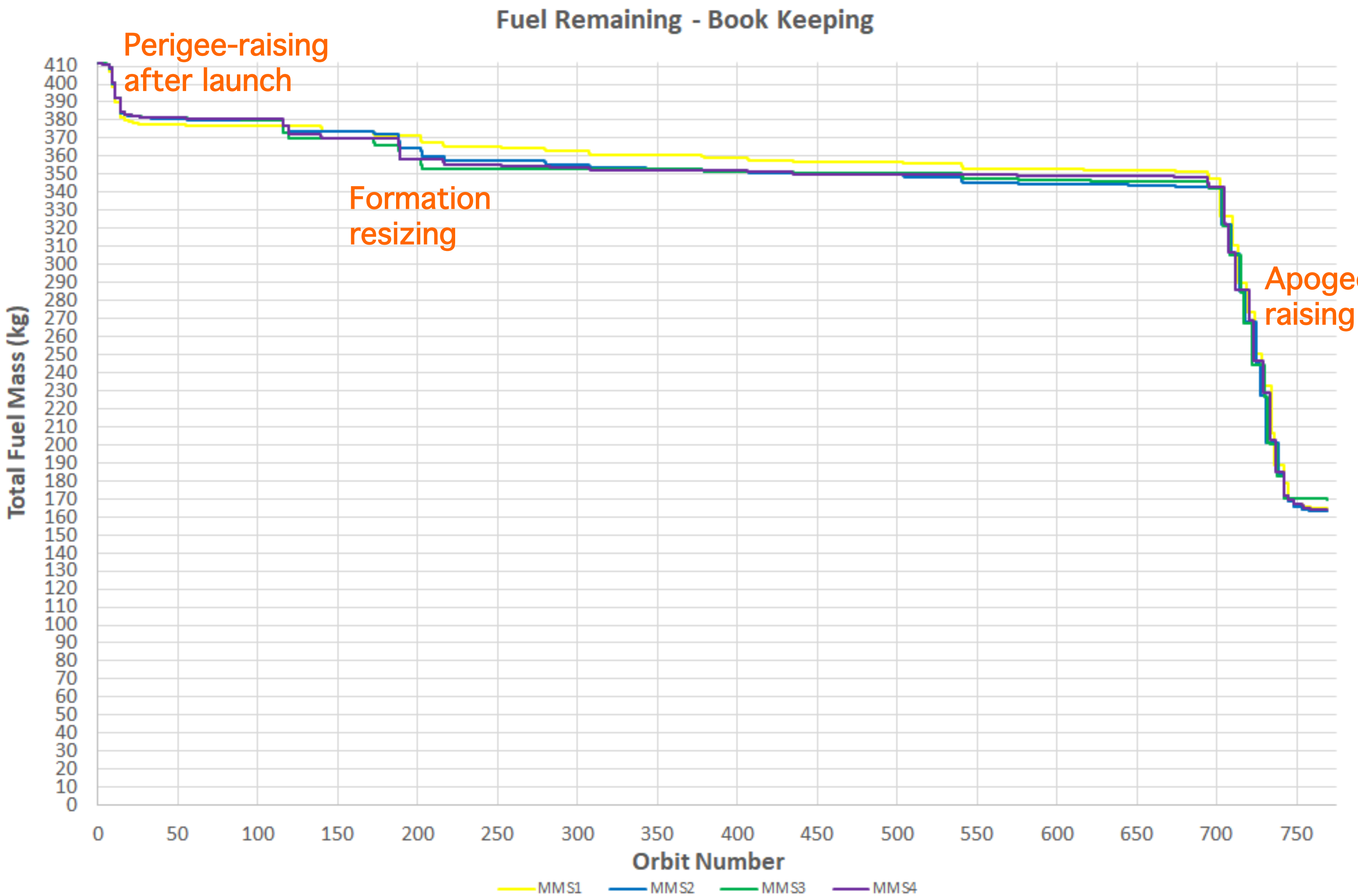


Apogee-Raising Errors and Fuel Use

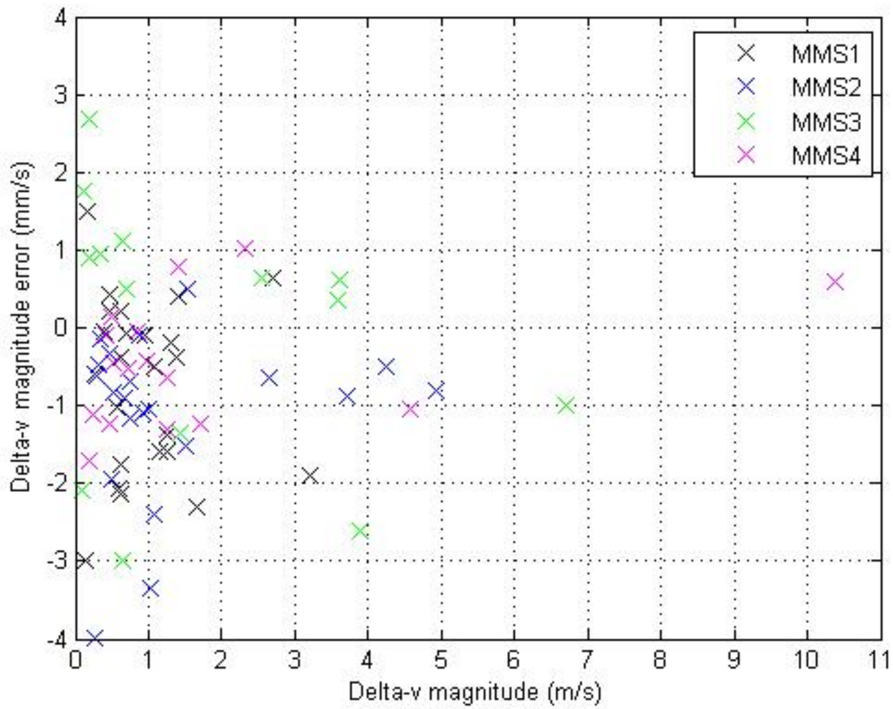
- Maneuver execution errors values, from orbit determination:
  - MMS1: 0.03-0.05% hot (usually 0.05%)
  - MMS2: 0.03-0.04% hot (usually 0.03%)
  - MMS3: 0.01-0.04% hot (usually 0.02%)
  - MMS4: 0.03-0.04% hot (usually 0.04%)
- These very small, repeatable errors were produced using the on-board closed-loop Delta-V controller: this controller takes accelerometer data, removes spin effects, and fires thrusters to follow a table of Dv *vs* time that is computed beforehand on the ground and then uploaded to MMS
- AR fuel usage, from bookkeeping: approx. 3% below predicted 165 kg

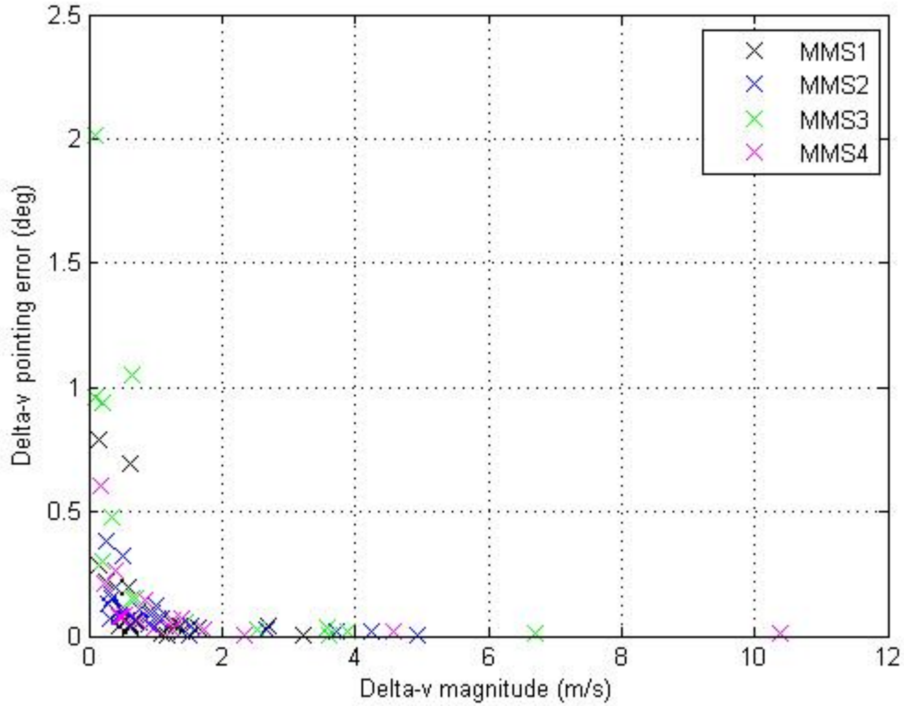
Spacecraft	Actual AR fuel consumed (kg)	Fuel remaining at end of AR (kg)
MMS1	159.3	188.6
MMS2	160.2	183.0
MMS3	159.5	182.5
MMS4	158.4	184.9

Fuel Left, Launch to End of Prime Mission



Overall Delta-V Execution Errors, 2015-16





- Burn execution errors are a key factor in determining formation lifetime
- The Delta-V controller has been far more accurate than its specs in both burn magnitude *(left)* and direction *(right)*. As a result, formation lifetimes are ~6 weeks; pre-launch, we had been *hoping* to get up to 2 weeks!
- Errors become larger, though, for very small burns. We therefore do not allow burns below 0.05 m/s when designing formations. This only prevents us from going to exceedingly small formation sizes

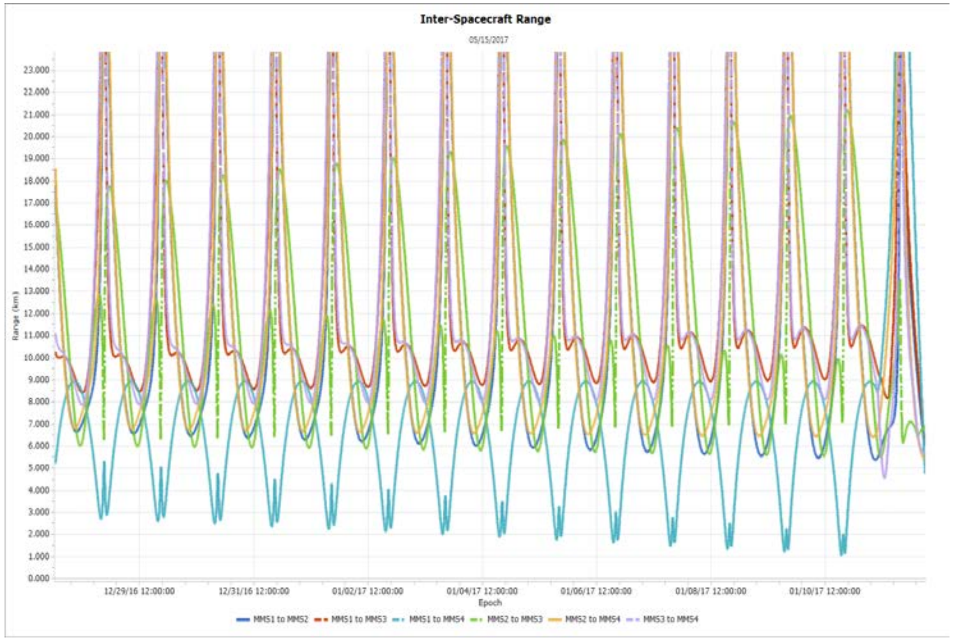
Dealing with Close Approaches

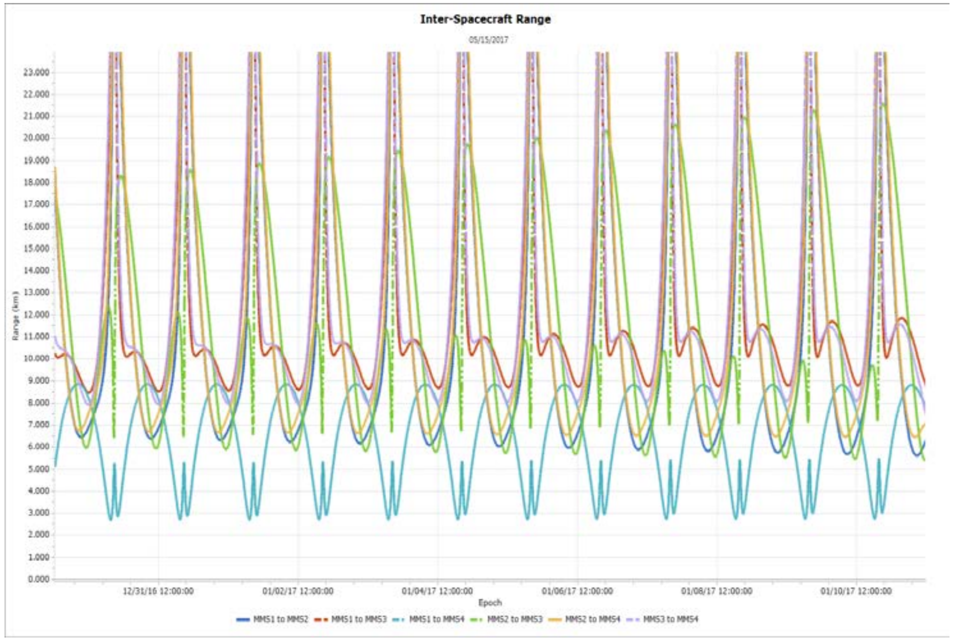
- MMSs may have close approaches (CAs) where their orbit planes cross (the left/right and up/down swapping already mentioned), about 90 deg away from perigee. The spacecraft typically drift slowly into such CAs
- CAs may also spring up more suddenly if a planned maneuver is missed
- If there is enough time, CAs can be dealt with by typical formation burns
- Alternatively, the *Dodge burn* is for use if a CA (MMS-to-MMS, or MMS-to-something else) is only detected shortly beforehand, with insufficient time to design an entire set of formation maneuvers
- The Dodge is a fixed size burn (0.25 m/s), in the orbit plane, with fixed direction relative to the velocity vector. This burn direction maximizes the displacement of the dodging MMS away from the predicted CA point
- A Dodge has never yet had to be performed, although we came very close after a missed burn… If we ever have to do one, it will take several orbits, and probably a few kg of fuel, to return the dodger to the formation

Trim Burns

- If two MMSs are slowly drifting uncomfortably close together, an alternative type of maneuver to deal with this is the *trim burn*
- Drift is caused by small differences in orbital period, produced by very small differences in semi-major axis (SMA): 10s of meters out of a total of ~83,000 km, or one part in around 3 million! Typical trim: 0.005 m/s
- The Delta-V controller cannot perform such small burns. They are instead carried out using ”Checkout Mode” (an open-loop system only intended for initial spacecraft testing) and the small 1 lbf axial thrusters
- Unlike a full set of formation maneuvers, a trim is performed by a single MMS. This therefore takes much less time away from science ops
- It also uses far less fuel: a typical trim burn is less than 1 s in duration, and consumes half a teaspoonful of hydrazine (2.7 grams *vs* on the order of 1 kg for a formation maneuver set)
- Several trim burns have been carried out to date, with very good results

Drift Before and After Trim Burn





- In this 7 km formation, MMS1 and MMS4 are initially *(left)* drifting slowly closer, as a result of an SMA difference of ~10 m. The original minimum spacing of 3 km is safe, but the final 1 km would not be. Alternatives: either carry out a trim, or perform an entire formation maneuver set

- It was decided to have MMS1 do a trim on Boxing Day (Dec. 26), 2016. This 0.7 s burn reduced the SMA offset between MMS1 and MMS4 to a fraction of a meter, freezing the minimum separation *(right)* at 3 km

Lunisolar Effects

- Perturbations caused by the gravitational attraction of “third bodies” (for MMS, both the Sun and Moon) can be significant for orbits with high apogees: at these high radii, the gravitational acceleration of the central body (Earth) does not overwhelm lunisolar accels

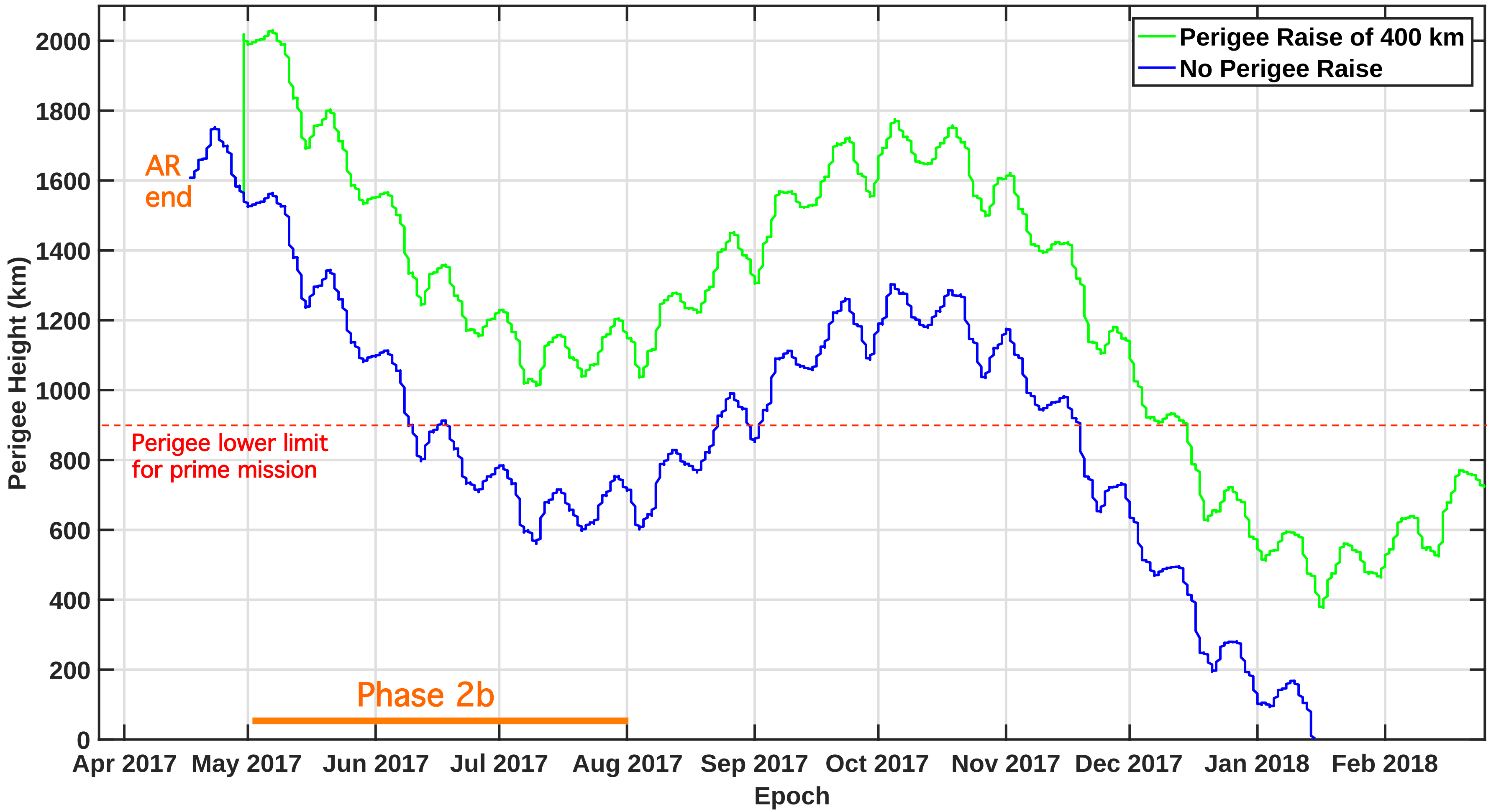
- Key effects: slow cyclic variations (period of around 6 years), with superimposed short-period oscillations of period 6 month (Sun), 14 days (Moon), in:
  - Eccentricity (affects perigee radius, hence reentry date)
  - Inclination (affects orbit plane orientation, hence eclipses)

- This variation is known as the *Kozai mechanism*: first described, for asteroid orbits, in Y. Kozai, *Astron. J.*, Vol. 67, pp. 591-8, 1962

- For MMS, lunisolar effects were minor at 12 R_E apogee radius, but became significant at 25 R_E. In particular, if no action were taken, reentry would have occurred in early 2018 (see p. 21). Instead, each spacecraft used 24-30 kg to raise its perigee. Reentry is now expected to occur in 2030, unless burns are used to delay it further

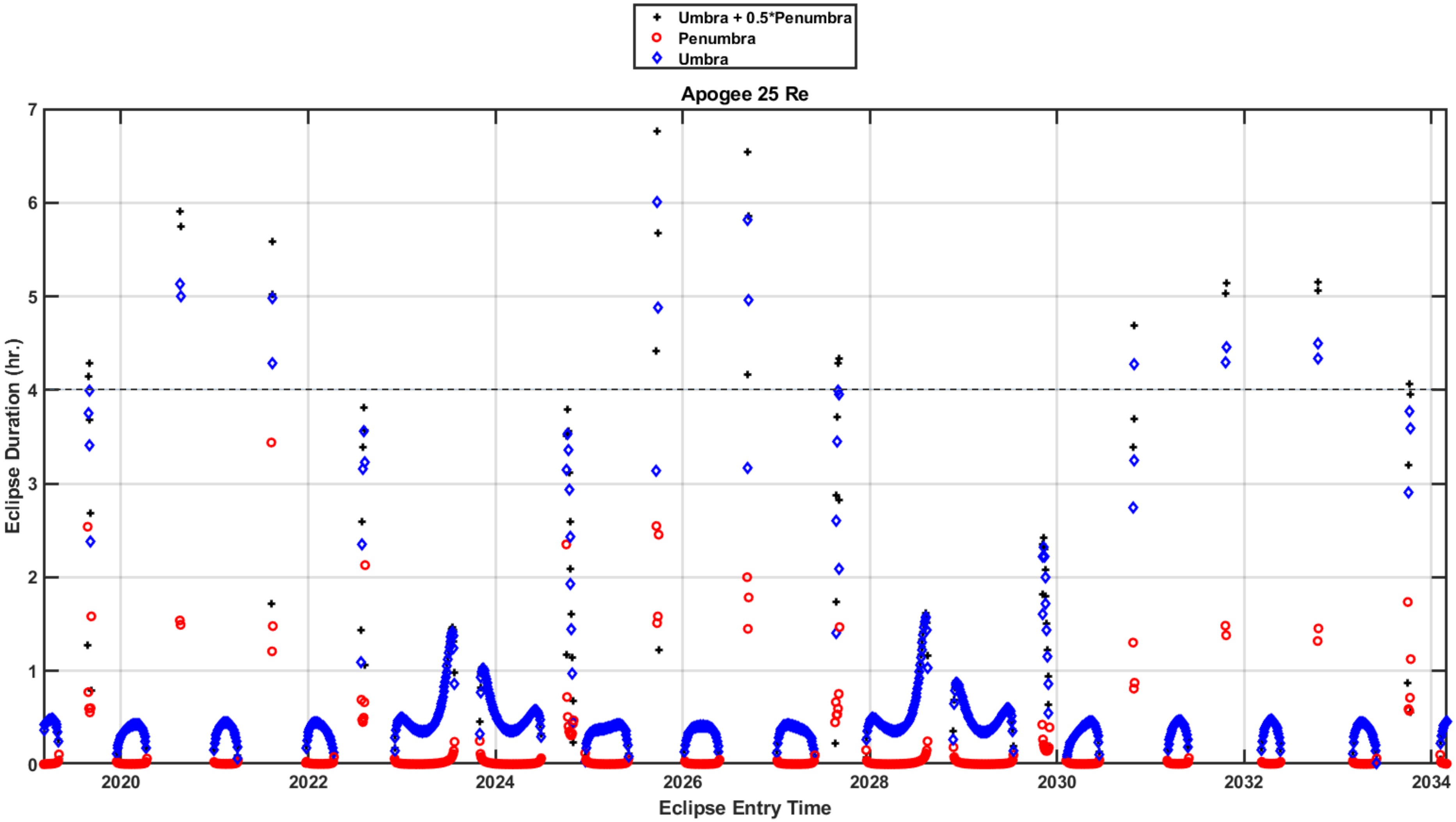
- The orbit plane orientation changes lead to a few eclipses in 2019-2022, 2024-2027, etc., that are so long that the spacecraft would likely suffer (p. 22). These can be greatly shortened by raising apogee further next year (p. 23): much less severe

Effect of First of Two Perigee-Raises (PRs)



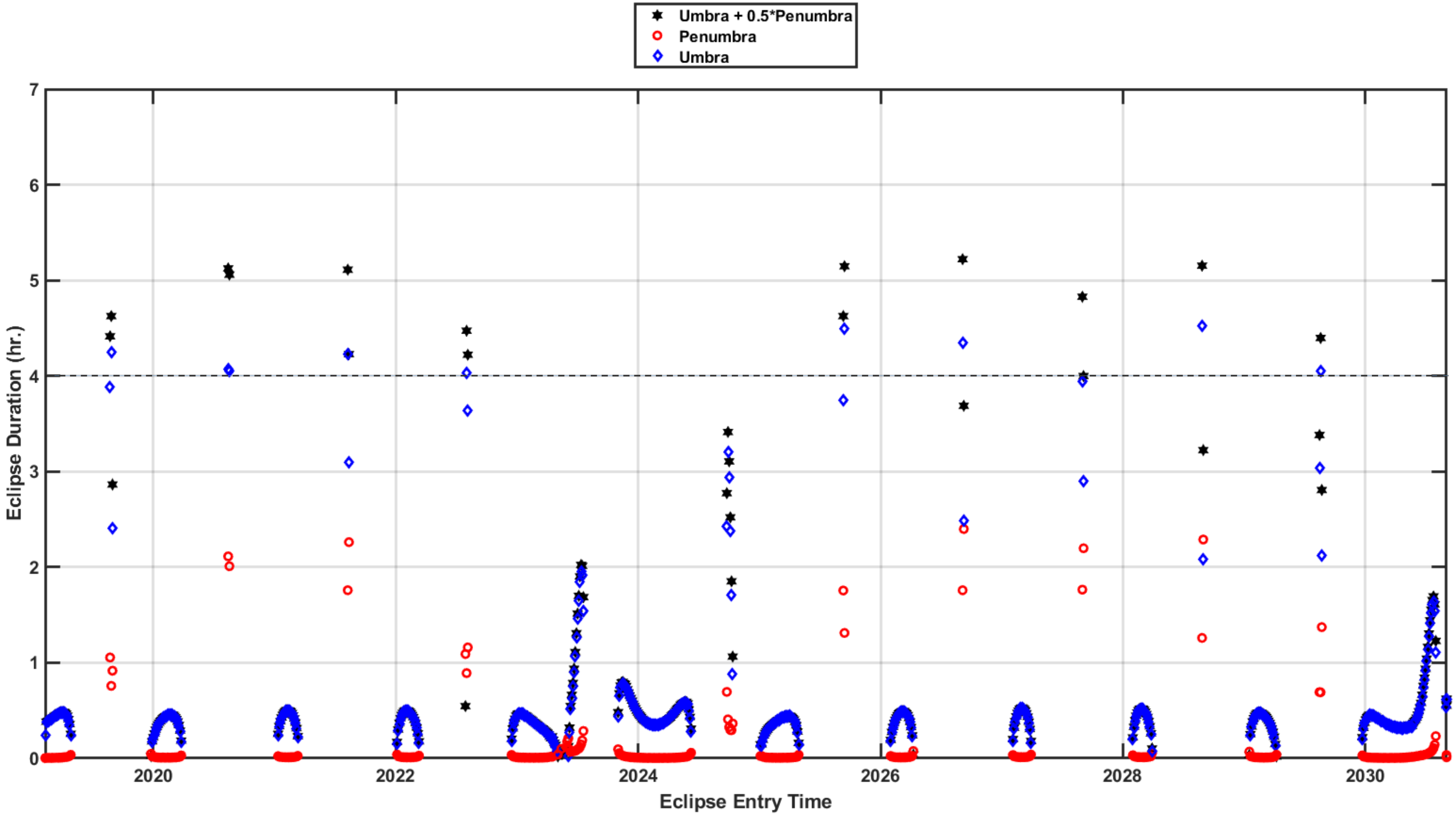
Eclipses if Apogee Radius Stays 25 R_E

Peak U+P/2 6.760 hr



Eclipses for AR to 29.34 R_E + Later "*m*-ARs"

Peak U+P/2 5.221 hr



Autonomy and Smallsat Formation Flight

- MMS has carried out over 450 maneuvers to date, and continues to perform formation burns about every 6 weeks. The apogee-raise and turbulence science campaigns in early 2019 will also involve many burns
- Although the spacecraft execution of maneuvers is autonomous, and soon will be done “in the blind” (i.e. out of radio contact), the ground flight dynamics team is heavily involved in the design and testing of all burns
- This approach makes sense for a mission on the scale of the $1 billion MMS, given the possible major consequences of any botched maneuver: “an ounce of prevention is worth a pound of cure”
- However, formation flying missions are being proposed using smallsats (e.g. Cubesats), in order to reduce hardware and launch costs. In order to also reduce operations costs, such missions will likely need to be flown with a smaller operations team on the ground
- Increased autonomy, not just covering maneuver execution but also maneuver design and testing, will therefore likely be a new development

Conclusions

- The MMS mission has successfully demonstrated tight formation flying of four spacecraft in very eccentric orbits so high that significant third-body perturbations from Sun and Moon are experienced. Plans must be made long ahead of time if these perturbations are to be coped with efficiently
- Over 450 maneuvers have been carried out by MMS so far, ranging from very small trims through small formation burns to large apogee- and perigee-raises. This has been challenging for spinning spacecraft
- MMS has demonstrated that autonomous GPS-based satellite navigation can work well at altitudes far above the GPS constellation: 40% of the way to the Moon now, and soon to be 50%. This performance has been even better than expected, and has implications for the now-planned use of GPS navigation on the Lunar Gateway space station in Moon orbit
- MMS is well into its extended mission phase, and has significant fuel reserves remaining. These will allow it to fly in formation for decades to come, probably until the hardware eventually fails or lunisolar gravitational perturbations cause reentry of the spacecraft