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RESULTS OF THE APOGEE-RAISING CAMPAIGN OF THE MAGNETOSPHERIC MULTISCALE MISSION

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This paper describes the apogee-raising campaign of the Magnetospheric Multiscale mission, where the spacecraft increased their apogee radii from 12 to 25 Earth radii in a total of 98 maneuvers. These maneuvers included an initial formation resize set to spread the spacecraft apart for safety, 32 apogee-raise delta-v maneuvers, their associated slews, four perigee-raise maneuvers and the associated slews, and finally a set of maneuvers to get back into formation. These activities were all accomplished successfully and on schedule with no anomalies, and at a fuel consumption somewhat less than predicted. As a result, MMS was set up ready to carry out *in situ* studies of magnetic reconnection in the magnetotail, with sufficient fuel remaining for a significant extended mission.

INTRODUCTION

The NASA Magnetospheric Multiscale (MMS) mission is flying four spinning spacecraft in highly elliptical orbits to study the magnetosphere of the Earth [1][8]. Launch on an Atlas V 421 occurred from Kennedy Space Center on Mar. 12, 2015, with insertion into a high-eccentricity orbit that was designed to satisfy a complicated set of science and engineering constraints [2]. After roughly 5 months of commissioning, the spacecraft were flown in tetrahedron formations of varying dimensions [4][5] in order to perform magnetospheric science measurements. In the first phase of the mission, these measurements were taken on the dayside of the Earth, in a Region of Interest surrounding the apogee of the MMS orbit. (Apogee was at 12 Earth radii [R_E]; the Region of Interest included all points above 9 R_E.) The goal during Phase 1 was to observe the magnetic reconnection events that were expected to occur near the bow shock where the solar wind impinges upon the magnetosphere. Measurements during the later Phase 2b, with apogee radius now 25 R_E, are currently being taken in the magnetotail [3], to similarly observe nightside magnetic reconnection events. Taking simultaneous measurements from four spacecraft allows spatial derivatives of the electric and magnetic fields to be determined, allowing variations that are functions of distance to be distinguished from those that are functions of time.

This paper will describe the results of the MMS apogee-raising (AR) campaign which has recently been completed. This covered the period Feb. 9-Apr. 9, 2017, and more than doubled apogee radius to 25 $\mathrm{R_E}$. It required a total of 32 delta-v burns, eight by each spacecraft: these had durations of around one hour, in burn arcs centered at perigee. These extended durations, and the large total number of maneuvers, are a consequence of the low force (18 N each) generated by the MMS monopropellant hydrazine thrusters. A key operational constraint is that the maneuvering spacecraft must be in contact with the ground at the start of the maneuver, in order to allow commanding; furthermore, only one MMS can be in contact at any given time. The maneuvers therefore took place one at a time on successive perigees. In addition, it was required that the spacecraft start the apogee-raising campaign from a formation, and finish it back in close proximity, so that they can get back into formation without performing excessively large maneuvers. This led to breaking up the maneuvers into four “snakes” (Adder, Boa, Cobra and Diamondback) of eight burns each, as will be discussed.

Details will also be given of the performance of the on-board maneuver controller that was deduced from navigation data. The resulting estimated execution errors were much smaller than the specification values for the controller, which led to small differences between the actual spacecraft orbits and the predicted

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ones. An implication of this was that the MMS inter-satellite ranges were close to those that were predicted before the start of the AR campaign. However, as this good accuracy was not known *a priori*, it was necessary to guarantee an adequate separation between the spacecraft throughout the AR campaign, so as to ensure no conjunctions [10]: this was achieved by increasing the size of the pre-AR formation, as well as by means of a "period target bias" technique for the burns making up the first snake that will also be discussed.

Since the maneuvers were so accurate, it was calculated that the pre-burn predictions of MMS position were accurate enough for subsequent acquisition by Tracking and Data Relay Satellite System (TDRSS) spacecraft on the subsequent perigee. However, acquisition difficulties were encountered after the first two AR maneuvers: these were attributed to Doppler differences between the predicted orbits and those that were actually achieved. Since navigation data collected at this perigee is what was originally planned to be used for producing updated post-burn acquisition data, a different solution was clearly required. This was achieved by using navigation data from a particular set of Deep Space Network (DSN) passes that followed the AR maneuvers, as will be detailed.

In addition, the fuel usage for the apogee-raising maneuvers will be discussed. Since apogee-raising is the main single fuel consumer throughout the entire MMS mission, requiring about 40% of the initial on-board capacity, determining the precise AR fuel usage was a key factor in planning for a possible extended mission.

Finally, once apogee was raised to the vicinity of 25 RE, lunisolar perturbation effects on the MMS orbit were greatly increased. A consequence of this was that it was recognized pre-launch that maneuvers to raise perigee would be required at some point during Phase 2b. The decision was ultimately taken to perform maneuvers shortly after AR, prior to putting the spacecraft back into formation, that raised perigee by about 600 km: this ensured a safe altitude throughout the remainder of the prime mission. The reasons for carrying out these maneuvers immediately after AR, the details of their implementation, and the results obtained are also summarized in the paper.

MMS APOGEE-RAISING CONSTRAINTS AND DESIGN

Need for apogee-raising

In order to collect the science data that is required for studying magnetic reconnection [n], the MMS spacecraft must study the two regions in which this phenomenon is expected to occur. The first of these is in the vicinity of the bowshock of the magnetosphere, where the magnetic field lines of Sun and Earth can interact. This region is broadly sunward from the Earth, at a radius that varies with the strength of the solar wind; a typical value though is 9-12 Earth radii (R_E). The second promising region for the study of reconnection is in the down-Sun magnetotail, where the solar wind stretches the magnetic field lines of the Earth on either sides of the separating neutral sheet [3]: the northern field lines are directed towards the Earth, the southern ones away from it. Magnetic reconnection occurs if these nearly anti-parallel field lines snap and join together. A typical distance from Earth at which tail-side reconnection occurs is between 15 and 25 R_E.

The MMS spacecraft study reconnection by flying in tetrahedron formations of various scale sizes in what is termed the Region of Interest (RoI), an extended zone surrounding apogee [Other MMS paper(s)]. MMS was launched into an orbit with apogee radius 12 R_E: this phase of the mission (Phase 1) was designed to study the sunward reconnection region, so the RoI was defined to be all points at radii above 9 R_E. Two passes were made through this region, spaced roughly a year apart. After this, the mission entered into the apogee-raise campaign (Phase 2a) which is the subject of this paper and raised the MMS apogee to 25 R_E. This is currently being followed by a sweep through the tailward reconnection region: the RoI in this case is defined to be all points above a radius of 15 R_E. At the completion of this sweep the prime mission will be at an end; however, it is expected that an extended mission will follow, allowing at least one further pass through the tailward reconnection zone.

Apogee-raising constraints

It can be seen that the *in situ* study of reconnection in the magnetotail would not be possible without this more than doubling of the MMS apogee radius. Several features made this challenging. Firstly, the MMS thrusters are sized for the small formation maintenance and resize maneuvers that the spacecraft more typically perform: this makes them rather undersized for extensive orbital maneuvering. To be specific, each of the four spacecraft has an average dry mass of 937.9 kg, an initial fuel mass of 411.6 kg, and is equipped with eight 4 lbf (18 N) radial thrusters (firing in the MMS spin plane), together with four 1 lbf (4.5 N) thrusters aligned with the spacecraft spin axis (two along +Z, two along –Z). The resulting low acceleration implies that apogee-raising cannot be carried out in a single maneuver: this would require burning over an extremely long burn arc, leading to excessive "gravity losses". Since apogee-raising uses approximately 40% of the total available for the mission, efficiency is clearly important. In addition, the time available for apogee-raising was limited to roughly three months: any more would eat into the limited duration available for reconnection science collection in the magneotail. (Phase 2b is the single tail passage included in the MMS prime mission.) In order to balance these two considerations, it was decided that each spacecraft should perform a sequence of eight maneuvers.

A further complication is that it is required to be in contact with each spacecraft for at least the start of each maneuver[*], and it is only possible to communicate with one MMS at a time. This led to an arrangement where a single spacecraft would burn on nearly each successive perigee. It was also desired that all four spacecraft finish apogee-raising relatively close together, so as not to require excessive fuel to get back into formation. This requires not only that the spacecraft have the same phasing at the completion of the campaign, but that they not become too separated in altitude during the AR sequence: such a separation would be likely to lead to large differential lunisolar perturbations to the orbits.

Nominal apogee-raising "snake" design

The scheme that was developed was to break the apogee-raise campaign into four "snakes", each of which consists of two maneuvers for each spacecraft, or eight in total. These are performed upon successive perigees in the order MMSa MMSb MMSc MMSd MMSd MMSc MMSb MMSa, with a "blank" perigee between the two MMSd burns for orbit determination and replanning of the second burn. In addition, a perigee without maneuvers was inserted after the first and second snakes, to allow additional time to recover from any contingencies that may have occurred.

Each of the eight burns in a snake is targeted to achieve an equal increase in orbital period: this can be seen to lead, in the absence of maneuver execution errors, to the satellites becoming widely separated halfway through the snake, but back in phase at its end. A small modification to the first snake was that "period biasing" was used to spread the spacecraft out somewhat, in order to protect the satellites from conjunctions that could possibly have occurred as a result of the predicted effects of maneuver execution errors. This biasing increased the targeted period change of the first burns by 2 min, and reduced the change introduced by the second burns by 2 min. This intentionally alters the rephasing property of the snake, leaving the spacecraft spread by several hundred km at apogee at its completion. Note that this separation is accomplished without the use of either additional fuel or time. By contrast, the original plan to ensure safety from conjunctions had been to increase formation size to 160 km immediately before the start of the apogee-raising campaign: this does consume additional fuel. Using the period biasing technique allowed this formation resize to be reduced to 60 km, so reducing the amount of fuel required to achieve it.

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[*] The original position was that continuous contact was required throughout all maneuvers. However, after much discussion and analysis, this was revised to requiring contact only at the start of each burn.

Table 1 lists the total number of maneuvers (broken into Delta-V [DV] translational and Delta-H [DH] attitude burns) required either to perform apogee-raising, separate the spacecraft for safety before it, or get back into formation afterwards. (The reason why perigee-raise maneuvers were needed following apogee-raising will be described later in the paper.) Table 2 then gives the planned parameters for each of the eight apogee-raise burns performed by each spacecraft.

Table 1. Number of Apogee-Raise-Related Maneuvers.

Maneuver Type	Number of DVs	Number of DHs	Total
Formation resize (Phase 1, to 60 km)	6	7	13
Apogee-raise	32	32	64
Perigee-raise	4	4	8
Formation Initialization (Phase 2b 160 km)	6	7	13
Total	*48*	*50*	*98*

Table 2. Planned Apogee-Raise Maneuvers.

Burn ID	Δv: finite burn; equivalent perigee impulse (m/s)	Post-burn Apogee Radius (R_E)	Post-burn period (hr)
Phase 1 orbit	*N/A; N/A*	*12.000*	*23.875*
Adder I	35.6; 28.7	12.829	26.159
Adder II	27.9; 24.7	13.634	28.443
Boa I	36.4; 30.9	14.782	31.808
Boa II	30.1; 25.8	15.890	35.173
Cobra I	41.1; 34.0	17.613	40.623
Cobra II	32.1; 27.0	19.260	46.073
Diamondback I	48.6; 38.9	22.218	56.419
Diamondback II	34.1; 28.5	25.000	66.764

Attitude for apogee-raising

The MMS spacecraft spin at approximately 3.05 RPM, with four 60 m long wire booms extended in the spin plane to hold instruments at their tips. The nominal science attitude has the spin axis nearly aligned with Ecliptic North, tipped 2-3 degrees towards the Sun. It is difficult to perform large slews with these flexible-body spacecraft, so the apogee-raise maneuvers were performed in science attitude. (In any case, the ideal attitude for apogee-raising would have introduced thermal problems as a result of the Sun angle on the spacecraft.) A key MMS launch window constraint was therefore that Earth oblateness should cause the orbit normal to precess to relatively close to the Ecliptic normal at the start of the apogee-raising campaign in order to keep the cosine losses of the apogee-raise maneuvers moderate. (See [2] for details on the MMS launch window problem.)

In addition, in order to avoid Pythagoras losses, the burns were performed using essentially only the radial (spin plane) thrusters; this led to a small amount of out-of-plane thrusting, but this was equal for all four spacecraft and in any case only produced only an insignificant change in the orbit geometry. Of course, since the radial thrusters spin into and then out of the desired delta-v direction during each spacecraft rotation, they had to be modulated on and off at approximately 3.05 RPM. This reduced the net spacecraft acceleration, making the AR burn durations greater than if the spacecraft had been three-axis stabilized.

A small attitude slew, referred to as a DH maneuver, followed around 4-6 hours after each apogee-raise DV burn: this was used to clean up spacecraft attitude, as well as to help null any wire boom dynamics that may have been excited by the DV. These DH maneuvers will be returned to later in the paper.

Navigation for apogee-raising

The orbit determination data that is used as input to the Formation Design Algorithm (FDA) [4][5] is produced by the on-board Goddard Enhanced Onboard Navigation System (GEONS) [6]. GEONS estimates the spacecraft's position, velocity, clock bias, clock bias rate, and clock bias acceleration using an Extended Kalman Filter (EKF) coupled with a high-fidelity dynamics model to process GPS L1 pseudorange (PR) measurements referenced to the Ultra-Stable Oscillator (USO) clock. The Navigator's weak signal acquisition capability allows the receiver to acquire and track GPS signals well above the GPS constellation and deliver highly accurate navigation solutions. The key MMS on-board orbit determination (OD) requirements were designed to ensure that the FDOA team would be able to safely and accurately maintain the range of nominal formation sizes throughout the mission. Given the extreme importance of SMA for evaluating formation persistence, the most critical requirement from GEONS is to determine SMA accurately. This is best evaluated from state data obtained after each perigee passage, when the MMS orbit passes below the GPS constellation: GEONS therefore has access to main lobe signals from typically 12 GPS satellites through perigee.

The interested reader is referred to the companion paper [11] for a detailed discussion of the performance of the MMS navigation system throughout the apogee-raise campaign.

TDRS visibility for apogee-raising

As mentioned previously, it is required that any maneuvering MMS be in contact with the Mission Operations Center (MOC) at least for the start of its burn. Since the apogee-raise maneuvers occur around perigee, where visibility from ground stations is limited, these maneuvers were monitored using the Tracking and Data Relay Satellite System (TDRSS). However, the burn arcs were quite large (up to roughly ±90 deg from perigee), so the ranges of longitudes covered by any given AR burn was up to around 180 deg. In some cases, this entire arc would be in view of a single TDRS, but in others (9 of the total of 32 burns) a transition from one TDRS to another had to occur during the burn. Fig. 1 shows that, for instance, the first four AR burns began under TDRS-East coverage but then switched to TDRS-West. This transition took a total of 8 minutes out of the total burn time of approaching an hour. It should be noted that the MMS orbital period in Phase 1 was close to 24 hr, leading to a groundtrack that nearly repeated from day to day. It would therefore have required an extremely long time to wait for the burn arc to "walk" around in longtitude to a geometry where these burns could be monitored using a single TDRS. This was consequently not a practical option.

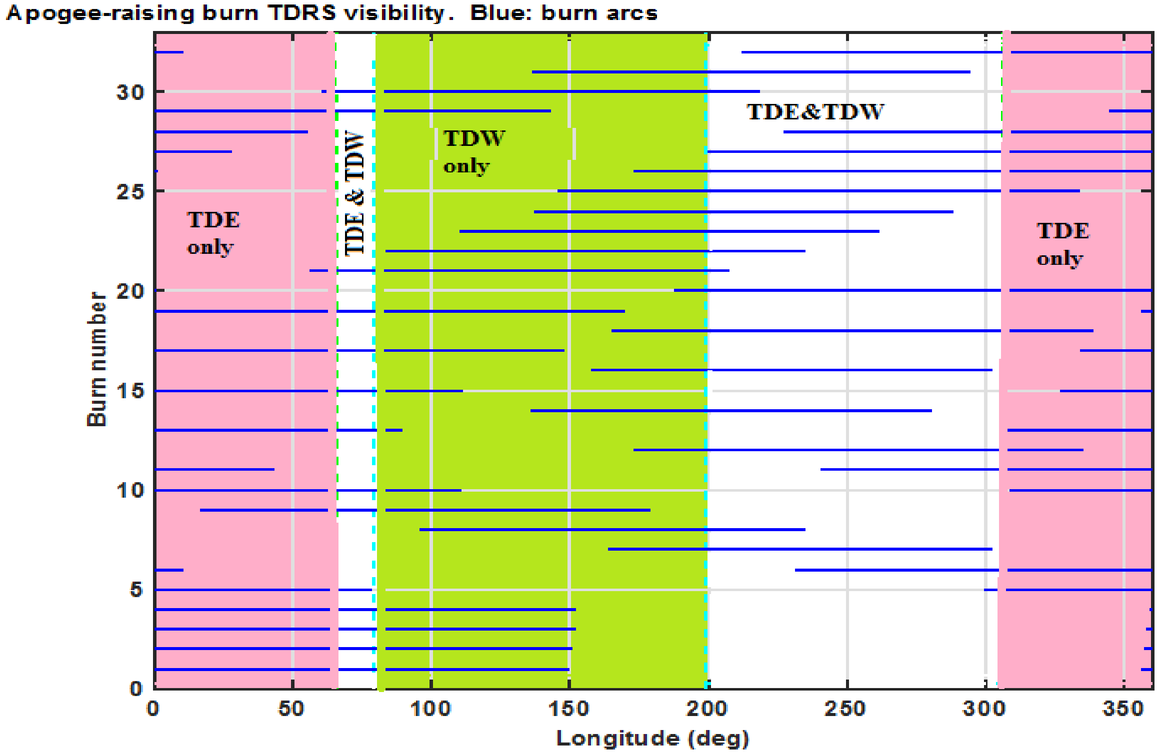

Figure 1. Longitude ranges, and thus TDRS visibility, of the AR burns.

APOGEE-RAISE CONTINGENCY RECOVERY MANEUVER DESIGN

If a spacecraft misses a burn or performs a partial one, it will no longer complete apogee-raising at the same time and general location as the other three. In other words, it becomes a "straggler" and must perform a modified set of maneuvers that are designed to allow it to catch up with the other three MMSs, both in terms of apogee radius and phasing on its orbit. A detailed maneuver design technique was developed before the apogee-raising campaign to achieve this goal; fortunately though, it was never needed.

In outline, the three nominal spacecraft continue their original apogee-raise maneuver sequence, burning on the originally planned perigee passes. The straggler performs a set of burns that are constrained, in order not to lead to excessive gravity losses, to be no larger than the largest Δv in the nominal apogee-raise sequence. The specific orbits on which these burns occur are selected by the contingency maneuver design algorithm in order to satisfy the following criteria. Firstly, if the botched burn was a result of an MMS anomaly, time would generally be required to trouble-shoot: this will define the earliest time at which the first recovery burn can be scheduled to occur. (By contrast, if a missed burn resulted from a ground station problem, recovery could, in principle, be started at the next perigee pass.) Secondly, the straggler no longer has its originally planned orbital period, so its perigee passes come at different times from those intended. The revs on which it maneuvers must be selected so that these burns are not nearly simultaneous with ones being executed by the other three MMSs. These considerations lead to a quite different burn sequence from that originally planned; in fact, in certain cases, the straggler may conceivably arrive at the final orbit before the remainder of the formation.

In addition to reaching the desired apogee radius of 25 R_E, the straggler must also get back in phase with the other spacecraft. This is achieved by breaking the recovery sequence into two parts: this is the "longterm recovery” approach of Ref. 12. The first part performs a series of burns to increase the straggler orbital period to 50 hr, without considering or correcting its relative phasing to the other three MMSs. In the second part, a sequence of two burns is then used to reach not only the desired final apogee radius, but also get back in phase with the other MMSs. The reason for the selection of the intermediate period of 50 hr is that this is sufficiently different from the final period of 66.8 hr that an arbitrary phasing offset can be corrected by waiting only a moderate number of rev (typically 3-6) between the last two burns.

Since gravity losses are limited, by constraining the recovery burns to be no larger than the nominal apogee-raise ones, recovery from a contingency should not increase the total fuel used. The main penalty would be that additional time would generally be required to get into the final formation. This can be seen from the results for a simulated case where MMS2 misses a burn (the second in the AR sequence). It can be seen that MMS2 does not reach the desired final apogee radius (Fig. 2), and desired small ranges to the remaining three spacecraft (Fig. 3) until roughly three weeks after the originally planned date. This delay could likely be reduced somewhat, but it was definitely a concern given the short duration of Phase 2 of the MMS mission. Fortunately though, this remained an academic concern only, as no botched burns occurred during the apogee-raising campaign.

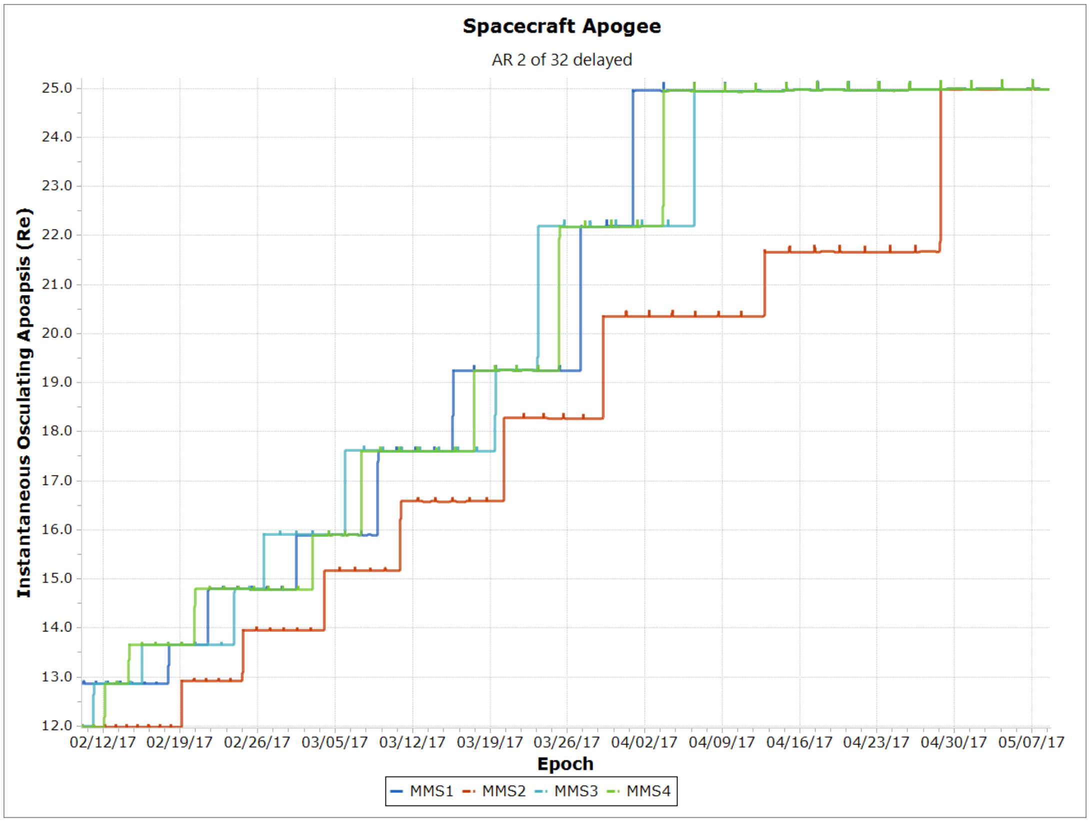

Figure 2. Apogee radii for simulated recovery from missed AR burn 2.

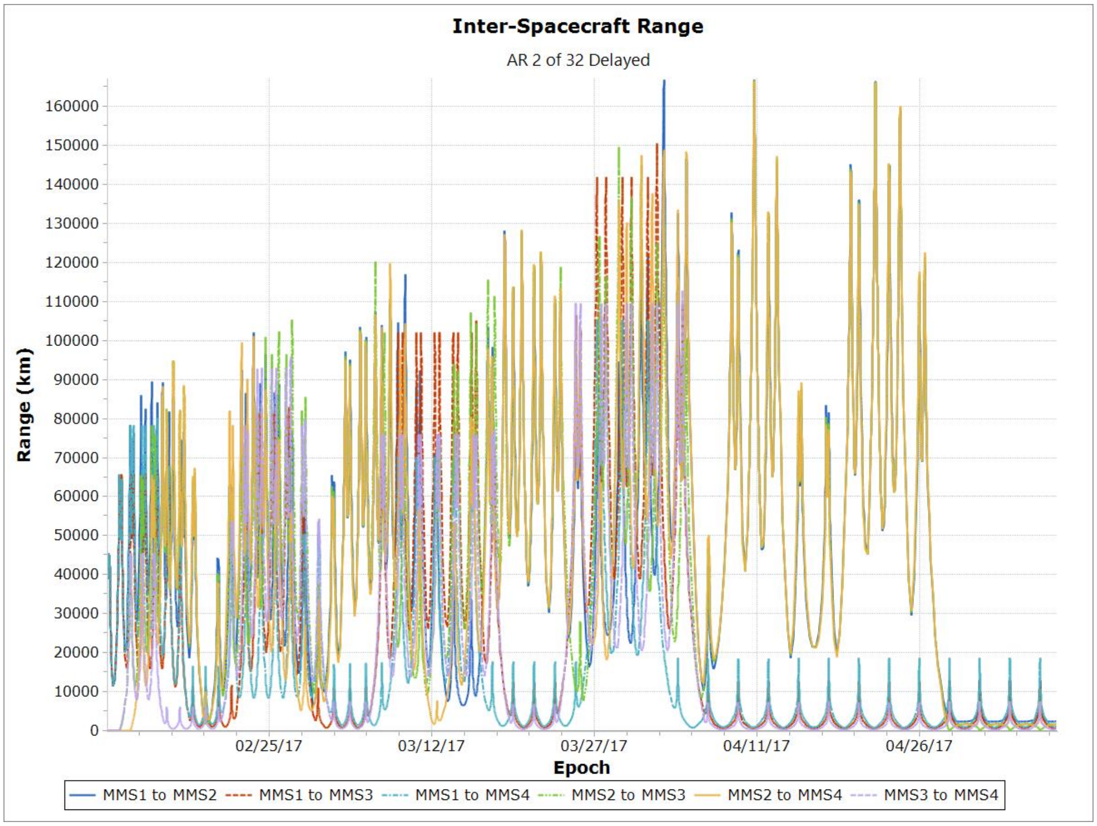

Figure 3. Inter-satellite ranges for simulated recovery from missed AR burn 2.

APOGEE-RAISE CAMPAIGN FLIGHT RESULTS

A fundamental point concerning the performance of the apogee-raising maneuvers is, of course, the evolution of apogee radius thoughout the campaign. Figure 4 shows this for the four spacecraft. Comparing this actual data with the simulated data of Fig. 2 shows how close (with the exception of MMS2, which is the straggler in Fig. 2) the achieved apogee values came to those that were originally planned.

Figs. 5-8 then illustrate the evolution of the six sidelengths between the MMS spacecraft during apogee-raising, with Fig. 5 first showing the entire campaign. It can be seen that the satellites spread apart during the first half of each snake, reaching a wide but stable separation after the first four burns. At this point, each spacecraft has the same apogee radius, and hence the same orbital period: the inter-satellite ranges therefore remain fixed until the fifth and subsequent burns are applied. During this second half of the snake the satellites close in again, reaching relatively close spacings at the end of this snake and before the start of the next. Fig. 6 shows the details of the spacings between the first (Adder) and second (Boa) snakes. It can be seen that the period bias technique that was used for Adder only, as desired for safety, did indeed lead to an increased spacing between the spacecraft. The spacecraft exited Adder roughly in a string of pearls configuration, with MMS4 leading, MMS3 next, followed by MMS2, and finally MMS1, with a spacing between each consecutive pair of approximately 500 km at apogee. Figs. 7-8 show the corresponding ranges after snakes Boa and Cobra, respectively. It can be seen that the minimum ranges come down slightly from those after Adder, but the rough string of pearls configuration, and safety, are maintained.

Since apogee-raising consumed about 40% of the original MMS fuel load, the efficiency of the maneuvers was a significant concern, particularly as it has a major impact on whether an extended mission would be feasible. Fig. 9 shows the fuel remaining on the four spacecraft throughout the apogee-raising campaign. It can be seen that each MMS consumed approximately 160 kg for apogee-raising: this compared favorably with the originally predicted value of 165 kg.

Finally, Table 3 shows the execution errors for all 32 AR burns as determined from navigation data after each maneuver. The tabulated values are the amounts by which the achieved changes in apogee radius differ from those originally targeted. It can be seen that these errors are all positive (i.e. all burns were "hot"), fairly consistent across all eight maneuvers for a given spacecraft, and quite small. In fact, the actual errors are far smaller than the requirements that were imposed on the Delta-V controller, and smaller than was expected prior to apogee-raising. (The controller has been performing much better than specified for formation maneuvers throughout the mission to date, but it was not known to what extent this experience would apply for the very different apogee-raise maneuvers, which required applying an acceleration along a constantly changing direction to track the orbital velocity direction on the burn arc around perigee.) It would therefore actually have been safe to fly the spacecraft somewhat closer than they were during the apogee-raise campaign, with no fear of execution errors inducing conjunctions between MMSs. This lesson may prove useful when MMS performs a small further apogee-raise to 28 R_E radius later in its proposed extended mission. This increase in apogee is designed to magnify lunisolar perturbations: these drive down perigee, so ensuring that MMS reenters within 25 years of the end of its active mission. If apogee radius were to remain at 25 R_E, a side effect of the perigee-raise maneuvers during Phase 2a (described later in the paper) and during the extended mission is that MMS would violate the 25 year rule, which is a key step taken to prevent the creation of orbital debris. Increasing apogee to 28 R_E overcomes this problem, and has the additional benefit of providing enhanced science data.

Table 3. Apogee-Raise Maneuver Execution Errors (%).

Burn ID	MMS1	MMS2	MMS3	MMS4
Adder I	0.053	0.292	0.023	0.035
Adder II	0.035	0.032	0.030	0.035
Boa I	0.032	0.033	0.024	0.037
Boa II	0.049	0.042	0.015	0.033
Cobra I	0.044	0.038	0.021	0.038
Cobra II	0.048	0.033	0.011	0.044
Diamondback I	0.046	0.041	0.022	0.029
Diamondback II	0.046	0.040	0.020	0.026

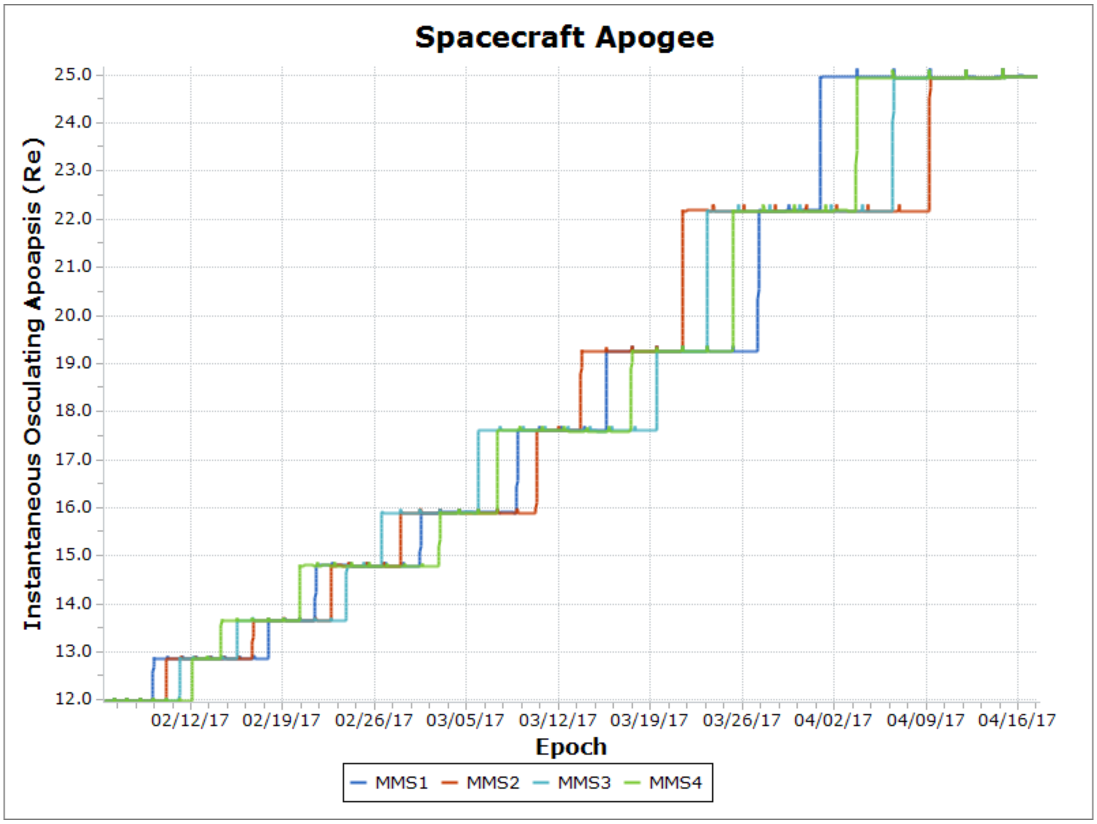

Figure 4. Evolution of apogee radii throughout AR campaign.

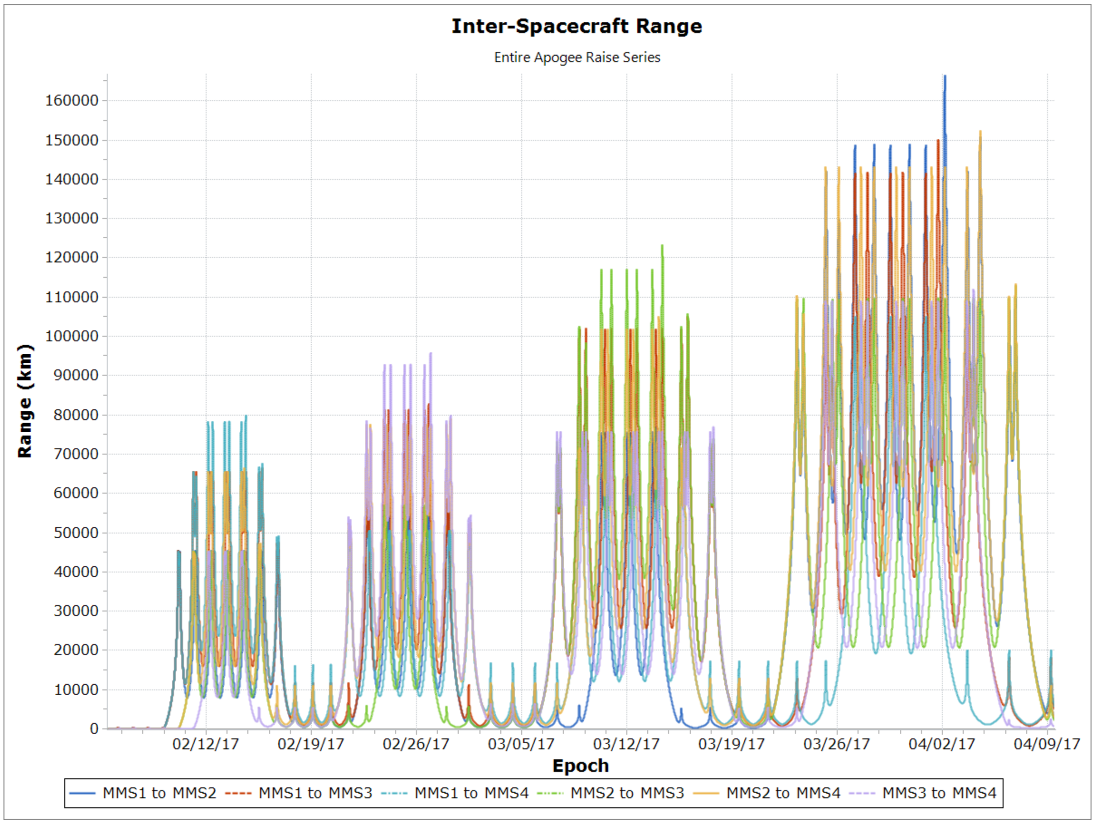

Figure 5. Inter-satellite ranges throughout AR campaign.

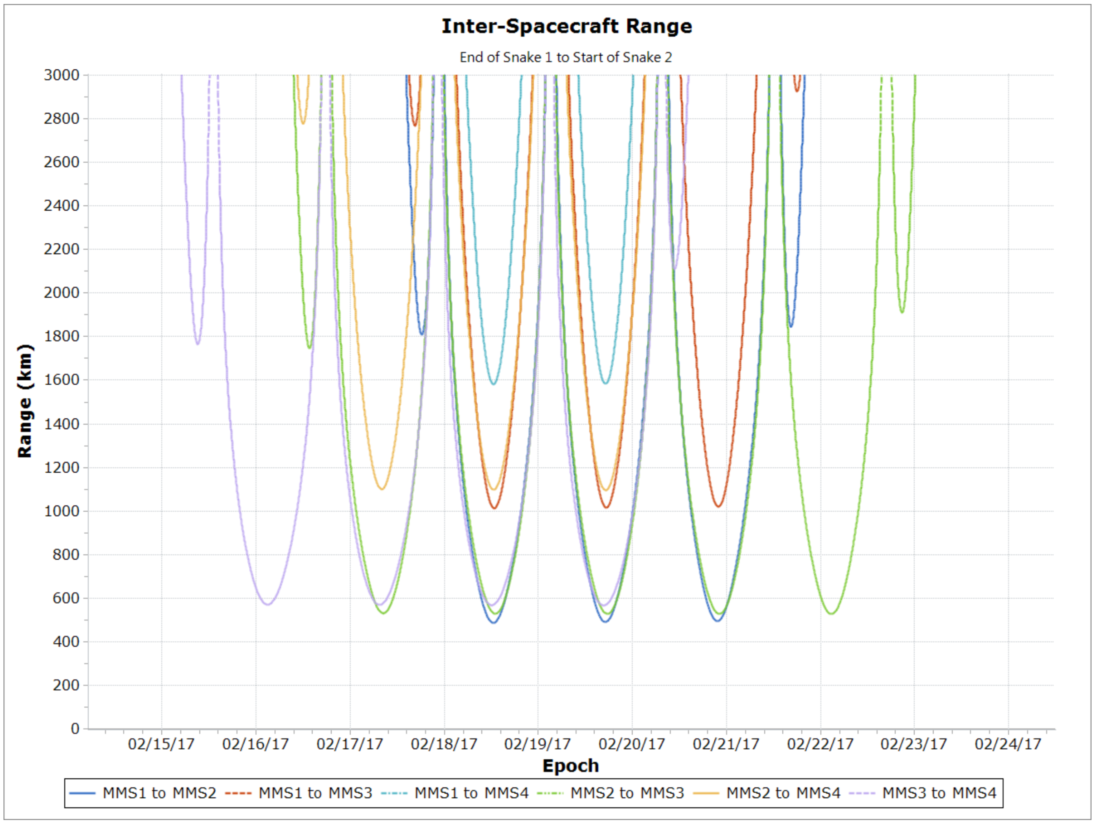

Figure 6. Inter-satellite ranges, snakes Adder to Boa.

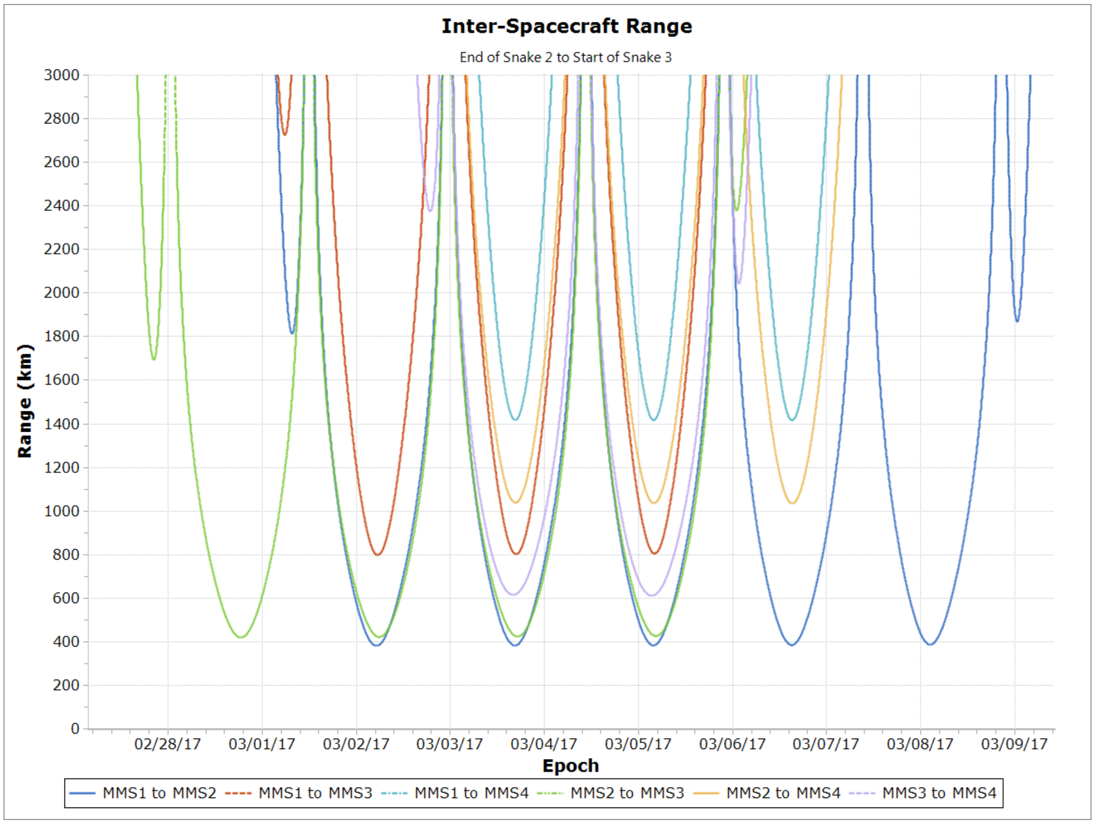

Figure 7. Inter-satellite ranges, snakes Boa to Cobra.

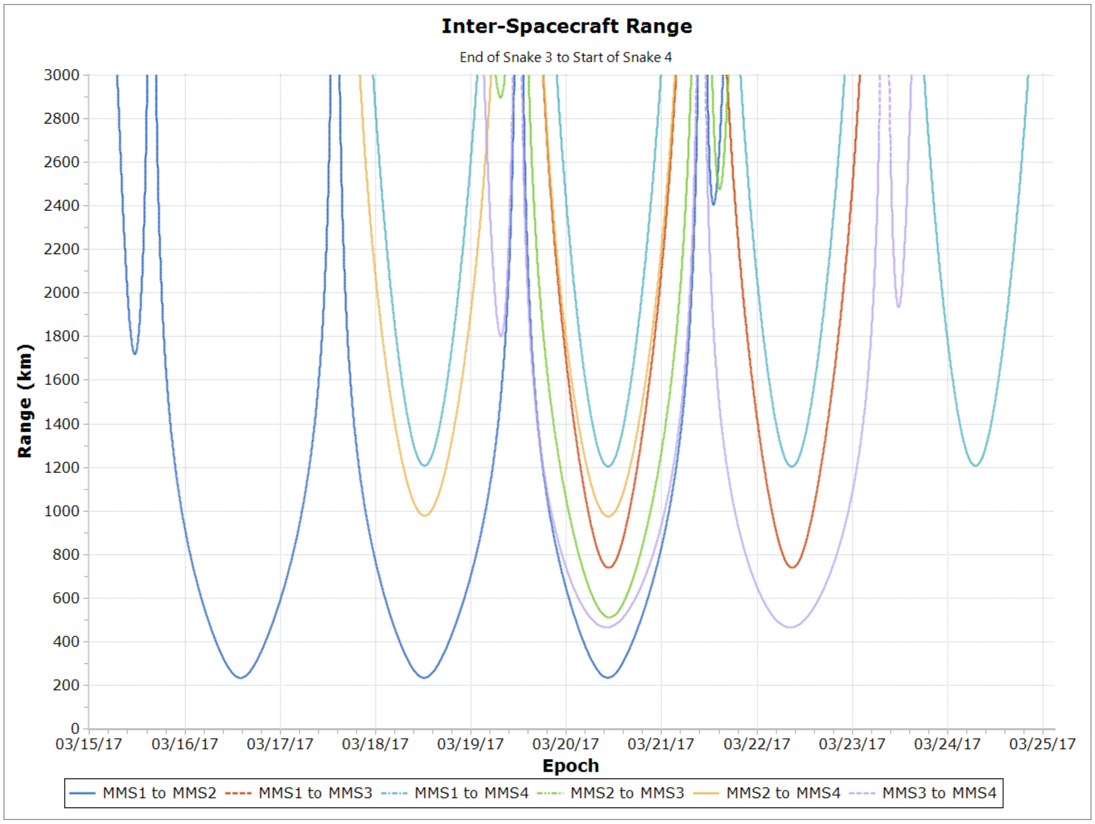

Figure 8. Inter-satellite ranges, Cobra to Diamondback.

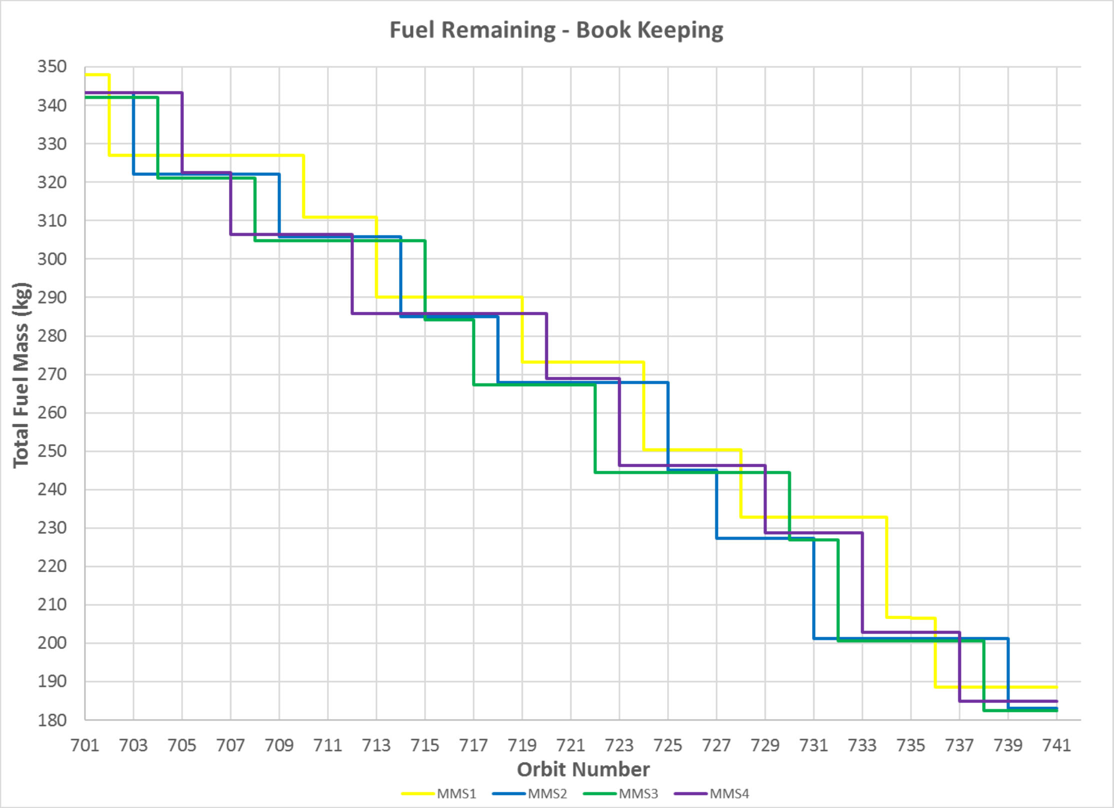

Figure 9. Fuel remaining throughout AR campaign.

EFFECTS OF MANEUVER EXECUTION ERRORS ON TDRSS CONTACTS

The maneuver execution errors that were originally predicted for apogee-raising were expected to potentially lead to difficulties with acquiring the spacecraft during later communication passes. For this reason, it was planned to update the acquisition predicts as soon as possible based on post-maneuver navigation measurements. A complication is that the process noise gains of the GEONS navigation filter must be “opened” prior to each delta-v maneuver, in order to prevent the navigation solution from diverging as a result of the large non-gravitational accelerations produced by thrusting. However, this greatly reduces the accuracy of the orbit determination solution. For example, the standard deviation of the estimate for the semi-major axis, a key navigation parameter, is typically at most tens of meters when not maneuvering, but increased rapidly to around ten kilometers immediately after an apogee-raise burn. Consequently, the earliest that the GEONS solution returns to typical non-maneuvering accuracy is after the perigee pass following the maneuver, when the large number of GPS signals tracked around perigee provides enough good data to “reset” the GEONS solution.

The original plan was therefore to provide updated acquisition predicts based on the GEONS solution from the first post-maneuver perigee pass. This data is sent to the ground during post-perigee TDRSS passes. Acquisition during these passes themselves would be based on pre-maneuver predictions: this was expected to suffice, especially given the small maneuver execution errors that were discussed in the last section. However, difficulties were encountered acquiring MMS1 immediately before the perigee following the first AR burn: TDRS saw a signal from MMS1, but it was too weak to acquire. This was initially thought to be unrelated to maneuver errors, particularly as MMS4 had also recently had a failed TDRSS pass that was attributed to problems on the ground. However, on the next rev (the first pre-perigee pass following MMS2’s first AR burn), TDRS was again not able to acquire data from MMS2. At this point, it became clear that execution errors were somehow causing acquisition difficulties, and the original plan of waiting for post-perigee data to update the predicts was not workable.

Fortunately, an alternative did exist: as previously noted, DH slew maneuvers were carried out 4-6 hours after each apogee-raise maneuver, on Deep Space Network (DSN) passes. The original assumption was that the GEONS navigation solution would still be significantly degraded at this point as a result of the filter being opened up for the delta-v maneuver. However, further analysis showed that the solution was already reasonably accurate at this point, and indeed accurate enough for acquisition use. The modified approach was therefore to downlink the GEONS solution from the DH passes, use this to produce updated TDRS acquisition predicts, and deliver these to the Space Network (SN) in White Sands prior to the TDRS passes immediately before the first post-maneuver perigee. This approach worked well, with no more missed TDRS passes being encountered during the apogee-raise campaign.

The reasons for the TDRS acquisition difficulties were initially somewhat unclear, as the small maneuver execution errors did not alter the MMS position enough to push it outside the TDRS field-of-view. (For instance, the period error produced by the first MMS1 burn was about 1.7 s, giving a position offset of only around 16 km.) However, it was determined that the culprit was actually Doppler errors: these vary quickly around perigee, where the MMS velocity vector is large and rapidly changing direction. These must be taken into account in a TDRSS link and, if estimated incorrectly, can prevent locking onto the MMS signal.

Figs. 10 and 11 compare the position and velocity errors, respectively, resulting from the DH GEONS solution (blue curve, upper subplot) with those resulting from the predicted maneuver orbit estimate (blue curve, lower subplot). It can be seen that, at the post-maneuver perigee (the spikes near the right-hand side of both subplots), the improvement in velocity error is at least a factor of 50. Since velocity error is the key factor that causes Doppler difficulties, this confirms the reasoning that using the DH navigation solutions should indeed work well for allowing successful TDRSS acquisition following each apogee-raise maneuver.

The interested reader is referred to [11] for further details on MMS navigation performance during the apogee-raising campaign.

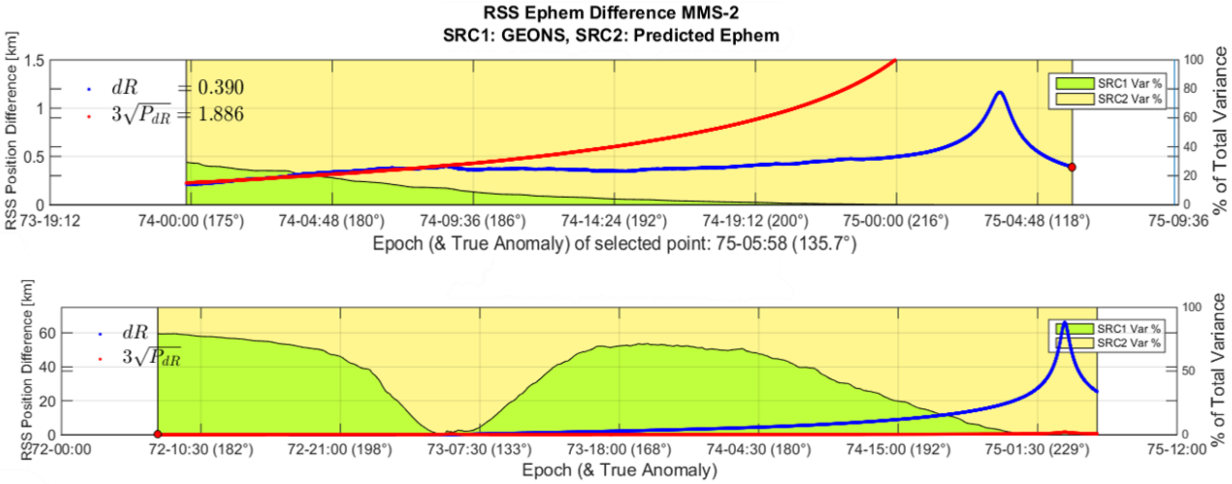

Figure 10. Position differences resulting from maneuver execution errors.

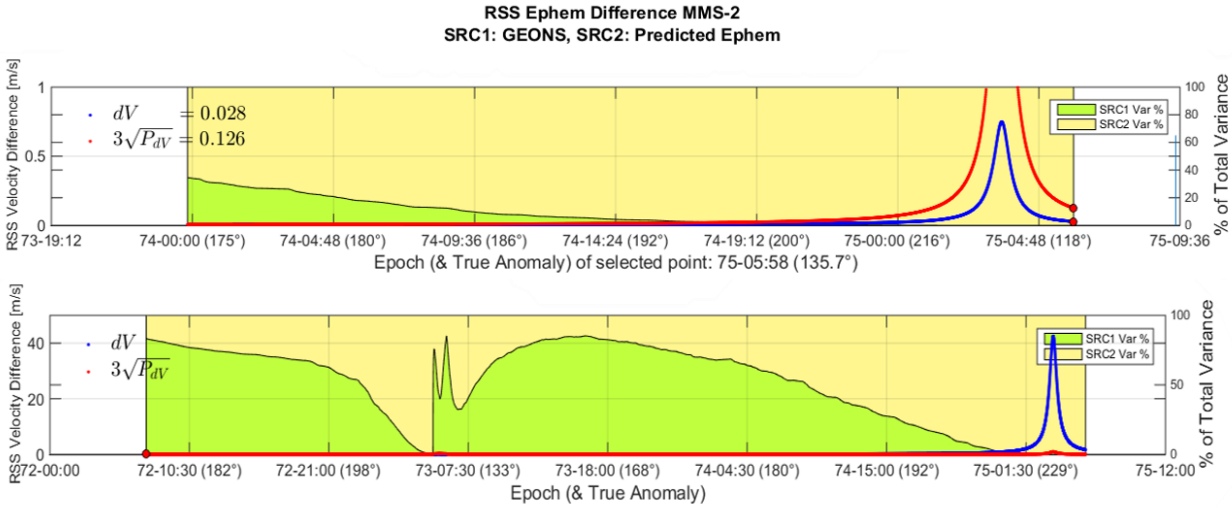

Figure 11. Velocity differences resulting from maneuver execution errors.

MMS PERIGEE-RAISING MANEUVERS

Need for perigee-raising

Raising apogee radius from 12 to 25 R_E would obviously be expected to result in increased orbital perturbations caused by the gravitational attraction of the Sun and Moon. However, it is striking just how much larger these effects actually become. For example, one of the key consequences of lunisolar perturbations is a variability in the inclination of the satellite orbit. Examining the equatorial inclination of MMS shows that it only moved from the initial value of 28.7 deg by about 0.2 deg throughout the first year in the 12 R_E Phase 0/1 orbit. By contrast, it will decrease to 1.3 deg during the first year in the Phase 2b orbit and, some years after that, it will exceed 73 deg.

The other key lunisolar effect is a variation in perigee radius: this linked variation of inclination and perigee radius is termed the *Kozai mechanism* [9]. This effect is again quite pronounced for the MMS Phase 2b orbit, whereas it was not significant during Phases 0 and 1. An important implication for MMS flight dynamics is shown in Fig. 12 (blue curve): this is that, if no action were taken to counteract them, lunisolar effects would cause the spacecraft to reenter in Jan. 2018, so precluding an extended mission.

Implementation of perigee-raise maneuvers

The original plan was to reboost perigee by means of a set of maneuvers, two per spacecraft, that were combined formation maintenance/perigee-raise burns. However, these were found in simulations to be quite inefficient in fuel terms: the first burns would typically push perigee down while achieving the formation targets, requiring the second burns to push perigee up considerably to reach the desired value. It was determined that approximately 15 kg of fuel could be saved per spacecraft if a dedicated set of perigee-raise maneuvers, one per spacecraft, were carried out on a single apogee pass shortly after the end of apogee-raising. At this point, the satellites were not yet back in formation, so the perigee-raise and formation maintenance functions were decoupled. The green curve in Fig. 12 shows the results obtained for a preliminary simulated perigee-raise of 400 km (the final value that was selected was 600 km): this can be seen to keep perigee altitude above the specified lower limit of 900 km throughout the summer of 2017 (i.e. Phase 2b).

The final implementation was termed a Perigee-Raise/Orbit Stabilization (PR/OS) maneuver, and was a combination of PR and OS maneuvers that were carried out during Phase 0 of the mission. The difference between this and a simple PR burn is that the spacecraft initially raise perigee by differing amounts, as seen in the large spikes on Apr. 16, 2017 in Fig. 13. This gives them differing semi-major axes (Fig. 14), and so differing periods, so causing them to drift closer together (Fig. 15). Since the total spread between the four spacecraft at the completion of apogee-raising is approximately 1,100 km, and the initial tetrahedron that is set up by the Formation Initialization maneuvers (the two discontinuities in late April/early May in Figs. 13 and 14) has size 160 km, this would require a considerable amount of fuel if all achieved by Form Init. It is much more efficient to achieve this resizing by means of a slow drift introduced by the PR/OS maneuvers. Fig. 15 shows the resulting inter-satellite ranges: these were indeed driven from a maximum spread of 1,100 km down to about the formation scale size before the Form Init burns were applied. The resulting Form Init fuel usage was quite moderate as a result of this drifting technique.

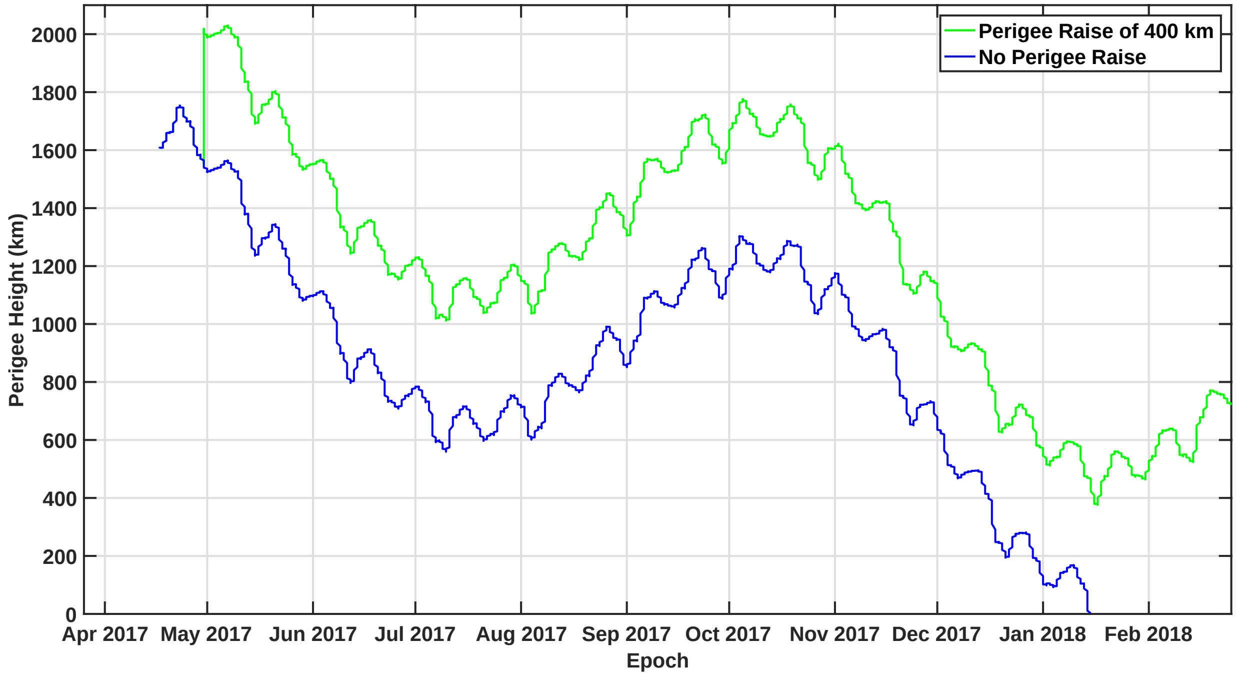

Figure 12. Perigee altitude, Phase 2b and beyond, with and without 400 km PR.

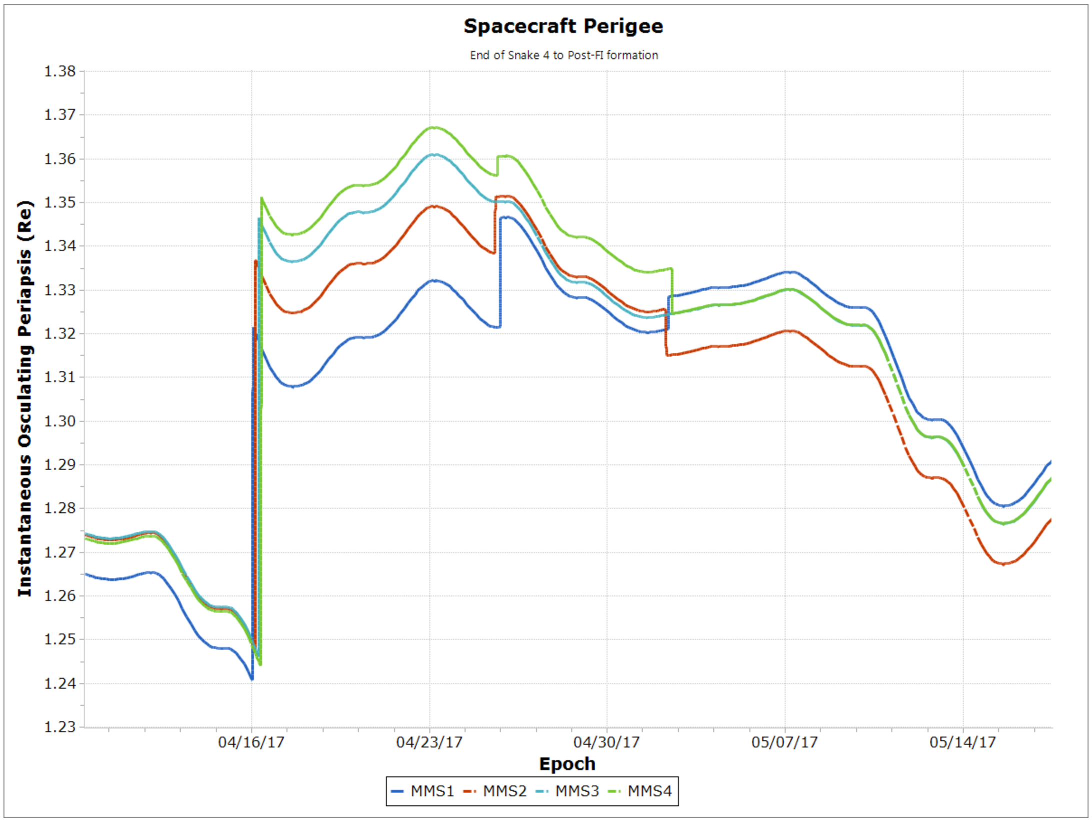

Figure 13. Perigee radii, PR/OS and Formation Initialization.

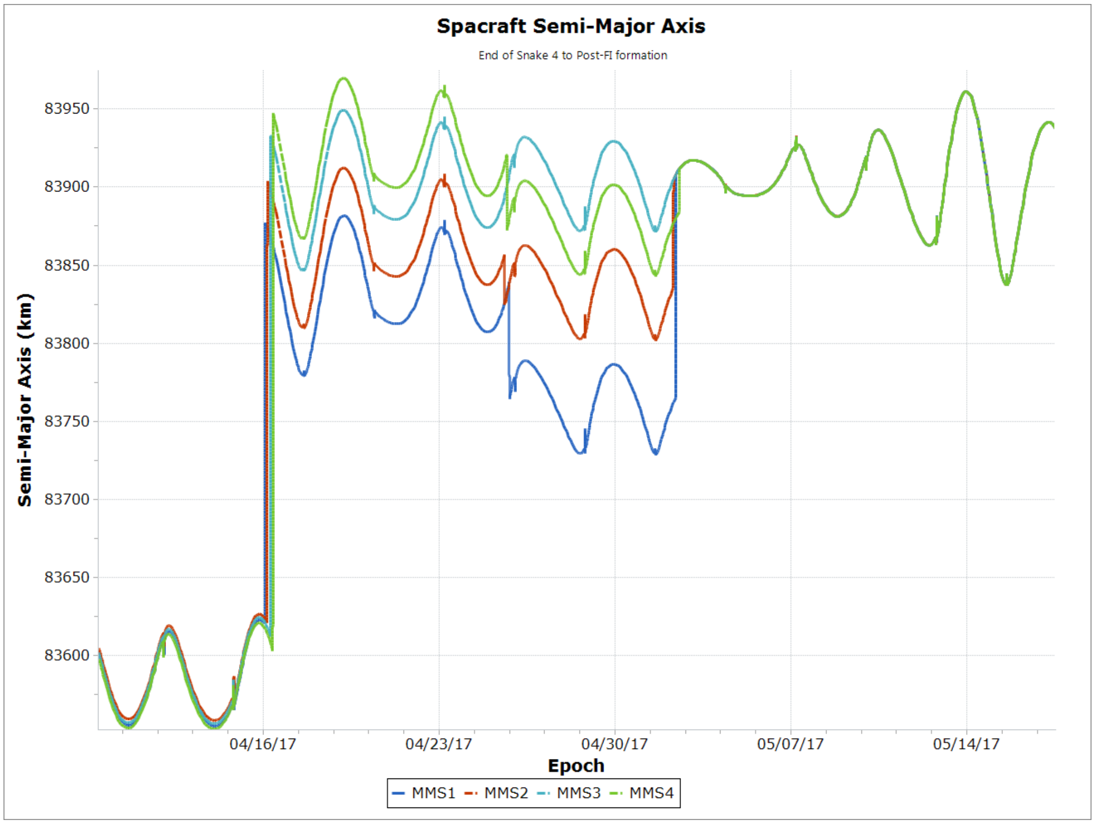

Figure 14. Semi-major axes, PR/OS and Formation Initialization.

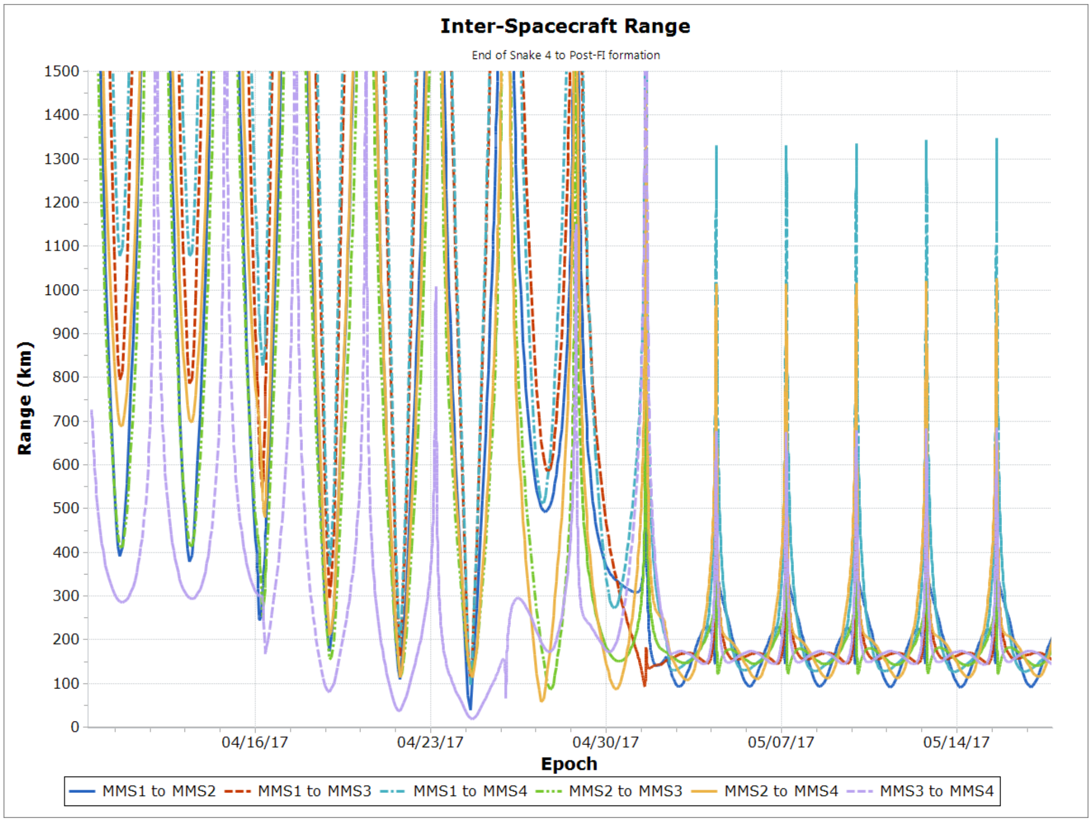

Figure 15. Inter-satellite ranges, PR/OS and Formation Initialization.

CONCLUSIONS

This paper has described the apogee-raising campaign of the Magnetospheric Multiscale mission, where the spacecraft increased their apogee radii from 12 to 25 Earth radii in a total of 98 maneuvers: an initial formation resize set to spread the spacecraft apart for safety, 32 apogee-raise delta-v maneuvers, their associated slews, four perigee-raise maneuvers and the associated slews, and finally a set of maneuvers to get back into formation. These activities were all accomplished successfully and on schedule with no anomalies, and at a fuel consumption somewhat less than predicted. As a result, MMS was set up ready to carry out *in situ* studies of magnetic reconnection in the magnetotail, with sufficient fuel remaining for a significant extended mission.

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