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MMS EXTENDED MISSION DESIGN: EVALUATION OF A LUNAR GRAVITY ASSIST OPTION

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This paper describes maneuvers that were recently considered for a later extended mission phase for the Magnetospheric Multiscale (MMS) mission. These are apogee-raises to set up a lunar gravity assist, which in turn raises perigee for enhanced magnetopause science collection, followed by apogee-lowering to inject into a 3:1 lunar resonance orbit. Since a lunar encounter is only achievable when the MMS apogee vector lies approximately in the lunar orbit plane, the possible dates are mid-2021 or early 2027. This study was made feasible by the fact that MMS is consuming fuel for formation maintenance at a far slower rate than expected pre-flight, and completed the prime mission with a significant amount of fuel remaining.

INTRODUCTION

The NASA Magnetospheric Multiscale (MMS) mission is flying four spinning spacecraft in highly elliptical orbits to study the magnetosphere of the Earth [1][2]. 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 [3]. After roughly 5 months of commissioning, the spacecraft were flown in tetrahedron formations of varying dimensions [4][5] for science data collection. 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 (radius 12 R_E). The goal during Phase 1 was to observe the magnetic reconnection events that are expected to occur near the magnetopause, where the solar wind impinges upon the magnetosphere. Measurements during the later Phase 2b, after apogee radius was increased to 25 R_E (roughly two fifths of the way to the Moon), were taken in the magnetotail [6], 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. The prime mission was completed successfully in Sept. 2017, and MMS is currently carrying out further science data collection in an extended mission.

This paper describes a study that was carried out on the design of a set of maneuvers that were considered for the later stages of an extended mission. The goal of these maneuvers was to put MMS into a significantly different orbit from those flown heretofore, so allowing science collection in a different region of the magnetosphere. This study was made feasible by the fact that the rate at which fuel is being consumed to maintain small formations on the MMS high-apogee orbit is less than expected pre-flight: the current consumption rate is only about 2 kg/yr/spacecraft, compared to 12 kg/yr/spacecraft that was expected pre-launch. In addition, the spacecraft finished the prime mission with a significant amount of fuel remaining: this was about 1-sigma above the mean when compared with pre-launch Monte Carlo simulations. The resulting situation is similar to that of a libration orbit mission, where station-keeping requires so little fuel that any margin at all will lead to an extensive mission lifetime. In the case of MMS, the spacecraft could, if desired, perform formation flying in the current orbit for several decades.

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Alternatively, the spacecraft could use a significant fraction of the remaining fuel to perform major orbit modifications, while still leaving enough to conduct formation flying for on the order of a decade.

For the highly eccentric MMS orbit, the most efficient type of maneuver by far is a change in apogee. The extended mission maneuvers studied here are apogee-raises, with the goal of setting up one or more lunar gravity assists. Geometry dictates that a lunar encounter is only achievable when the MMS apogee vector lies approximately in the lunar orbit plane: Fig. 1 shows that this limits the possible dates to mid-2021 or early 2027. Unlike the staggered burns of the previous MMS apogee-raise campaign [7], the maneuvers that set up a gravity assist must be performed simultaneously by all four spacecraft, in order to achieve the desired lunar phasing.

The goal of the lunar gravity assist is to use the gravity of the Moon to produce an orbit alteration that is desirable for science and beyond what would be achievable by purely propulsive means. Two objectives have been considered: either rotating the plane of the MMS orbit so as to better align it with the magnetotail neutral sheet [6] (improving nightside science), or raising perigee with the goal of "skimming" the magnetopause (improving dayside science). Raising perigee is far more difficult than altering apogee for the MMS orbit: expending all of the remaining fuel would allow a propulsive change in perigee of less than 1 R_E. By contrast, a lunar encounter can easily raise perigee radius to 10 R_E or more: see the red contours on the B-plane targeting plot of Fig. 2.

Note that a significant consideration here is that the MMS orbit is pre-defined, as opposed to the case of a to-be-launched mission, where the launch window can be defined so as to set up the desired conditions at the Moon. By contrast, MMS has only a limited capability to alter its approach conditions: the design variables are basically the arrival time, and the apogee radius of the pre-encounter orbit. The implications of this will be analyzed in the paper.

If the post-encounter orbit is to remain stable, with no untimely reentry or escape, it is necessary to prevent future unplanned lunar close approaches. This can be achieved by putting MMS into an orbit with a 9 day period (i.e. in a 3:1 resonance with the lunar orbit), and phased so that each MMS apogee is as far as possible from the Moon. The IBEX spacecraft has been in such an orbit for around 8 years, and has not had to perform any reentry-prevention burns [17]. In May 2018 the TESS spacecraft was placed into a 2:1 lunar resonance orbit for similar reasons [18]. Putting MMS into a 3:1 resonance orbit involves lowering apogee some time after the lunar encounter, which again is a comparatively efficient maneuver.

Two examples of the resulting science resonance orbits will be described in the paper. The corresponding fuel budgets will be given, showing that a modest margin remains in each case. It has also been shown by detailed simulation that the MMS GPS-based navigation system [8] performs well even at these extreme altitudes, far above the GPS constellation: this greatly exceeds all pre-flight expectations. In addition, the orbits have been demonstrated to be stable for at least five years without perigee-raise maneuvers, providing a significant time for science data collection. In terms of science, the time that each spends in the neutral sheet, and the number and location of magnetopause and bow shock crossings, will also be shown.

Note that lunar gravity assists were also considered [9] in the early stages of MMS mission design, making up what was then termed Phases 3 and 4. However, a significant difference between the old studies and the current one is the delta-v available: this was assumed to be in the range 400-1,000 m/s in the original Phase 3/4 designs, but is only about 180 m/s now. The large original delta-v values did not fit within the MMS fuel budget, which led to the elimination of these mission phases. Careful maneuver design and execution has brought back the possibility of a lunar gravity assist, but with significant constraints that result from the more modest propellant that is available in reality. The implications of these constraints will be discussed in the paper. In addition, the pre-defined high inclination of the MMS orbit to that of the Moon at the encounter epochs makes double lunar swingbys of the type discussed in [9] infeasible: this will also be discussed.

The decision taken by the MMS science team was to remain in the 28 R_E apogee radius orbit and fly in formation for as long as possible. This decision was taken because the team is very happy with the science data that is being collected in this orbit, and wishes for it to continue. It must be borne in mind though that the remaining fuel must somehow be expended at the end of mission, in order to passivate the spacecraft. This could be done by performing a plane change or perigee-lowering, or possibly by taking advantage of the second family of lunar gravity assist opportunities that occurs in 2027. If the latter option were to be executed, the study described in this paper will form useful background information.

AVAILABLE FUEL AND IMPLICATIONS FOR EXTENDED MISSION OPERATIONS

The MMS spacecraft each had roughly 40% of the original fuel load of 412 kg still remaining at the end of the prime mission. The reasons for this are, to a large extent, that certain operational changes were made to the mission after the propulsion system was sized, and often after launch. Notably, the perigee altitude at which the spacecraft were released was originally to be 240 km; however, the performance margin of the Atlas launch vehicle allowed this to be increased to 585 km, saving approx. 17.3 kg of fuel per MMS for raising perigee altitude to the nominal value of 1,276 km. In addition, the 400 km formation in Phase 2b was deleted by the science team after examining the data collected during Phase 1, where the science collected while flying in smaller formations was generally the most interesting. This deletion resulted in an average savings of 8 kg per spacecraft. Also, lunisolar perturbations required that perigee altitude be reboosted by 600 km just prior to the start of Phase 2b. The pre-launch planned maneuvers to accomplish this consisted of two combined perigee and formation burns per spacecraft. However, these were found to be quite inefficient: the first burn typically decreased perigee in the course of setting up the desired formation geometry; the second burn then had to provide not only the desired perigee reboost, but also make up the perigee decrease produced by Burn 1. Replacing this scheme by a single dedicated perigee maneuver per MMS near apogee saved approx. 15 kg per spacecraft. Finally, the pre-launch allocation for attitude control burns throughout the prime mission was 25 kg; the actual usage was found to be less than 1 kg.

Taking these changes into account, the results of an extensive series of pre-flight Monte Carlo runs were modified to better reflect actual flight conditions. The resulting predicted fuel loads at the end of the prime mission had a minimum of 98.4 kg, a mean of 148.9 kg and a maximum of 198.6 kg. By comparison, the actual fuel remaining at the end of the prime mission (from bookkeeping analysis) spanned the range 162.7-169.5 kg across the four spacecraft: this is roughly one standard deviation above the modified predicted mean value. Given that considerable care was taken during operations to perform formation maneuvers as efficiently as possible, this indicates good agreement between the predicted and actual fuel usage.

Another aspect of the difference between pre-flight predictions and actual operations is the rate at which fuel is used to remain in formation. A reasonable pre-launch prediction for this consumption rate in the high Phase 2b orbit was 12 kg per MMS per year. However, it has been found that the actual rate is more like 2 kg/yr/spacecraft on average across the fleet. One major reason for this reduction is the superior performance of the onboard closed-loop DV controller. This controller [14] has been demonstrated to regularly produce maneuver execution errors that are considerably smaller than the specified levels. This then leads to formations that persist for longer durations than were expected before launch, so leading to less frequent maneuvers and a decreased fuel consumption rate. In addition, formation flying in the 3-day Phase 2b orbit is inherently more efficient than in the 1-day Phase 1 one, with any inter-satellite drift rates that are produced by execution errors being naturally lower. Finally, the science team has again requested that the spacecraft fly in smaller formations than originally planned:

months have been spent at a 20 km scale size, as opposed to the pre-flight minimum planned size of 30 km. Since maneuver magnitudes are roughly proportional to formation size, this change has also contributed to the low fuel consumption rate.

The consequence of these various effects is that the MMS spacecraft will each have approximately 120 kg (29%) of fuel remaining available for extended mission operations following a "mini-apogee-raise" to 29 R_E in early 2019: this is clearly more than sufficient to remain in formation up until reentry, which will occur, as a result of lunisolar perturbations, in 2030. Even if a minor perigee-raise maneuver is used to delay reentry to the next possible date of 2036, considerable fuel will still remain. There is now a requirement that all spacecraft be "passivated" at the end of their active operations, by expending all energy sources (notably fuel and battery energy), so as to prevent a future debris-producing explosive event. Consequently, significant maneuvers will have to be performed at some point later in the MMS extended mission in order to drain the fuel tanks. It would clearly be desirable to have these maneuvers achieve some useful goal, rather than executing them purely for the purpose of burning fuel. The set of such goals that have been considered for MMS will now be examined.

POSSIBLE MANEUVERS FOR LATER EXTENDED MISSION

Apogee-Lowering

The first candidate maneuver type that was studied was an apogee-lowering campaign, with the following motivation. The initial MMS apogee radius of 12 R_E was selected so as to put apogee in the vicinity of the magnetopause on the sunward side of the magnetosphere. After two passes through this dayside science region, the raising of apogee to 25 R_E was to allow science data to be collected in the down-Sun magnetotail. There would definitely be scientific interest in lowering apogee back to 12 R_E again, in order to carry out additional magnetopause campaigns. This is despite the secondary consideration that operations would become somewhat more expensive, as many flight dynamics procedures (e.g. delivering ephemeris data) is done once per orbit, and so would now have to be performed more frequently.

A study was therefore carried out of how far apogee could be lowered if all of the "excess" MMS fuel was used for this purpose. Lowering apogee radius all the way to the original 12 R_E would not be possible, as the available fuel mass is 120 kg per spacecraft, and the orginal apogee-raising campaign used around 160 kg. However, an open question was how close apogee could be brought to this original value. After extensive study, it was determined that apogee radius could only be reduced to around 18.5 R_E, coincidentally halfway between the Phase 1 and Phase 2b values. This value assumed that the planned apogee-raise to 28 R_E proceeds as planned in 2019; however, even if MMS remained at its current 25 R_E apogee radius, expending all available fuel would only lower the achievable apogee radius to about 17.5 R_E. Neither of these values is low enough to lead to a significant increase in the number of magnetopause crossings: neither one is therefore of interest for improving dayside science.

Flight in Extremely Large Formations

The Cluster II mission has flown its four spacecraft in configurations (not always approximating regular tetrahedra) with inter-satellite ranges of up to several thousand kilometers. Consideration was therefore given to using the available fuel to fly MMS in very large tetrahedral formations with similarly large scale sizes. One complicating factor is the significantly higher eccentricity of the MMS orbit: 0.92 vs 0.76 for the 2.5 x 18.3 R_E Cluster orbit. The variability of inter-satellite ranges from apogee to perigee is therefore greater for MMS than for Cluster, somewhat complicating the design of viable formations. In addition, it was found that the MMS Formation Design Algorithm (FDA) that is used to generate the maneuvers that are required to put the spacecraft into a desired tetrahedron would produce excessively large Δvs unless the increase in scale size were limited to around 200 km. Resizing to a scale size of several thousand kilometers would therefore have to be carried out in many steps: this would necessarily take a considerable time, probably several months. In addition, the FDA usually generates a tetrahedron with an orientation different from that of the old when generating a new set of maneuvers. The resulting rotation in the case of a large formation produces major changes in the position of each spacecraft, which require large Δvs in order to be accomplished. The combination of the extremely long time and large Δvs required to achieve very large formations for MMS makes them an impractical option.

Propulsive Plane Changes

Performing burns along the orbit normal direction can be used to change the orientation of the orbit plane. The specific reorientation obtained depends on the location at which the maneuver is carried out, as the new and old orbital planes must intersect at this point. Two particular examples that have been examined for MMS are: burns out-of-plane at apogee, rotating the orbit plane about the line of apsides; and burning at true anomaly 90 and/or 270 deg (i.e. at the latus rectum of the orbit), shifting apogee laterally. Both of these approaches are of quite limited effectiveness in the case of MMS, as the 120 kg of "excess" fuel equates to a Δv of around 180 m/s, which is small when compared with the orbital speed at either apogee (428 m/s) or true anomaly 90/270 deg (7,073 m/s). The resulting maximum rotation of the velocity vector at the burn location, i.e. the maximum plane change angle, is therefore about 24 deg at apogee, and only 1.5 deg at the latus rectum. The former could increase the ecliptic inclination of the MMS orbit from its maximum value without maneuvers of 48 deg (see Fig. 2) to about 72 deg: this remains far short of the old MMS Phase 3/4 goal of an orbit normal to the Ecliptic. The second option of burning at 90/270 deg could only shift apogee laterally through a distance of approximately 0.65 RE, which does not significantly alter neutral sheet dwell time, etc. Propulsive plane changes are therefore not an attractive option for the MMS extended mission.

Exploitation of Lunar Gravity Assist for Improved Mission Science

Since by far the most efficient type of orbital maneuver for the MMS orbit is a change in apogee radius, consideration was then given to raising apogee radius to the neighborhood of that of the Moon. If phasing can be adjusted so as to set up a relatively close lunar encounter, this Lunar Gravity Assist (LGA) would allow the lunar gravity to be harnessed in order to perform significant changes to the MMS orbit far beyond what could be achieved propulsively. It was determined that MMS does indeed have enough remaining propellant to raise apogee to the Moon, perform all required post-LGA maneuvers to get into the modified science orbit, and then carry out formation-keeping for an extended period afterwards. Since this approach was found to be so promising, it will form the focus of the rest of the paper.

A candidate science goal that was originally investigated for the LGA was to rotate the plane of the MMS orbit so as to better align it with the magnetotail neutral sheet [5] with the objective of improving nightside science. While an LGA trajectory was designed that achieved this rotation, it was found that the neutral sheet dwell time (the key nightside science metric) was not improved radically over that of the original orbit. Two other possible LGA goals were also briefly considered: exploiting lunar gravity to raise MMS ecliptic inclination to 90 deg, as in the old Phase 3/4 studies, and using it to put the spacecraft on a trajectory to a libration point orbit. However, the current scientific interest in either of these options was limited, so they were not pursued further.

A final alternative science goal was then focused on, namely to raise perigee to a radius in the range 10-12 R_E so as to "skim" the magnetopause, with the objective of improving dayside science. This is an alternative approach to the apogee-lowering that was already examined and discarded: it would similarly lead to an increased number of magnetopause crossings. Note that this goal is not achievable using propulsive perigee-raising: since the change in semi-major axis that is produced by a burn along the velocity vector is proportional to the orbital speed at the point of application,

$$\Delta a = \frac{2a^2}{\mu} v_{orb} \Delta v \, , \tag{1}$$

and the speed at the MMS Phase 2b apogee is only about 5% as great as that at perigee, perigee-raising is far less efficient than apogee-raising for MMS. In fact, using the entire “excess” fuel load could only raise perigee by less than 1 R_E. This would not take perigee anywhere near the magnetopause. By contrast, it will be shown that feasible LGA geometries do exist that will raise perigee radius to the 10-12 R_E range. This approach is therefore the basis for the LGA trajectories that have been examined in detail and will be described below.

LUNAR GRAVITY ASSIST ANALYSIS AND DESIGN

Constraints Resulting from Pre-Existing MMS Orbit Geometry

A key consideration in these LGA studies is that the MMS orbit geometry (apart from apogee radius) is already specified up to the minor adjustments that are achievable with the amount of fuel that is available. In this way, the problem differs significantly from that of a new mission that is to be launched into an orbit that is set up specifically to lead to desirable LGA conditions. In the latter case, the launch window can be specified in such a way as to lead to a favorable lunar encounter. MMS, on the other hand, was launched into an orbit that was carefully defined [3] so as to satisfy all engineering and science constraints during the prime mission. Setting up desirable conditions for an LGA during the later stages of an extended mission was never a consideration in this launch window analysis.

One consequence of the MMS orbit geometry is that the “seasons” during which an LGA is feasible are quite constrained. A lunar encounter is only achievable when the MMS apogee vector lies nearly in the lunar orbit plane, which (see Fig. 1) only occurs in mid-2021 or early 2027. Periods of several months centered on these two dates are therefore the only candidate times for a gravity assist. Note, though, that the MMS orbit plane is not close to being aligned with that of the Moon at these dates: in fact, Fig. 2 shows that it reaches its maximum lunar inclination of around 45 deg during both of these periods. In other words, the MMS line of apsides is nearly in the lunar orbit plane during these “seasons”, but the MMS orbit plane is rotated by around 45 deg about this common line. This high lunar inclination will be seen to have implications for LGA maneuver design.

LGA B-Plane Targeting and Solutions

The B-plane is a common way of describing the geometry of planetary (or lunar) encounters: see Fig. 3 (Fig. 8 from [16]). A key parameter is the aim point at which the incoming asymptote direction intersects the B-plane, i.e. where the spacecraft trajectory would fly past the planet if it were not affected by the gravity of that body. For the case of an MMS lunar encounter, selection of this aim point specifies the three key parameters of the post-encounter MMS Earth orbit: apogee radius, perigee radius, and the angle by which the plane of this orbit is rotated relative to that of the pre-encounter orbit. Fig. 4 shows (for a representative “MMS-like” orbit) that, if the aim point can be positioned arbitrarily, two of these parameters can be freely selected: for instance, perigee radius (red) can be set to 10 R_E and simultaneously apogee radius (blue) set to 60 R_E. The third parameter, the plane change (green), is then also specified, i.e. it cannot be selected independently. Note that there are two solution points that give the desired apogee and perigee radii: for the values given, these points are at about (T, -R) = (-1.2, -2.8)x10^4 km and (T, -R) = (1.1, -0.7)x10^4 km. These two solutions both give a plane change angle of about 7-8 deg; however, this is not always the case. For example, if the targets for perigee and apogee radii were 6 R_E and 65 R_E, respectively, the plane changes corresponding to the two solution points then differ considerably: they are about 6 and 85 deg.

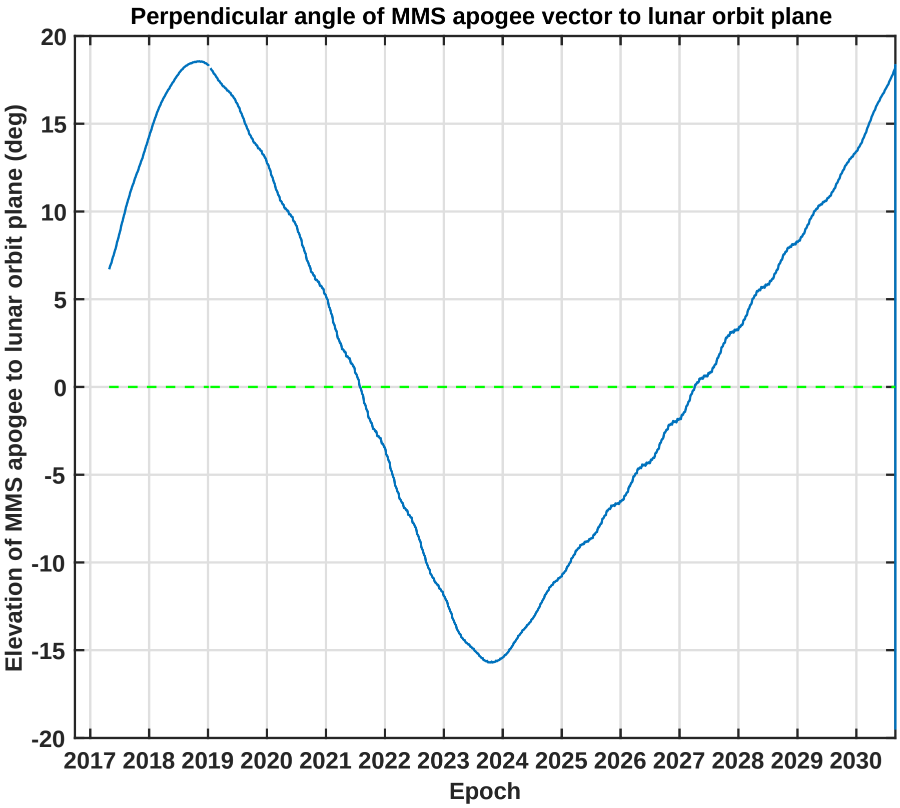


Figure 1. Elevation of MMS apogee vector to lunar orbit plane.

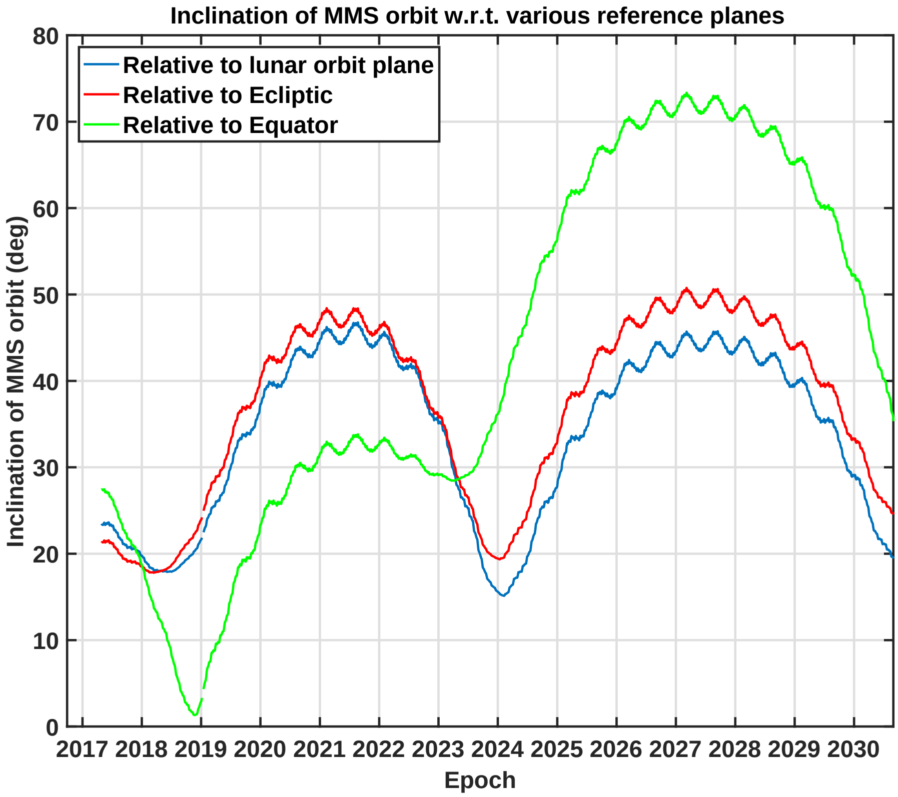


Figure 2. Equatorial, ecliptic and lunar inclinations of MMS orbit.

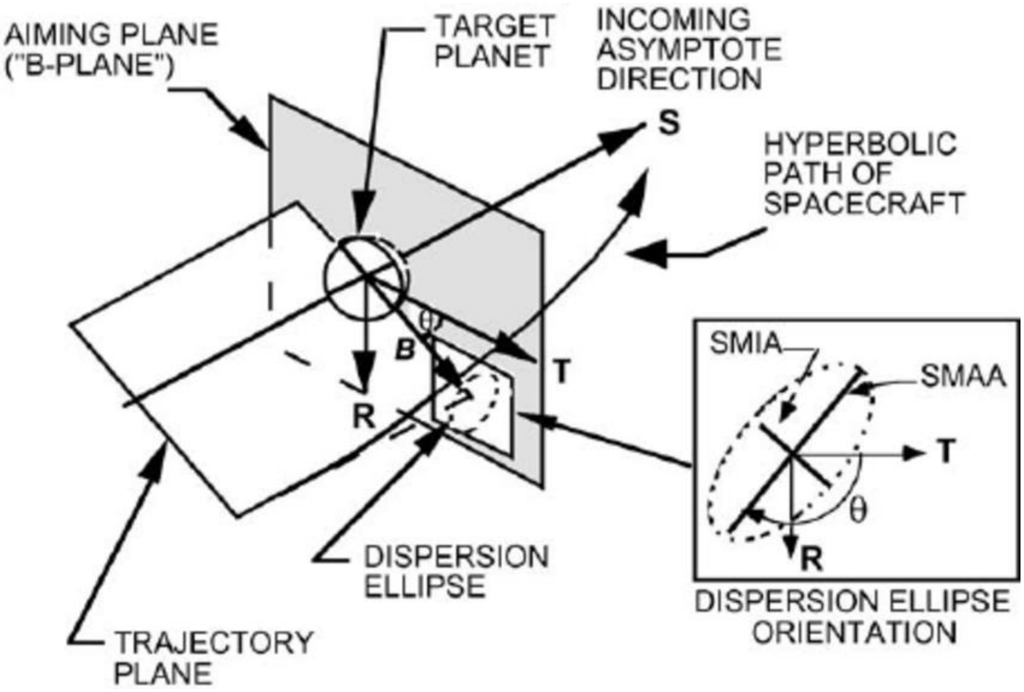


Figure 3. B-plane encounter targeting.

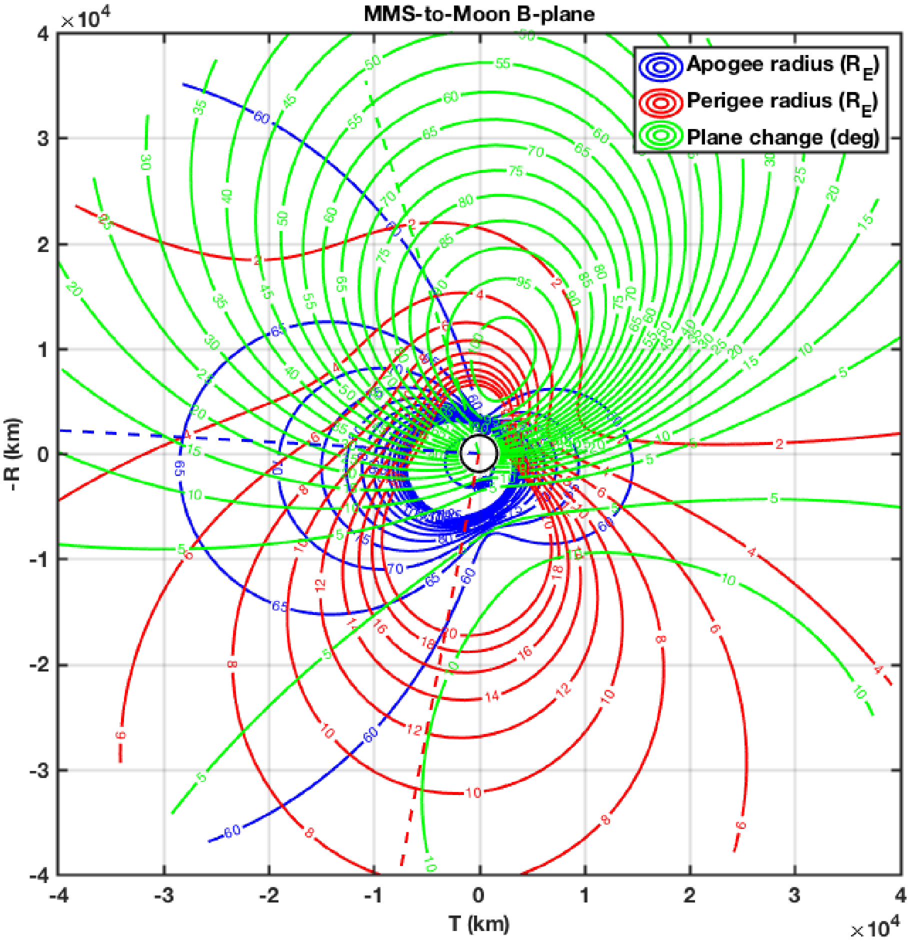


Figure 4. Representative MMS orbit B-plane contours.

However, it is not practical to target MMS to an arbitrary B-plane aim point, again as a result of the pre-defined geometry of its orbit. Instead, it is really only feasible to alter two parameters of the approach trajectory to the LGA: the pre-encounter apogee radius, and the precise time at which the closest approach occurs. Both of these variables can be adjusted by altering the relative sizes of the four apogee-raising burns, on successive perigee passes, that are used to set up the LGA. Note that, unlike the original MMS Phase 2a apogee-raising campaign [7], where the spacecraft burned on separate perigee passes, apogee-raise burns to set up an LGA must be performed simultaneously, in order for all four spacecraft to have the correct arrival phasing relative to the Moon. This simultaneous burning capability will be demonstrated during the MMS "mini-apogee raise" campaign in early 2019. An additional difference between Phase 2a apogee-raising and that required to set up an LGA results from the high inclination (see Fig. 2) between the MMS orbit and the Ecliptic at the feasible times for LGAs. This implies that, if the spacecraft remained in their nominal science attitude, with spin axis approximately aligned with the Ecliptic normal, the burn direction for apogee-raising (along the orbital velocity vector) would lie far from the spacecraft spin plane. These burns would therefore have to be performed using a combination of the radial and axial thrusters [7], so leading to large "Pythagoras fuel losses". To keep fuel use more moderate, a large slew of around 45 deg is therefore required before the start of apogee-raising. (Such a slew was not required for the Phase 2a apogee-raise campaign, as one of the constraints that the launch window had to satisfy [3] was that the spin plane and orbit planes be roughly aligned.) Fortunately, this slew is roughly along the Sun line, so does not result in a significant change in solar elevation on the spacecraft, or any associated power or thermal concerns.

Fig. 5 gives the locus of arrival points in the B-plane that are obtained if the MMS pre-encounter apogee radius is equal to 61 R_E and arrival time is varied over a range of roughly 5 days by adjusting the apogee-raise maneuver sequence. Note that the Moon is shown to scale in the figure: it can be seen to be small in comparison to the closest achievable approach radius of approx. 10,000 km. This is an important consideration in terms of the feasibility of the four MMS spacecraft performing simultaneous lunar encounters: if the miss distance were much smaller, each spacecraft would experience quite different lunar accelerations, which would serve to disperse the formation. Miss distances of the magnitudes seen in the figure appear well suited to feasible simultaneous LGAs.

Consider first the case where pre-encounter apogee radius is held constant. Given that there is now essentially only one degree of freedom available in the placement of the aim point in this B-plane, rather than the two that were assumed when positioning it arbitrarily, it should be expected that it will now only be possible to arbitrarily assign a single post-encounter orbit parameter, for instance perigee radius. This is indeed the case, as is seen in Fig. 6: this shows the post-encounter apogee and perigee radii and plane change angle that are obtained for a range of arrival times. It can be seen that if, for instance, the perigee radius is to be set to 10 R_E, there are two possible arrival times that will achieve this, and the resulting apogee radius and plane change are both also immediately specified. Additionally, it can be seen that one of the possible solutions has a large plane change and the other a small one: this is often, but not universally, the case.

There still remains, however, the second design LGA parameter of pre-encounter apogee radius that can be adjusted within a fairly narrow range of values. Varying this radius gives a somewhat different achievable locus in the B-plane, and consequently a somewhat different range of post-encounter orbit parameters as a function of arrival time. Fig. 7 shows the resulting apogee and perigee radii and plane change angle if pre-encounter apogee radius is increased to 62 R_E. It can be seen that in this case the two 10 R_E perigee radius solutions have small plane changes and somewhat different values for post-encounter apogee radius. Adjusting both pre-arrival apogee radius and arrival time by adjusting the apogee raise maneuver sequence therefore allows, for instance, full control over post-LGA perigee radius, together with more limited control over post-LGA apogee radius; the plane change is then specified also.

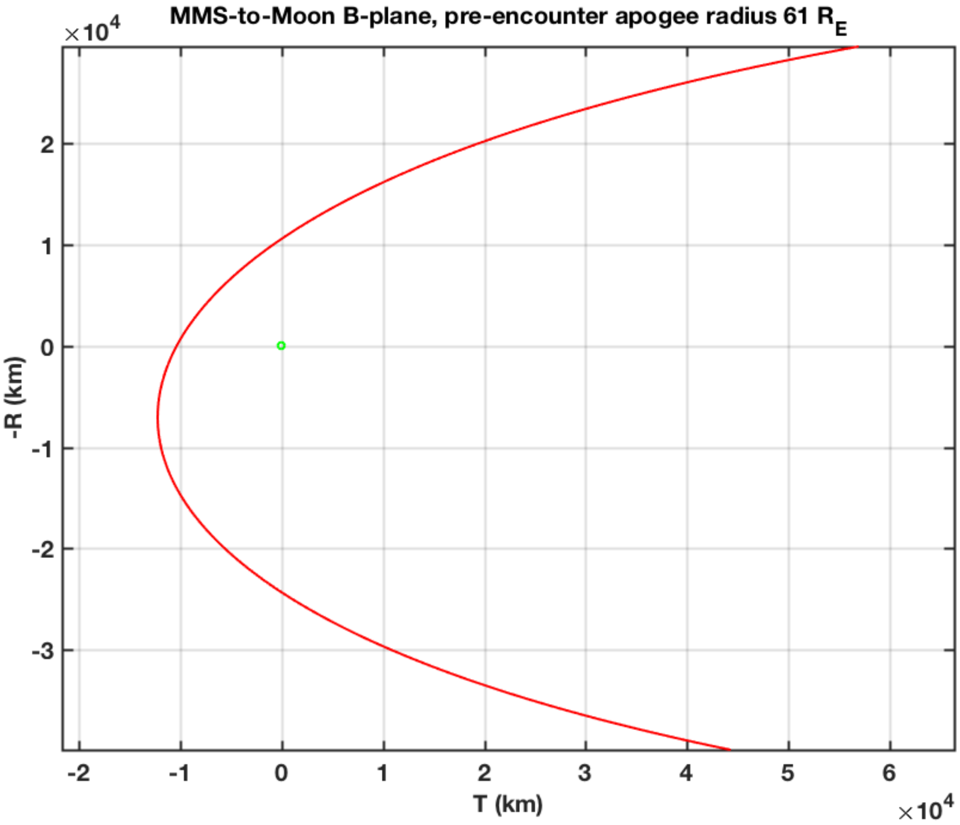


Figure 5. Locus of achievable MMS B-plane aim points, 61 R_E pre-LGA apogee radius.

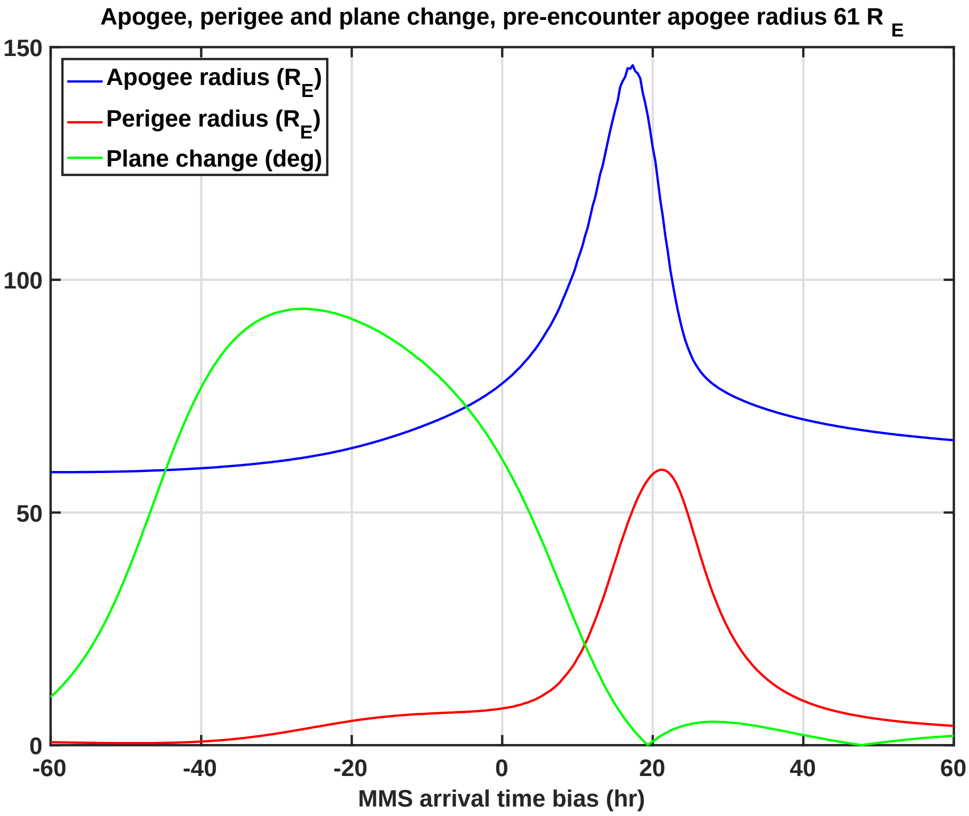


Figure 6. Resulting post-encounter orbit parameters, 61 R_E pre-LGA apogee radius.

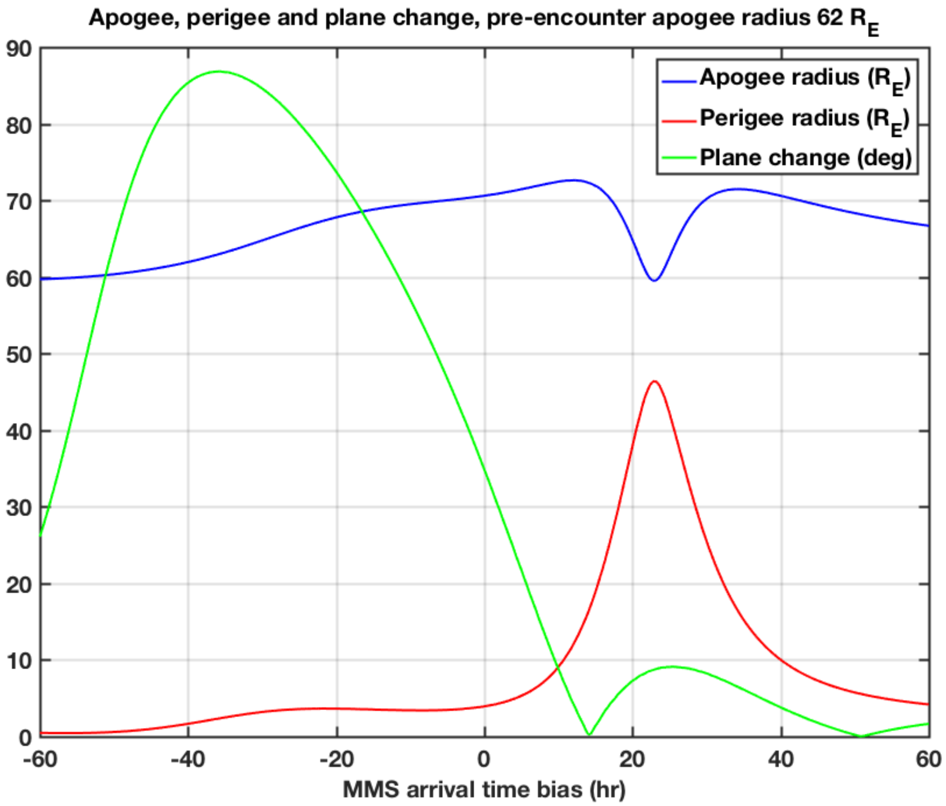
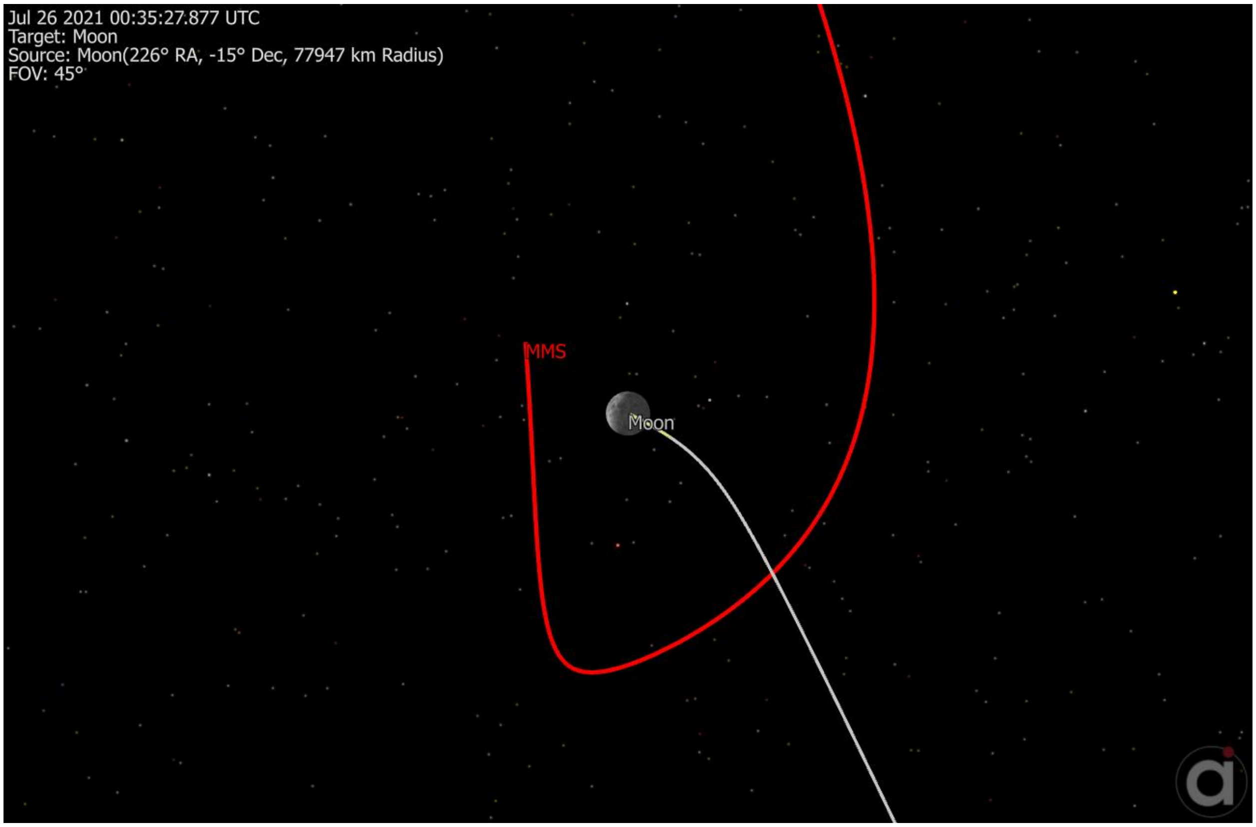


Figure 7. Resulting post-encounter orbit parameters, 62 *R_E* pre-LGA apogee radius.



Jul 26 2021 00:35:27.877 UTC
Target: Moon
Source: Moon(226° RA, -15° Dec, 77947 km Radius)
FOV: 45°

Figure 8. Trajectory of MMS relative to Moon during encounter.

Given that the orbital speed of the Moon is considerably greater than that of MMS at apogee, the spacecraft are overtaken by the Moon. The closest approaches of the four MMS satellites to the Moon therefore occur over the trailing lunar face relative to its travel around Earth, as illustrated by Fig. 8. It is therefore possible that the MMS instruments could collect useful science data, albeit over a brief period of some hours, of the lunar wake area in the solar wind during the lunar encounter period. Detailed characterization of this point has not yet been carried out.

Post-LGA Orbit Design

Once the MMS orbit has been transformed to the desired new science geometry by means of the targeted LGA, it is important that further lunar encounters do not occur to produce additional undesired orbital changes. For this reason, a relatively small propulsive apogee-reduction is carried out to place MMS into an orbit with period in resonance with that of the Moon. The two cases considered were either a 2:1 resonant orbit, with period 13.5 days (half that of the lunar orbit), or a 3:1 resonant orbit, with period 9 days (one third that of the Moon). Figure 9 shows the approximate dimensions of these orbits. The goal of a resoance orbit is to set up a repeating geometry such that, when the spacecraft is at its apogee (and so potentially near the Moon, and thus experiencing significant lunar perturbations), the Moon is kept as far as possible away from it. For the 2:1 resonance case, the spacecraft must be phased such that, at one apogee, the Moon leads the spacecraft by 90 deg, and on the next then trails it by 90 deg. For the 3:1 resonance case, the spacecraft orbit must be phased such that the Moon is 60 deg, 180 deg and -60 deg away from successive apogees.

In order to achieve the desired lunar resonance geometry, it is important to phase the spacecraft correctly so that, once apogee-lowering is carried out, the Moon is 60, 90 or 180 deg, as appropriate, away when MMS is at apogee. This requires that the spacecraft must remain in their post-LGA orbit for N.5 revs before lowering apogee, where N is an integer chosen to yield the correct phasing. This integer is clearly a function of the post-LGA period, and hence apogee radius. There are therefore two constraints on acceptable post-LGA apogee radii: not being so high that the apogee-lowering Δv becomes excessive, and ensuring that N not be too large to be practical. The result of these constraints was that the 2:1 lunar resonance orbits were discarded in favor of the 3:1 cases with higher plane change angles.

The IBEX spacecraft has been flying in a 3:1 resonance orbit for roughly the past 8 years, and has not had to perform any perigee-maintenance maneuvers to prevent reentry throughout this period [17]. Before entering the 3:1 orbit, such maneuvers were required regularly. Similarly, TESS was recently inserted into a 2:1 resonance orbit, with the goal of keeping its perigee well above the GEO belt for at least 18 years without the need for perigee-maintenance maneuvers [18]. It should be noted that these missions do not experience unchanging perigee radii, but rather ones that vary within a range moderate enough to not cause reentry. The MMS resonance orbits experience similar behavior with respect to perigee, as can be seen in Fig. 10 for a 3:1 lunar resonance orbit with initial dimensions 10 x 48 R_E. The inertial view of Fig. 11 shows the overall stability of this same orbit over a five-year period. Fig. 12 then shows the resulting eclipse behavior for this orbit. It can be seen that only a few eclipses occur over the five year period, with none reaching 4 hours umbra plus half penumbra (the MMS eclipse metric). The MMS spacecraft and intruments would have no difficulties surviving such eclipses.

A key final point is that the fuel remaining on the MMS spacecraft is adequate to perform this extended mission lunar option. The details vary depending upon the precise perigee radius that is selected, but a typical result is that about 17 kg would remain after spending four years in formation in the post-LGA 3:1 resonance orbit, giving a ten-year total mission duration. At this point, science operations could continue further if desired, or disposal (either reentry or escape) could be initiated by performing a small maneuver (on the order of 1 kg) to set up eventual lunar ecounter(s).

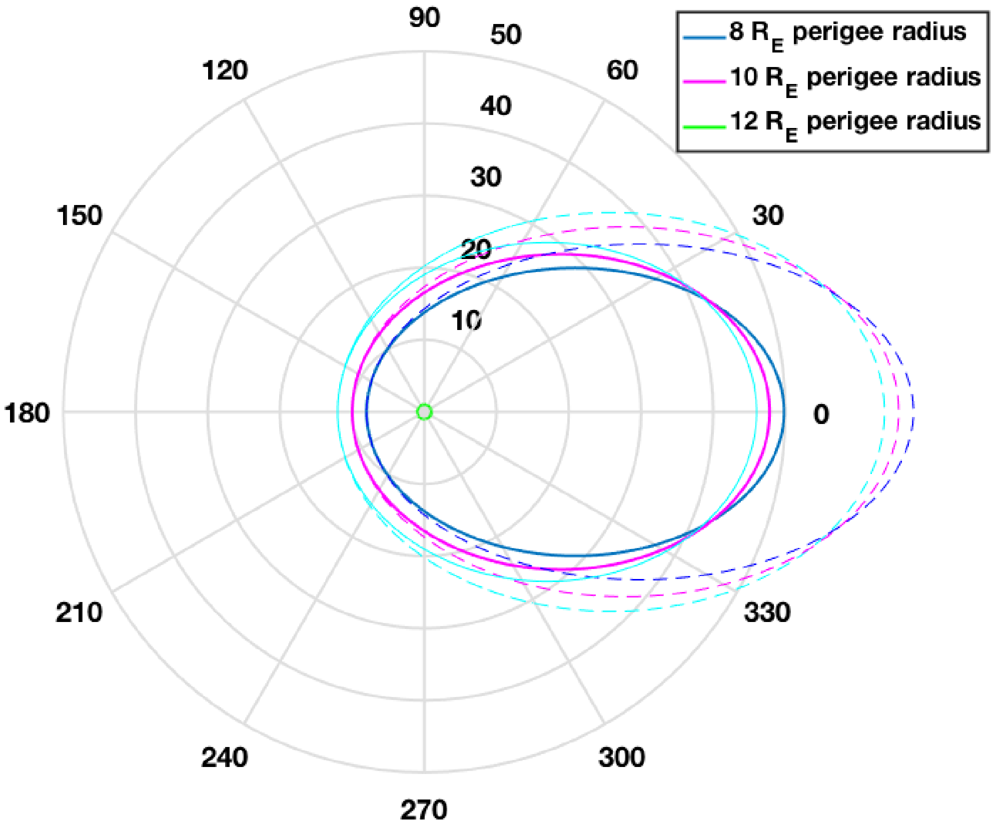


Figure 9. Geometries of 2:1 (dashed) and 3:1 (solid) lunar resonant orbits.

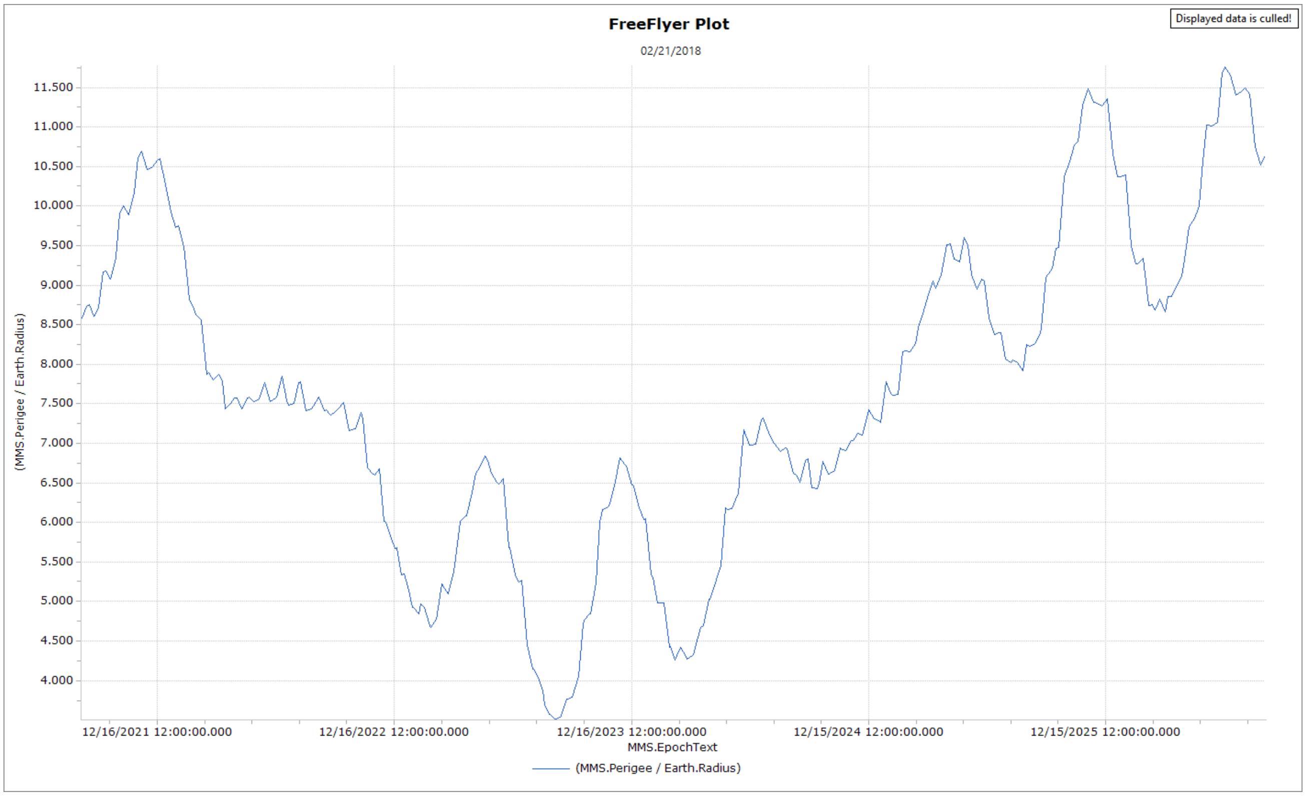


Figure 10. Evolution of perigee radius for 3:1 resonance orbit over 5 years.

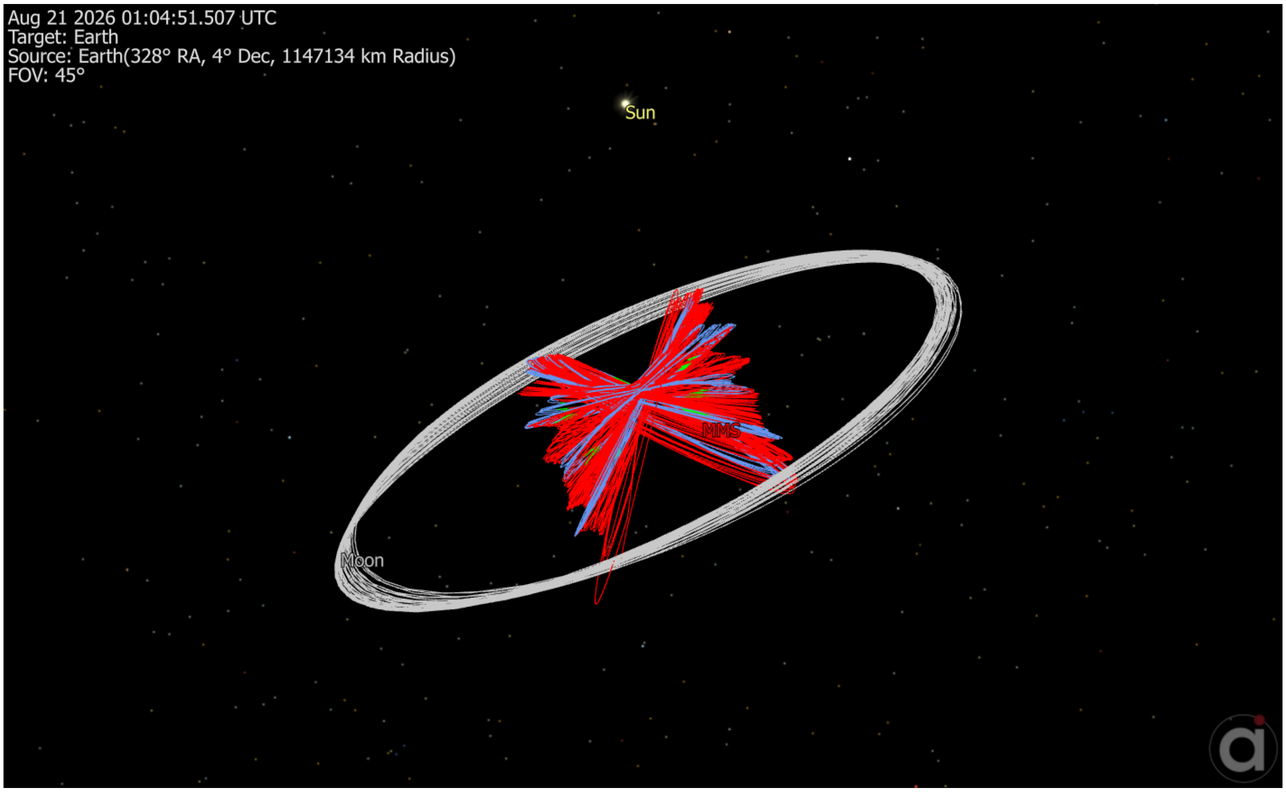


Figure 11. Stability of 3:1 resonance orbit over 5 years.

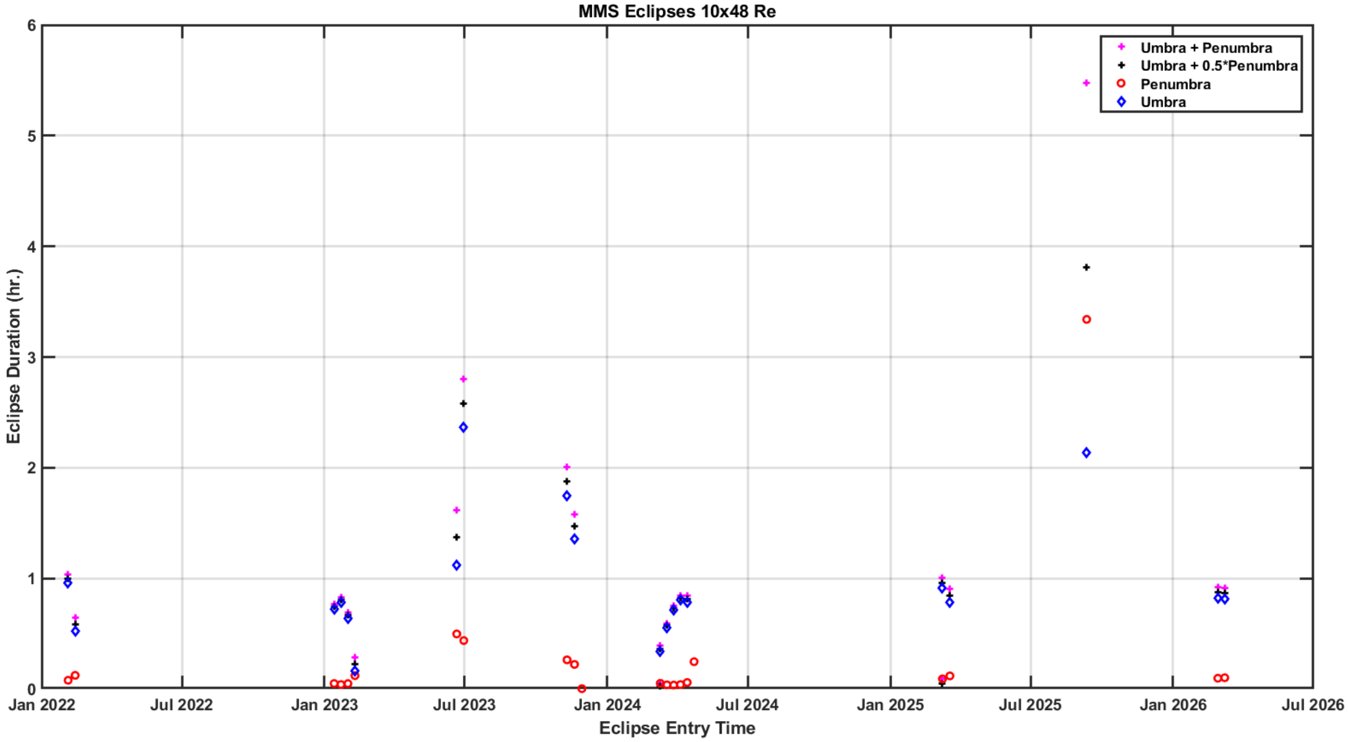


Figure 12. Eclipses for 3:1 resonance orbit over 5 years.

GPS-Based Navigation in Post-LGA Orbit

The orbit determination data that is used as input to the Formation Design Algorithm (FDA) is produced by the on-board Goddard Enhanced Onboard Navigation System (GEONS) [8]. 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 semi-major axis (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.

Pre-flight predictions were that the MMS Navigator GPS system would see only occasional GPS side lobe signals around apogee on the Phase 1 1.2 x 12 R_E orbit, with these becoming very sporadic on the Phase 2b 1.2 x 25 R_E orbit. It has been found that the actual performance is far better than this, even sometimes obtaining GPS point solutions (requiring signals from 4 simultaneous GPS satellites) as high as 25 R_E. It is anticipated that performance will remain good next year, when apogee radius in increased to 29.34 R_E.

This flight performance has been incorporated into a detailed simulation of the MMS navigation system, to investigate what performance can be expected in a 10 x 48 R_E orbit. It should be noted that the perigee of this orbit is considerably above the GPS constellation, which initially would have seemed to preclude successful GPS-based navigation. However, the results of this simulation indicate that this system should work well on this lunar resonance orbit. In particular, Fig. 13 shows that a small number of GPS signals are expected to be seen even around apogee in this orbit. Fig. 14 then shows that the expected 3σ absolute position error of each spacecraft is only around 700 m: this is small enough to allow formation flying using GPS-based navigation on this high orbit.

As a final point, note that consideration is being given to flying GPS-based navigation on the Orion crewed lunar spacecraft. It would therefore be an extremely interesting engineering test if MMS were able to demonstrate GPS navigation at lunar altitudes.

Science in Post-LGA Orbit

For the five years from Aug. 22, 2021 to Aug. 21, 2026, Figs. 15 and 16 show the points on the 10 x 48 R_E 3:1 resonance orbit at which crossings occur of the magnetopause (red), bowshock (blue) or neutral sheet (gray). Since these are the prime locations for dayside and nightside science, the numbers of magnetopause and bowshock crossings and the number of hours spent in the neutral sheet form metrics of the quality of an orbit for magnetic reconnection science. These figures are defined in terms of the GSE frame, so the Sun is along the +x_{GSE}-axis: to the left in Figure 15, and behind the viewer in Fig. 16.

As noted on the figures, the post-LGA orbit experiences about 2,300 magnetopause crossings over this period, and approximately 500 hr bowshock crossings. By comparison, the baseline extended mission orbit experiences 3,628 magnetopause and 1,034 bowshock crossings, respectively, over the different 5-year period of Oct. 2017-Oct. 2022. It can be seen that the totals are actually higher for the baseline orbit, despite the fact that the post-LGA orbit has perigee skimming the magnetopause. This is a consequence of the longer orbital period of the 3:1 lunar resonance orbit: although the resonance orbit sees roughly twice as many magnetopause crossings per rev as the baseline orbit, its period of 9 days *vs* 67 hr leads to fewer revs per year, and so a lower annual total. This could be overcome by lowering the MMS apogee radius far lower, for instance back to 25 R_E, if there were sufficient fuel remaining to do so: indeed, in the original MMS Phase 3/4 planning, the post-LGA orbit would indeed be a 12 x 25 R_E orbit. However, given the realities of the fuel currently remaining, this is not an option.

As a consequence of this, together with the fact that science data collection is going very well in the current orbit, the lunar option has not been selected for the later stages of the MMS extended mission. Instead, current planning is to keep flying MMS in formation on its post-2019 1.2 x 29.34 R_E orbit until reentry occurs in 2030 or 2036, assuming long-term funding is available. However, if considerations such as spacecraft and instrument health, evolving science focus or funding constraints were to alter the situation, it is very likely that fuel will remain to carry out the lunar option during the later lunar alignment of 2027. The approach taken would essentially be the one that has been described here.

Points for Further Investigation

Several questions were not addressed, or covered only in a preliminary fashion, during this investigation of an MMS lunar option. If the situation were to change in the future so as to bring this option back into the planning for an extended mission, these questions will have to be returned to. A brief summary of two of the key questions will now be given.

Firstly, if perigee is put roughly at the radius at which magnetopause and bow shock crossings occur, science will be collected in the region around perigee, rather than around apogee as in Phases 1 and 2b. A preliminary formation design effort has shown that tetrahedra formed around perigee tend to be considerably less stable than those around apogee: these preliminary formations persisted for only a few revs. Several possible approaches may perhaps alleviate these problems: for instance, imposing a new constraint on acceptable tetrahedron orientations in the Formation Design Algorithm (FDA); applying small trim burns [11] to control inter-satellite drifts; or including differential lunisolar effects in the propagator used by the FDA (this was not necessary for the lower orbits of Phases 1 and 2). These approaches may well improve formation stability, although this is not yet known for certain. A final alternative would be to design formations around apogee as usual, even though science data is collected around perigee. Since the eccentricity of the 3:1 resonance orbits is considerably lower than those of Phases 1 and 2b (0.6-0.7 *vs* 0.8-0.9), the distortion of the formation when flying from apogee to perigee will now be less, so producing a more acceptable geometry around perigee.

Secondly, a promising LGA trajectory approach that has been taken for various previous missions, for instance Wind, is the Double Lunar Swingby (DLS) [9]. A DLS is conceptually very attractive for MMS, in that it can be used to “crank” the line of apsides around, putting apogee back into the neutral sheet without having to wait for an entire year to pass. In order for a DLS to be feasible, two conditions must be satisfied by the trajectory that is produced by the first LGA: the spacecraft orbit plane must be near-coincident with that of the Moon, so that both spacecraft and Moon can be in essentially the same position at the desired location of the second LGA (which, for the DLS case of interest for MMS, is not collinear with the first LGA); and the phasing must be correct, so that both Moon and spacecraft arrive together at the second LGA location. An investigation of the conditions that can be generated by the first LGA for the pre-existing MMS orbit indicated that no solutions exist which satisfy both these necessary DLS conditions simultaneously, even if additional integer MMS revs were added to attempt to help satisfy the phasing condition. It is believed [15] that the high lunar inclination of the MMS orbit contributes to this lack of solution. It is perhaps possible that a complicated series of trajectory steps, including “lunar backflips”, might allow a DLS; however, even if this were to prove to be possible, it would require a considerable amount of time, and probably more fuel for maneuvering (including getting back into formation after each LGA) than MMS has available. The DLS option for MMS therefore does not appear to be feasible, although this conclusion could be revisited if interest in the lunar option were to return.

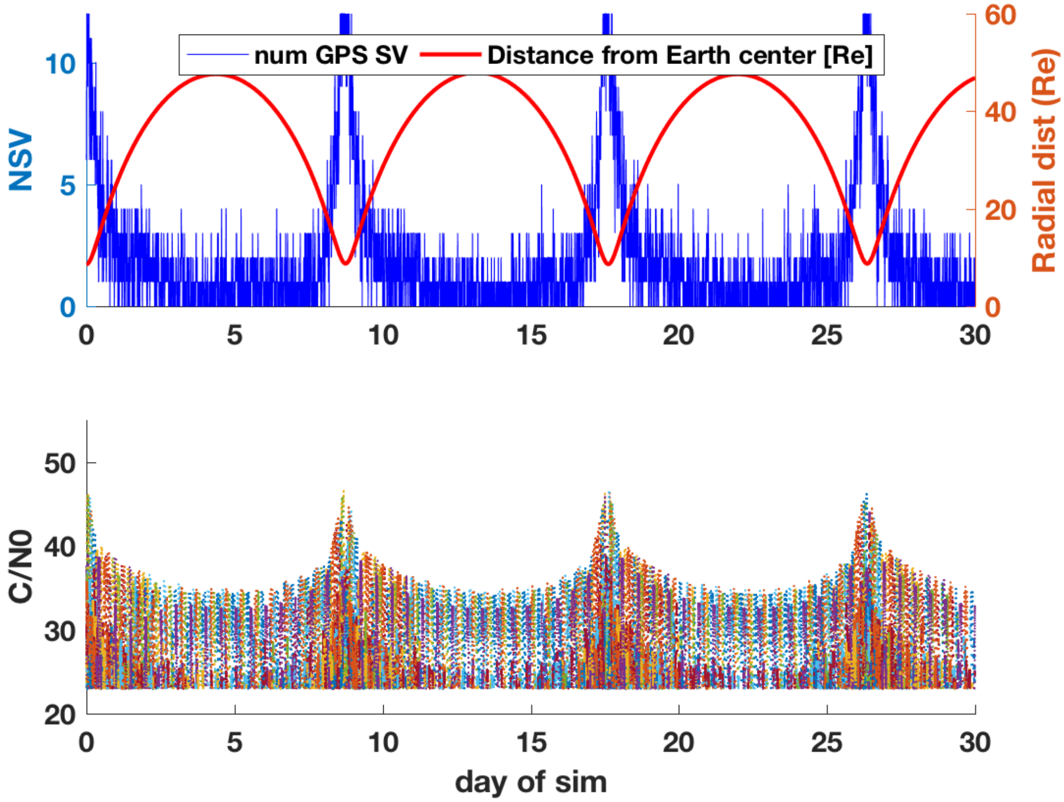


Figure 13. Navigation in 10 x 48 RE orbit: GPS performance.

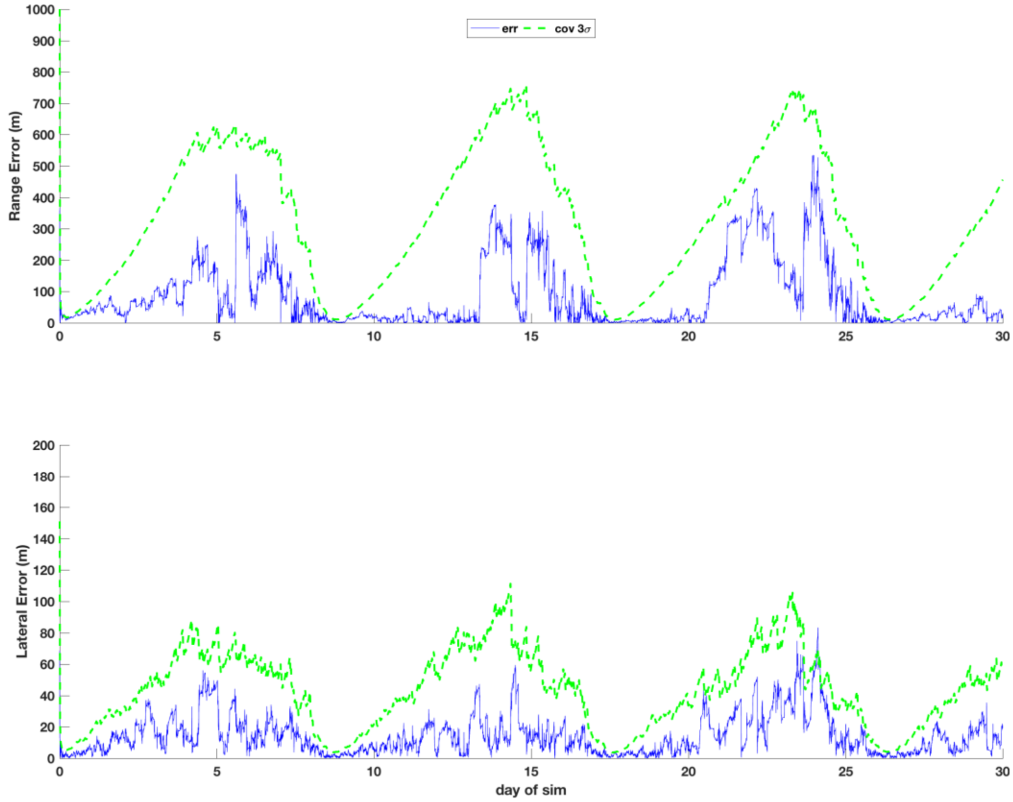


Figure 14. Navigation in 10 x 48 RE orbit: resulting position errors.

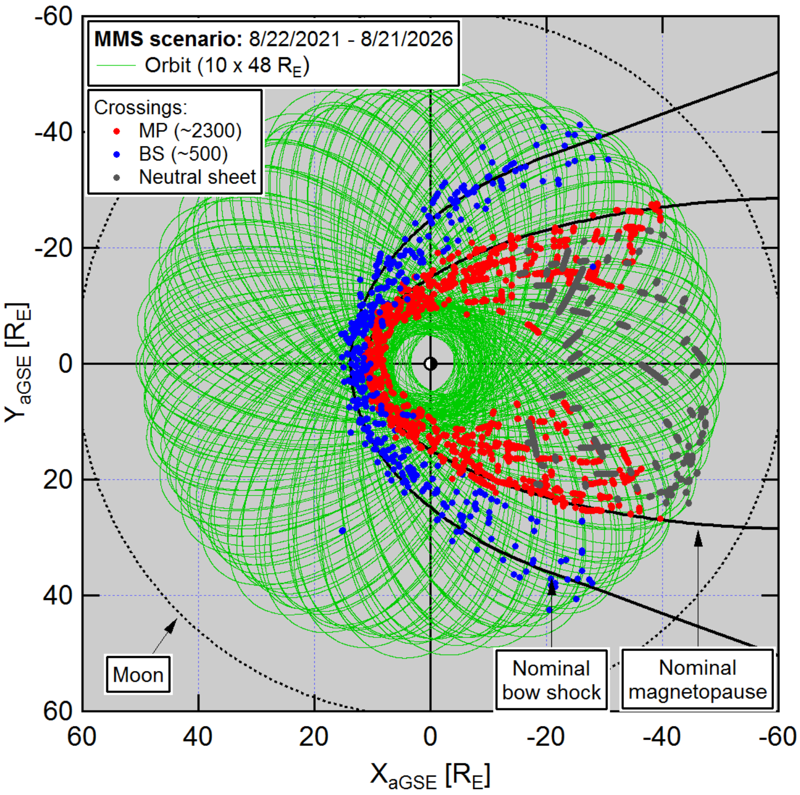


Figure 15. Science events in 10 x 48 RE orbit: view in Ecliptic plane.

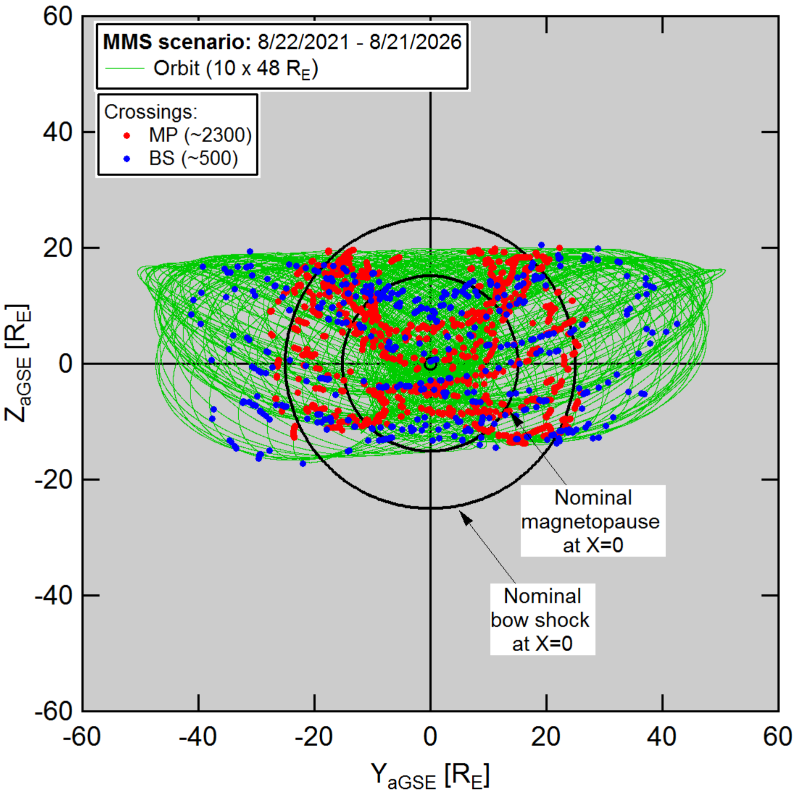


Figure 16. Science events in 10 x 48 RE orbit: view from Sun.

CONCLUSIONS

This paper has described maneuvers that were recently considered for a later extended mission phase for the Magnetospheric Multiscale (MMS) mission. These are apogee-raises to set up a lunar gravity assist, which in turn raises perigee for enhanced magnetopause science collection, followed by apogee-lowering to inject into a 3:1 lunar resonance orbit. Since a lunar encounter is only achievable when the MMS apogee vector lies approximately in the lunar orbit plane, the possible dates are mid-2021 or early 2027. This study was made feasible by the fact that MMS is consuming fuel for formation maintenance at a far slower rate than expected pre-flight, and completed the prime mission with a significant amount of fuel remaining. The ultimate decision of the science team was to continue flying in the current orbit rather than carry out the lunar option, as the data collected to date has been of such high quality. However, if circumstances change and raising perigee to skim the magnetopause becomes of interest in the future, the approach taken in the recent study would form a good basis, and has therefore been documented here.

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