Operational Techniques for Dealing with Long Eclipses during the MMS Extended Mission

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Abstract—**Launch window design for the Magnetospheric Multiscale (MMS) mission ensured that no excessive eclipses would be encountered during the prime mission. However, no orbit solutions exist that satisfy the eclipse constraints indefinitely: most extended mission years contain 1-3 eclipses long enough to potentially damage either the spacecraft or its scientific instruments. Two steps were taken to improve the situation. Firstly, raising apogee radius from 25 to 29.34 Earth radii altered the Sun-Earth-MMS phasing, so efficiently achieving reductions in the long eclipse durations. These maneuvers were performed early this year, in preparation for the first pair of long eclipses in August 2019. Secondly, a set of operational steps were taken around the time of the eclipses to help maintain spacecraft and instrument temperatures while preventing power load shedding. These operational steps included raising key onboard temperatures through adjusting the spacecraft attitude to tilt the instrument deck towards the Sun, and engaging select heaters prior to going into eclipses. In addition, all scientific instruments were turned off, as well as high-power, non-critical spacecraft systems, to conserve energy. These steps each came with trade-offs which will be discussed in the paper. Finally, the results that were obtained when the spacecraft experienced the first extremely long eclipses will be discussed, as will lessons learned for future long eclipses.**

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1. INTRODUCTION

The NASA Magnetospheric Multiscale (MMS) mission is flying four spinning spacecraft (see Fig. 1) in highly elliptical orbits to study the magnetosphere of the Earth [1]. 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 [3][4] 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; see left-hand side of Fig. 2). 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; see right-hand side of Fig. 2) [5], 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 that is expected to be lengthy.

The launch window design for MMS [2] ensured that no excessive eclipses would be encountered throughout the prime mission and the first year of extended mission. However, it was not physically possible to find launch window solutions that would also satisfy the eclipse constraints after this time. Analysis showed that around 80% of each subsequent year would contain a handful (typically 1-3) of eclipses long enough to potentially damage either the MMS spacecraft or its scientific instruments. Several of the instruments are particularly susceptible to eclipse damage as they contain components (HV801 opto-couplers) that can suffer delamination in extremely cold temperatures. Given that the spacecraft are currently healthy and have sufficient fuel reserves to continue formation flying for a considerable number of years, there was therefore considerable interest in seeing if these deep eclipses could be survived. A two-prong approach was taken: firstly, suitable orbital maneuvers were executed some time beforehand to reduce the duration of the eclipses to the (limited) extent possible; and secondly, a set of operational steps were taken immediately before and during the eclipses to ensure that spacecraft temperatures and battery stored energy were maintained at safe levels. A description of the extensive design process that was gone through to design the eclipse mitigation maneuvers will be given below. Well over 200 candidate burns were considered; for completeness, these burns included ones that would use essentially all of the MMS "spare" fuel. However, it was found that the majority of these did not achieve a significant reduction in the peak eclipse duration that was seen: they mainly just altered where on the orbit, and on which revolution, the eclipses occurred. The most effective eclipse mitigation approach by far was found to be to adjust the apogee radius: this alters the orbital period, and hence the phasing of the spacecraft on their orbits. The Sun-Earth-MMS geometry is therefore also changed, so altering the eclipse locations and durations. Note that the NASA IBEX [10] and TESS [11] missions came to similar conclusions for their similarly highly eccentric orbits. Increasing MMS apogee radius from 25 to 29.34 R_E (Earth radii) reduced the predicted long eclipses from ones that would have likely led to instrument damage (Fig. 3) to ones that should not (Fig. 4). These maneuvers are also quite efficient, since adjustments in apogee radius are the cheapest orbital changes for a highly eccentric orbit like that of MMS: they used only about 19 kg out of the remaining total of around 150 kg for each spacecraft.

Details of the various operational techniques that were taken to maintain spacecraft temperatures and battery stored energy (and hence voltage), to prevent load-shedding being triggered, are given in the paper. These included turning off all science instruments and those spacecraft systems that used significant amounts of power. This notably included the GPS-based on-board navigation system, which required the spacecraft to remain in an "open-loop" formation for several orbits, with no possibility of navigation updates. The Navigator system then had to be turned back on and reinitialized, as will be discussed later. In addition, careful use had to be made of spacecraft operations, pre-conditioning and survival heaters to maintain temperatures while not drawing excessive current. This included heating the hydrazine fuel in the spacecraft beforehand, in order to act as a heat reservoir for the rest of the spacecraft. A key additional step was to tip the spacecraft upper face towards the Sun, increasing the solar heat input. This type of maneuver is challenging for the MMS spacecraft with their long, flexible wire booms, but provided a useful warming of the instrument deck, which is mounted near the top of the spacecraft. Finally, a discussion will be given of the results that were obtained when the spacecraft experienced the first extremely long eclipses in late August 2019, and lessons learned for future long eclipses discussed.

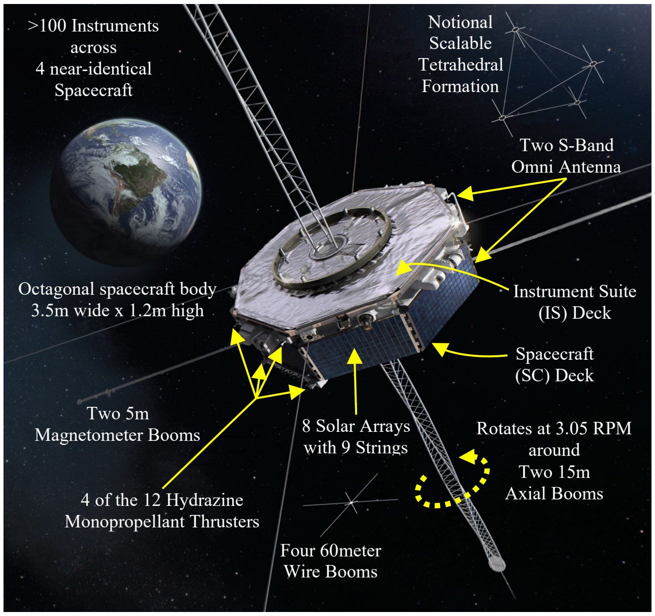


Figure 1. MMS Layout

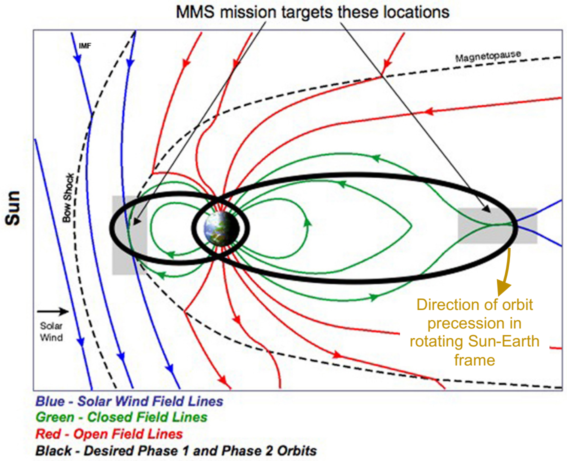


Figure 2. Sketch of MMS Orbit in Rotating Frame with Sun Always to Left

2. ECLIPSES DURING EXTENDED MISSION

The MMS launch window analysis [2] ensured, among other constraints, that no eclipses during the prime mission exceeded the maximum design value of 3.85 hr (umbra plus half penumbra [U+P/2]). In fact, the limit was even imposed during the first year of the extended mission, roughly the calendar year 2018: see Fig. 3 for the results obtained over this interval. These good results were produced despite the fact that flying through the neutral tail of the magnetotail, as required for MMS to collect its in situ science data, tends to put the spacecraft in locations where eclipses can occur. It was found to be physically impossible, though, to determine launch conditions that give eclipses in all subsequent years that also meet this requirement.

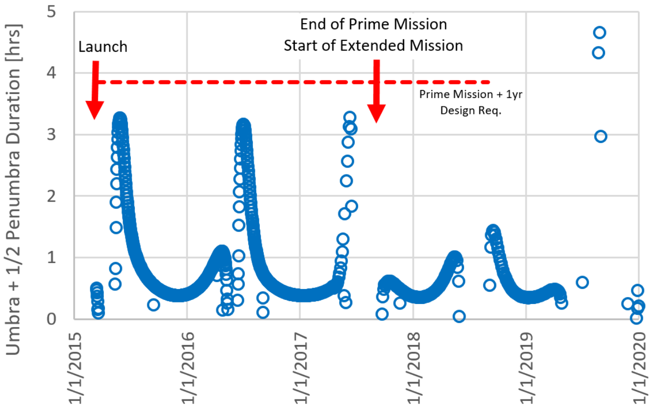


Figure 3. Eclipse Durations During Prime Mission and Early Extended Mission

Instead, what is found is that either two or three eclipses longer than the limit occur in each of the next four years of the extended mission in the 25 R_E apogee radius MMS Phase 2b orbit. There are then two years of moderate eclipses, resembling the behavior during the prime mission, after which the pattern repeats until eventual reentry. This is shown in Figure 4.

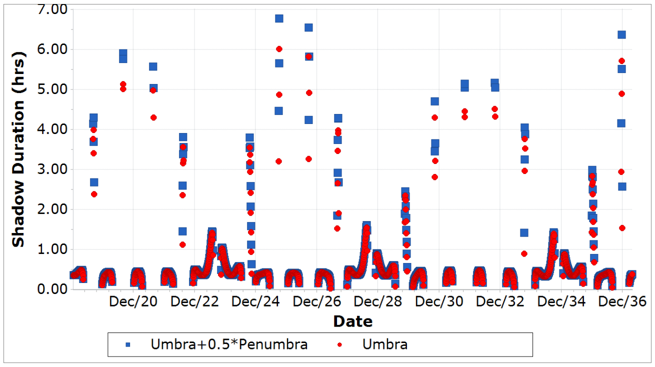


Figure 4. Eclipse Durations During Later Extended Mission if Apogee Radius Remains 25 R_E

The long eclipses occur on the upper flanks of the MMS orbit, where the spacecraft speeds are low. However, it should be noted that they are generally not at apogee itself: durations in such a case would be extremely long. Also, eclipses do not appear on many successive orbits, as would be the case if the MMS orbit lay in the Ecliptic. In the summer 2020 "eclipse season", for instance, there is a total of only two eclipses; however, the longer of these exceeds 5.90 hr U+P/2, which would be very likely to cause significant damage to certain of the MMS science instruments. The situation is even worse in 2025, when the peak eclipse duration is 6.76 hr U+P/2: survival of all instruments under these conditions would be very problematical. The sporadic nature of the eclipses is a consequence of the three-dimensional geometry of Sun, Earth and MMS. Note that the years with the longest eclipses are roughly centered on 2021 and 2027: these are the years for which the MMS apogee vector comes closest to lying in the Ecliptic [12]. Fortunately in terms of the resulting eclipses, the MMS orbit plane is tipped at a significant angle to the Ecliptic in these years: the orbits therefore cut through the Ecliptic rather than flying along it.

The MMS flight dynamics team was therefore requested to study whether anything could be done to moderate eclipses during the future extended mission. What made this activity possible was that the spacecraft have significant fuel still in reserve, as a result of both careful maneuvering and some luck: see [9] for details. Each spacecraft has roughly 78 kg of fuel "extra", after factoring in the estimated consumption for future formation-keeping etc., out of the original load of 412 kg: this equates to an available delta-v of around 117 m/s. The key question therefore was whether, if at most this quantity of fuel was dedicated to eclipse mitigation, a significant improvement in the peak eclipse duration could be achieved.

Well over 200 different dedicated eclipse mitigation maneuvers, differing by basic geometry, position on the MMS orbit, or magnitude, were examined. The motivation for these burns was to alter the geometry of the orbit relative to the shadow cone of the Earth, so moving the satellite out of eclipse. Since long eclipses can only occur on the high flanks, these burns focused on changing the geometry of the upper reaches of the orbit. Maneuver types studied included:

(1) Burning out-of-plane at true anomaly 90 and/or 270 deg, so shifting apogee laterally and potentially moving the flanks away from the predicted eclipse.

(2) Burning out-of-plane at apogee, so rotating the orbit around its line of apsides, altering its geometry relative to the shadow cone.

(3) Burning radially at apogee, so pushing the line of apsides fore or aft in the orbit plane, again moving it away from the shadow cone.

(4) Burning along the velocity vector at apogee, so altering perigee radius. Since the oblateness-induced orbital precession rate is a strong function of perigee radius, this approach should lead to a slow alteration in the inertial positions of apogee and the upper flanks. If performed long enough before a predicted long eclipse, it could potentially alter its duration.

(5) Burning along the velocity vector at perigee, so altering apogee radius. This alters semi-major axis, hence orbital period, hence the phasing of MMS relative to the Sun and Earth, shifting it relative to the shadow cone.

After an exhaustive study, it was found that none of maneuver types *(1)* - *(4)* achieved a useful decrease in the peak eclipse duration, even if the entire predicted fuel reserve of 78 kg were dedicated to this purpose. To use a technical term, what arose was a cosmic version of "Whac-A-Mole^{TM}": the eclipse on a particular orbit might be reduced by the maneuver, but one on some different orbit would be of virtually the original duration. A large amount of fuel would therefore be expended for no significant improvement in spacecraft conditions. This is partly a consequence of the extreme difficulty in altering the geometry of the MMS orbit: for instance, using all excess fuel for a maneuver of type *(1)* would rotate the orbit through less than 1 deg, which is small compared with the Sun-Earth line rotation of around 1 deg/day. Likewise, altering perigee radius propulsively is expensive for the MMS orbit: this is a consequence of the low orbital speed at apogee, where a perigee-raise maneuver would be carried out, since the *vis viva* equation gives the change in semi-major axis that is produced by a tangential burn of magnitude Δv, applied at point with orbital speed v_{orb} as

$$\Delta a = (2a^2/\mu)v_{\mathrm{orb}}\,\Delta v. \tag{1}$$

The most promising approach to eclipse mitigation is therefore altering phasing by carrying out a maneuver of type *(5)*. Altering apogee radius is far more efficient for MMS than changing perigee radius, since the speed at perigee is nearly 21 times that at apogee on the Phase 2b orbit: this certainly gives more scope for altering orbital behavior by this type of approach. Even this is somewhat limited by the fact that the MMS orbital period of ~3 day is comparatively short: the maximum change in phasing on any given rev is half the orbital period, or around 1.5 day. In this time, the Sun-Earth geometry does not change significantly. It is therefore not possible to radically alter the MMS eclipse behavior even using this most promising approach; it is, however, possible to improve things enough to be useful. Furthermore, this can be achieved without expending all of the "excess" fuel, leaving margin for possible future non-standard operations in support of improved science.

After MMS flight dynamics decided on eclipse mitigation by means of apogee-raising to alter spacecraft phasing, it was learned that the IBEX [10] and TESS [11] missions have previously taken very similar approaches to long-term eclipse mitigation. The orbits for these missions are of course different in detail from that of MMS: for instance, the 14-day TESS orbital period allows more scope for significant eclipse alteration through phasing changes than does the 3-day MMS one. However, all three orbits are quite similar in their essentials (in that they have high eccentricities and long lifetimes), and it was reassuring to learn that the other two missions had also come to similar conclusions to those reached by MMS.

3. APOGEE-RAISE CAMPAIGN

The 2019 eclipse-mitigation apogee-raise (AR) campaign was performed in a very different manner than the original Phase 2a AR in 2017 that took apogee radius from 12 R_E to 25 R_E [5]. The reasons for the changes were twofold: making use of an improved understanding of the performance of the MMS propulsion system, and a desire to reduce the time taken by the AR campaign, since this time is taken from science operations.

The design of the Phase 2a AR campaign was based on a key constraint that only one spacecraft was allowed to burn at a time. This followed from two factors: the original requirement that all burns were to be monitored in real time; and the fact that the ground can only communicate with one MMS at a time, since they share a single radio frequency. As a result, the Phase 2a AR campaign consisted of four "snake" sequences, with each of these made up of nine orbits. The perigee passes of each of the first four revs each included a single spacecraft burn; the fifth perigee had no maneuvers and is used for orbit determination; orbits 6-9 then each again included a single spacecraft burn at each perigee. The MMSs burned first in one sequence, e.g. 1-2-3-4, then in the reverse sequence, e.g. 4-3-2-1: this has the effect of making the MMSs spread out considerably midway through the snake, but then come back close together at its end. This approach also had the advantage that it could be made robust to maneuver execution errors by biasing the burns in the first snake so as to spread the satellites out along-track at the completion of this snake. Thus, at no additional expense in fuel, no credible apogee-raise maneuver execution errors could drive them into collision. (See [5] for further details.)

The disadvantage of the snake approach is that it is quite time-consuming, particularly at the longer orbital periods that MMS is currently flying at: since each snake consists of 9 revs and the Phase 2b orbital period is nearly 3 days, a snake would take nearly one month to carry out. The spacecraft would be out of formation for this entire time, so taking considerable time away from dayside science. Studies were therefore initiated to see if simultaneous apogee-raise maneuvers could be used instead: this would lead to an apogee-raise campaign of only 3 revs, or around 9 days, a considerable time saving. One key question was whether the MMS operations team would deem it practicable to maneuver three out of the four spacecraft "in the blind", as would be required in a simultaneous burn approach. This was achieved by pre-loading the maneuver commands and data on a previous pass, allowing the spacecraft to execute the burn without real-time ground intervention. This pre-loading approach was tested prior to apogee-raising, first on Delta-H slews and then on Delta-V orbital maneuvers, without any difficulties. Note that pre-loading is advantageous for routine formation maneuvers as well, as it allows these burns to occur nominally even if a ground station contact is lost. Without pre-loading, a lost contact can lead to a missed burn, which in turn can lead to a close approach between this MMS and one of the other three: see [8] for an example of when this actually occurred during Phase 1.

Another key factor that made simultaneous apogee-raising practical is that data collected during Phase 2a means that the MMS flight dynamics team has now characterized the performance of the propulsion system in much more detail than it had *a priori*. The Phase 2a execution errors, expressed as the differences between the actual and predicted increases in semi-major axis produced by each burn, were found to be much smaller than originally expected. Furthermore, they were quite repeatable from one apogee-raise maneuver to the next. Based on this data, and making the reasonable assumption that execution errors would be similar for the new apogee-raise campaign, led to the conclusion that the maximum inter-satellite drift that might be observed would be around 30 km at apogee. It was therefore concluded that having the spacecraft initially spaced at least 40 km apart at apogee should lead to a guarantee of safety during the AR campaign. An initial tetrahedron scale size of 40 km or more therefore seemed adequate for safety.

However, the mechanism by which AR execution errors lead to drifts between the spacecraft is the fact that these errors produce small differences in the orbital periods, causing small phasing errors. These errors give rise to much greater drifts low on the orbit, where speeds are higher, than the 30 km at apogee: the corresponding position shift at perigee is around 730 km. Now, some tetrahedron formations spread out in this manner around perigee, but others do not, and can even shrink. Performing simultaneous AR burns from a tetrahedron formation was therefore not found to provide sufficient inter-satellite range for safety. It was instead decided to maneuver the spacecraft into a "string of pearls" prior to apogee-raising. In such a string, the spacecraft are separated by small phasing offsets, sized so as to give the specified spacings at apogee. Since these phasing offsets are of precisely the same type as the outcomes of AR maneuver execution errors, they lead to commensurately increased spacings around perigee, and hence no risk of close approaches. The details of how maneuvers were generated to put the spacecraft into such a string in a fuel-efficient manner are given in [16].

As a prelude to the eclipse-mitigation AR campaign, the MMS spacecraft were put into the "safety string" configuration in late Jan. 2019. Two sets of simultaneous burns, at the perigee passes on Feb. 2 and Feb. 8, were then used to raise apogee radius to 29.34 R_E. (The dates of these maneuvers was found to be quite critical: delaying them by around a lunar month gave similarly good results, but a delay of, for instance, 1, 2 or 3 weeks would lead to significantly different long-term orbital behavior, potentially with an early reentry.) The resulting extended mission eclipse durations are shown in Fig. 5: comparison with Fig. 4 shows the significant improvement that was achieved by this increase in apogee.

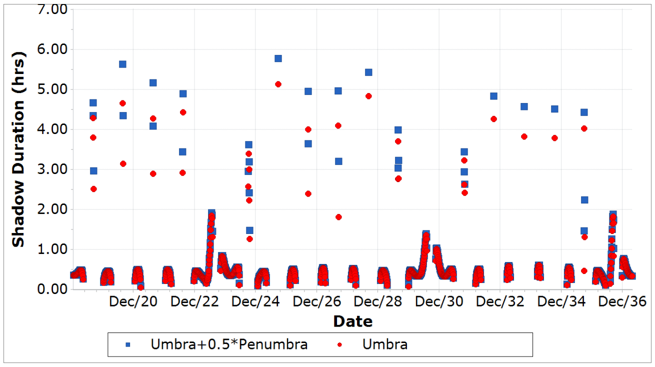


Figure 5. Eclipse Durations During Later Extended Mission if Apogee Radius Raised to 29.34 R_E, Feb. 2019

In addition, small "micro-apogee adjusts" (micro-AAs) are planned to be carried out, at a cadence of roughly once per year, to further tweak the durations of the future long eclipses. These maneuvers, which on occasion will lower apogee rather than raise it, by amounts of on the order of ±0.1 R_E, can be thought of as matching the durations of the long eclipses in any given year, slightly increasing the smaller one and decreasing the larger: this minimizes the peak duration. The micro-AA burns are small enough that it is expected that they will be performed with the spacecraft remaining in their current tetrahedron formation, so sacrificing virtually no science operations time. Including these small maneuvers, the extended mission eclipse durations are as shown in Fig. 6; the vertical lines denote the times of micro-AAs. The overall peak eclipse duration (defined as umbra plus half penumbra) of about 5.2 hr is not expected to cause damage to either spacecraft systems or instruments. By contrast, the overall peak of around 6.8 hr that would have been seen in the absence of any eclipse mitigation maneuvers would likely have been far more problematic.

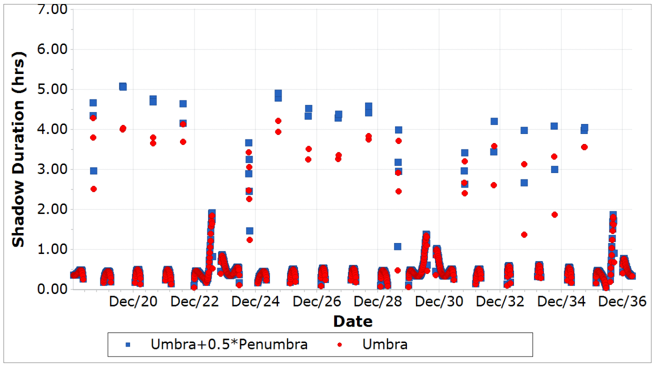


Figure 6. Eclipse Durations During Later Extended Mission if Apogee Radius Raised to 29.34 R_E, Feb. 2019 and Further Micro-AAs Performed

4. ECLIPSE OPERATIONS: OBJECTIVES AND APPROACH

The prediction of longer eclipses during the extended mission prompted considerable planning, analysis, and an amendment to the MMS operations configuration rule set in preparation for the first long eclipses in Aug. 2019. The principal objectives of dealing with these longer eclipse periods are to:

1. Maintain battery charge above 30.0V to avoid tripping autonomous power load shed limits.
2. Maintain instrument temperatures above 0°C.

The MMS Electrical Power System (EPS) uses a direct energy transfer topology such that in eclipse the bus voltage is the battery voltage. Battery state of charge is therefore an important metric to track. MMS has two sets of Failure Detection and Correction (FDC) pertaining to load shedding power usage. The first FDC is the Command & Data Handling (C&DH) Flight Software (FSW) limit checker with a threshold of 29.8V. Dropping below this limit would trigger the Instrument Suite (IS) and non-critical spacecraft (SC) components to be autonomously turned off. While the team's approach to these eclipses already turned most of these items off or to ultra-low power mode, there were a few spacecraft items such as Star Trackers and Navigator which were desired to remain in an on state. Triggering this first FDC limit would have required relatively minor additional recovery activities. The second FDC limit would have however had more substantial implications.

The second FDC for load shedding is internal to the Power System Electronics (PSE) with a threshold of 29.3V. Dropping below this limit would trigger a power cycling of the C&DH with loss on-board stored commands. Further ramifications of this would be: heater control defaults to survival heaters changing the carefully planned eclipse temperature profiles and hence an increased risk of causing damage to the spacecraft and instruments; contacts would have to be initiated in the blind; and recovery efforts would be prolonged to accommodate reloading and reconfiguring the spacecraft.

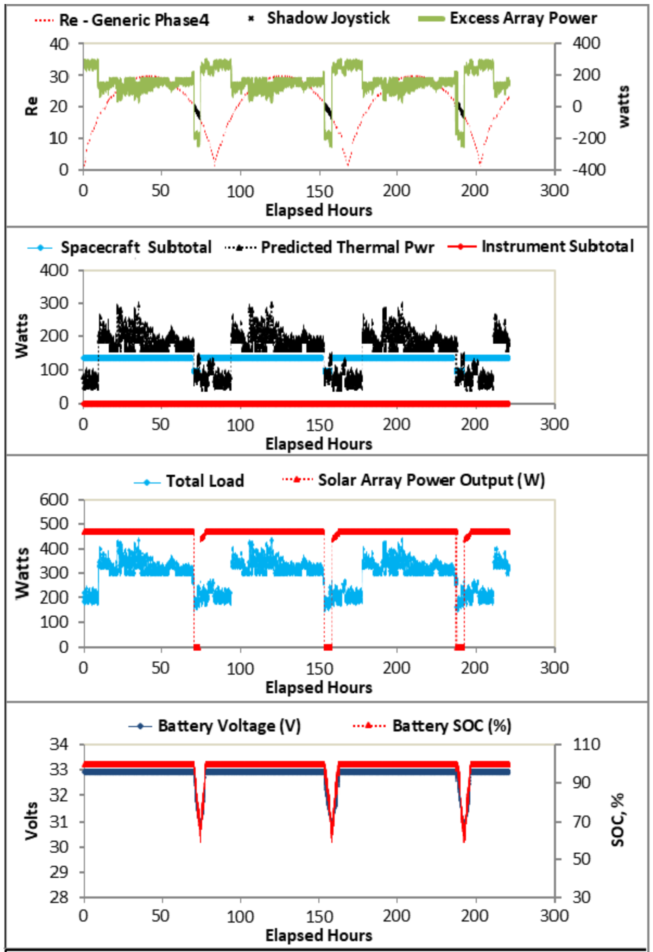
The second principal objective of maintaining instrument temperatures above 0 °C stems from a vulnerability in a high voltage component used in some of the MMS instruments. HV-801 opto-couplers, most notably in the MMS Fast Plasma Investigation (FPI) instruments, are susceptible to delaminating and failing under thermal cycles and cold temperatures [15]. Efforts were therefore made to increase the minimum temperature that these components would experience while in eclipse.

To achieve these two objectives the MMS team investigated methods to limit the maximum eclipse durations through orbit adjustments, means of increasing critical temperatures heading into eclipse, and power configurations for the various instrument and spacecraft subsystems. The team also implemented operational activities to effectively manage the off-nominal configuration surrounding the eclipse activities.

5. POWER AND THERMAL ADJUSTMENTS

Once the definitive orbit adjustments and resulting eclipses were identified, a new series of power and thermal profiles had to be analyzed for cases exceeding 4 hours. The goal was to maintain the spacecraft within the thermal and power constraints and hence reduce the chance of damaging the spacecraft or the instruments. The resulting power analysis was performed for eclipse durations in half hour increments up to 6.5 hours. Fig. 7 illustrates an example output of the analysis tool for eclipses 4.5 hours in duration. Note that the analysis tool models solar illumination as either "on" or "off", i.e. an eclipse is modeled as an equivalent umbra with no leading or trailing penumbra. In order to most accurately model an actual eclipse, therefore, this duration should be set equal to the actual umbra duration plus half that of penumbra. In particular then, the 4.5 hr analysis is used for comparison to the August 2019 long eclipses, the peak duration of which was 4.7 hr. For additional analysis results and details see [14].

The analysis was performed utilizing both the SC and Instrument Suite (IS) systems engineering teams based on the provided eclipse profile. Utilizing the power and thermal constraints as well as MOC and SOC considerations, the power engineering team used an MMS energy balance program to ingest the predicted thermal power draw, predicted orbit ephemeris, and predicted eclipse profiles. They then iterated through various scenarios changing the power configuration of different components until positive power margins were obtained while still meeting the thermal constraints [14].



Orbit #1: MIN VOLT : 30.7 : MIN SOC : 60.7 'Nominal' [observed at t =~ 74.5 hrs]
Orbit #2: MIN VOLT : 30.7 : MIN SOC : 60.7 'Nominal' [observed at t =~ 158.5 hrs]
Orbit #3: MIN VOLT : 30.7 : MIN SOC : 60.7 'Nominal' [observed at t =~ 242.5 hrs]
Orbit #4: MIN VOLT : 32.94 : MIN SOC : 100 'Nominal' [observed at t =~ 256 hrs]

Min Bat V Required [V] 30 **Battery Capacity [Ahrs]** 69.5

Notes: Preconditioning heater powered off one hour before shadow start.
- IS: All off except FPI (including CIDP, IDPU, DIS and DES
- SC: EVD, ~~TPS,~~ AMS off, and NAV Ultra low power (only USO powered)

Figure 7. SC & IS Energy Balance Scenario (4.5 hr Eclipse, 60 hr Preconditioning Heating, 24 hr Tank Capacitance Heating, 15 Degree Tilt) [14]

The result of the analysis prompted changes to the eclipse power document for eclipses between 3.5 and 4 hours and for eclipses greater than 4 hours. Both of these power profiles were utilized for determining the August 2019 eclipse operations.

For eclipses between 3.5 and 4 hours, it was concluded that eclipse pre-conditioning heaters (in locations such as the battery, C&DH box, PSE box, etc.) needed to be activated 24 hours prior to eclipse, NAV would be required to be placed into "Ultra-Low" power mode, AMS and its operational heaters would be powered off, and EVD would also be powered off.

NAV (Navigator) is the system that provides on-board navigation data and time determination. Navigator includes a weak signal acquisition GPS receiver, onboard GEONS navigation and orbit determination software (see, for example, [13] for further details), and the spacecraft Ultra Stable Oscillator (USO). The system is working well even in the new MMS orbit with apogee radius approximately halfway to the Moon, and so far above the GPS constellation. Flight at these high altitudes has already provided useful data on the likely performance of GPS at lunar distances: this is of great significance for possible future lunar operations using GPS. In particular, Navigator point solutions for MMS have been found to be nearly continuous below radii of about 20 R_E and, although they become sparser above this, point solutions have on occasion been obtained virtually at the new higher apogee.

The NAV Ultra-Low power mode keeps the USO warm but does not produce any navigation data. This makes the formation flying open-loop while in this mode. Without the USO data, a comparatively imprecise backup oscillator provided the reference for time propagation. The timing precision of the USO is needed largely for coordinating the science across the four MMS spacecraft. Any potential scientific data collected while using the less precise oscillator would therefore be diminished in value. In terms of long eclipse operations, all science instruments are in any case turned off whenever NAV is in ultra-low power mode. There is therefore no science data to be compromised.

AMS (Acceleration Measurement System) is one of the three MMS Attitude Control Subsystem (ACS) sensors. The AMS is predominantly used during closed-loop Delta-V maneuvers.

EVD (Engine Valve Drive) provides the drive electronics to the thrusters, latch valves, and magnetometer booms. With constraints to not perform maneuvers near long eclipses, turning the AMS and EVD off have no adverse effect.

For eclipses greater than 4 hours it was concluded that eclipse pre-conditioning heaters needed to be activated 60 hours prior to eclipse, the spacecraft would need to perform a Delta-H maneuver to tilt the IS deck (see Fig. 1) 15 degrees towards the sun, the IS would be powered off, the IS operational heaters would be powered off, the CIDP would be powered off, and a Thermal Capacitance (TCAP) test, where tank heaters are powered fully on for an extended period, would be performed for 48 hours prior to the long eclipses. (Note that the name TCAP is a consequence of the more common use of this procedure for estimating the remaining on-board fuel load from the rate at which the tank temperatures decrease afterwards: this is a function of the thermal capacitance of the fuel, which is proportional to fuel mass. In the current case, the TCAP approach was used instead to provide a heat reservoir for the overall spacecraft, to aid somewhat in maintaining safe temperatures throughout.)

With the IS powered off, the instruments inherently generate less heat and are colder. In an effort to boost the temperature of critical instruments, the spacecraft attitude was also turned to tilt the IS deck towards the sun by 15 degrees. A very similar tilt maneuver was performed, this time for science reasons, prior to the solar wind turbulence campaign that took place immediately following the eclipse-mitigation apogee-raise maneuvers. Each tilt took approximately 90 minutes to perform, as care had to be taken not to unduly excite vibration modes of the 60 meter MMS wire booms. These maneuvers provided useful experience ahead of the eclipse tilts; see [16] for further details. The eclipse tilts increased the solar absorption on the deck and raised the temperature of the instruments going into the eclipses. While this did decrease the solar array power generation somewhat, by the law of cosines, this reduction amounted to only a few percent. MMS generates ample power while in the sun, so this decrease was not a concern. Further ramifications of the tilt maneuver are discussed in the following two sections.

6. OPERATIONAL CONSIDERATIONS, IMPLEMENTATION AND EXECUTION

As show in Fig. 8, the MMS team executed the updated long eclipse procedures as specified in Section 4. Planning for operational requirements and procedures began in April of 2019. A significant portion of spacecraft configuration operations were conducted via preloaded Absolute Time Sequence (ATS) commanding. The ATS commands are generated on the ground via templates from the MOC's Mission Planning System (MPS). Once built they are verified and loaded on-board the spacecraft for execution. All spacecraft power management and maneuvers were conducted via established real-time procedures which issued the commands. Prior to beginning activities, a contingency plan was developed to cover various known scenarios and complications that may occur. This document was reviewed and published on the MOC's Local Operating Procedure (LOP) database for the flight team's access.

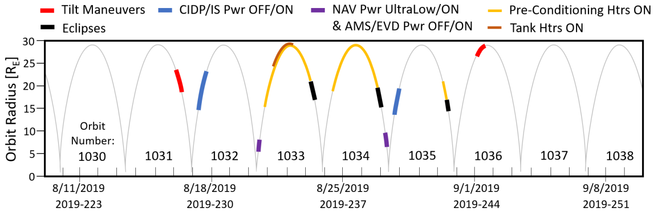


Figure 8. August 2019 Eclipse Operations Timeline

The first activity was to tilt the spacecraft instrument deck towards the sun 15 degrees. The primary consideration for this activity was the respective views for the two spacecraft omni-directional antenna. An antenna swap was required mid-maneuver in order to successfully execute these maneuvers. This procedure had already been successfully exercised earlier in 2019, which meant that the team had the MPS templates and ground procedures in place. This maneuver was executed two orbits in advance, in order to reduce complications.

The next activity was to power down the appropriate components of the spacecraft prior to the eclipses as defined previously. This was broken down into a two-phase process. The first objective was to safely configure the instrument side of the spacecraft for the long eclipses. The MOC, SOC and respective IS teams coordinated to power off the individual instruments safely in real-time. The MOC then powered off the broader IS and the CIDP after the SOC and instrument teams had completed their activities. With the IS and CIDP off, the team switched to a second ATS with covered the same times, but had all IS commands removed. The appropriate heaters were then managed to prevent instrument damage. The instrument power off was performed one and a half orbits in advance, in order to mitigate potential complications. The second objective was to safely configure the additional SC components necessary to prevent load shed discussed in section 4. The NAV was set to "Ultra-Low" and the required spacecraft time management was implemented, the AMS and its operational heaters were powered off, and the EVD was powered off. This was performed a little less than one orbit in advance to obtain the most recent post-perigee state while simultaneously allotting multiple communication contact opportunities prior to the start of the first long eclipse.

At the end of the first eclipse the states of health of the spacecraft were assessed using real-time telemetry as well as graphical plots of recorded telemetry from during the eclipse period. The assessment concluded that the spacecraft power system was performing slightly better than modeled, while the thermal model had proven accurate as seen in Figs. 9-11. The better than modeled power performance may be due to the analysis using battery performance based on its end-of-life state. Because the 24 hour thermal capacitance activity involving the fuel tank heaters was performed prior to the first eclipse, the assessment also allowed the flight team to conclude that the tank heaters only needed to be turned full on once at the beginning of the three-orbit eclipse season. A note was made that for future operations fuel levels and eclipse timing will require ad hoc inspection of the TCAP impacts.

At the end of the second eclipse another visual inspection of telemetry was performed upon receipt and it was concluded that performance was still mirroring that of the analysis models. The spacecraft components (excluding the instrument side of the spacecraft) were then powered up on the following individual spacecraft contacts with enough of a time buffer to allow the power bus and battery to reach a safe state as well as the spacecraft to reach a desired location for GPS NAV geometry. The components powered on during this time were the NAV, AMS, and EVD as well as the IS operational heaters. Once the NAV was powered on the clock propagator source was returned to the USO in order to prevent further time drift and the GEONS state was re-initialized. The flight team then waited until the end of each respective contact after GEONS had converged to re-enable NAV time on-board the spacecraft. Shortly after, on a different set of contacts, a partial IS power up was performed in conjunction with the SOC and respective IS teams.

At the end of the third and final eclipse a quick assessment was once again performed, and all four spacecraft were again found to be performing as expected. The rest of the IS was powered up in coordination with the SOC and respective instrument teams. Telemetry analysis was performed in order to verify the integrity of all four spacecraft with nominal operations resuming. Approximately one orbit later tilt maneuvers were performed to return the spacecraft back to its nominal attitude and an additional assessment of various spacecraft telemetry points verified spacecraft integrity.

7. RESULTS AND OBSERVATIONS

The 2019 Long Eclipse season for MMS consisted of 3 consecutive orbits with eclipses:

1. Orbit 1033 (August 23, 2019)
   Eclipse Duration: ~4.3 hours (U+P/2)

2. Orbit 1034 (August 26, 2019)
   Eclipse Duration: ~4.7 hours (U+P/2)

3. Orbit 1035 (August 30, 2019)
   Eclipse Duration: ~3 hours (U+P/2)

Note that Eclipse #3 above is within the original mission requirements which allowed the NAV, AMS, EVD, CIDP and most of the IS to be powered back on following Eclipse #2. The IS was still limited to not allow High Voltage (HV) operations during the orbit containing Eclipse #3. All components that were powered off for 2019 long eclipse season were powered back on with no functional or performance issues.

The bus voltage remained above the C&DH software (29.8 V) and PSE internal limits (29.3 V) as can be seen in Fig. 9. Note that third eclipse was within the original mission requirements and additional loads (IS, CIDP, NAV, AMS and EVD) were powered on following the second eclipse.

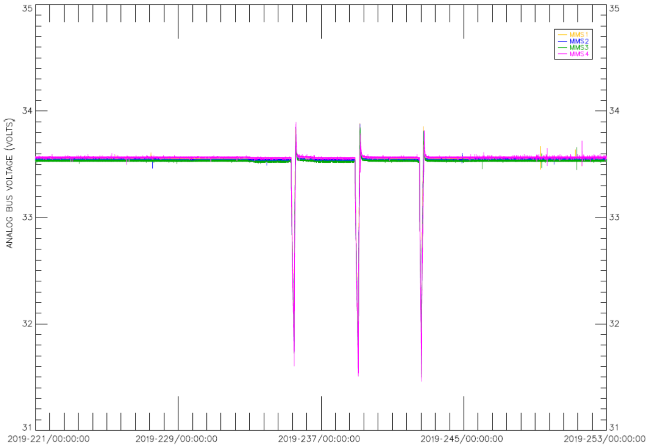


Figure 9. Spacecraft Bus Voltage during August 2019 Long Eclipses

Due to the large number of HV-801s, FPI was the instrument of primary concern with respect to the thermal conditions during the eclipses. Since FPI was powered off during the longest eclipses, IS Deck thermistors located near the FPI spectrometers were used as a proxy. IS Deck temperatures remained above 0 deg C during both Eclipse #1 and Eclipse #2 as can be seen in Figs. 10 and 11.

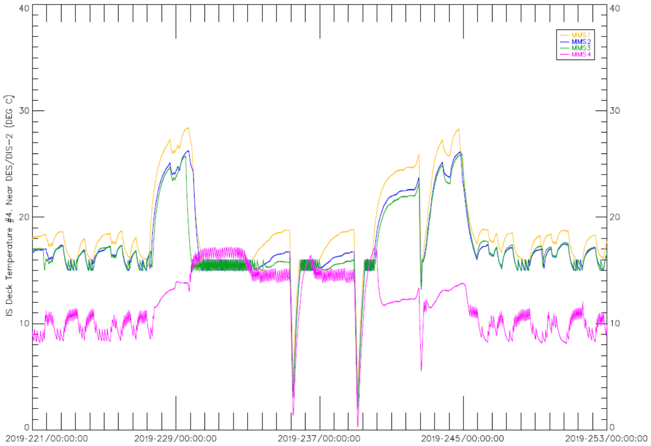


Figure 10. Instrument Suite Deck Temperature #4 during August 2019 Long Eclipses

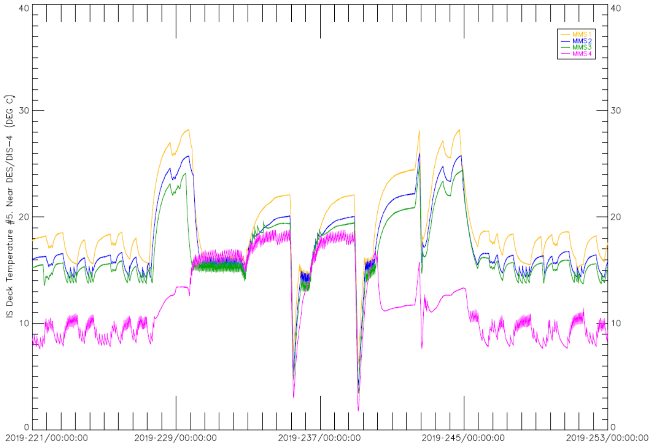


Figure 11. Instrument Suite Deck Temperature #5 during August 2019 Long Eclipses

One additional ramification of the tilt is to the communications link budget. MMS uses two "omni-directional" antennas, but their gain pattern is not truly uniform. In particular, the gain of both antennas drops considerably for lines of sight far from the spin plane. This drop-off limited the ground stations considered to be in view and viable for providing a communication link. It also downgraded the available data rate that MMS normally is able to utilize given a specific distance from Earth.

As previously noted, the Navigator system draws too much power at full operation to be left operating during long eclipses. However, it was recognized that power cycling Navigator into and out of ultra-low power mode around eclipses was too much of an operational burden. Pre-eclipse analysis showed that ground propagation of the state vector could meet mission requirements for up to 10 days. The decision was therefore made to leave Navigator in ultra-low power mode for the first two orbits with long eclipses.

Moding Navigator to ultra-low power occurred a few hours after perigee where on-board navigation data is considered most accurate due to the wide availability of GPS signals. A final estimated state and full covariance were downlinked from each MMS spacecraft prior to moding to ultra-low which was used as an initial state for ground propagation and spacecraft acquisition data.

During the period when on-board navigation was unavailable, ground propagation served as the primary source of the spacecraft ephemeris. Pre-shadow analysis showed that ground propagation of the state vector could meet nominal mission requirements for up to 10 days. Independent orbit determination was performed by flight dynamics using DSN tracking data to generate a backup ephemeris.

Navigator was restored to full power on each MMS spacecraft during subsequent contacts ranging from an initial orbit radius of 12.85 Re to 8.70 Re on the in-bound flank of the orbit of the second shadow. Navigator on-board each MMS spacecraft provided exceptional Time to First Fix (TTFF) performance with a mean TTFF of 10 minutes from cold-start. Persistent Navigator point solutions were computed as high as 12.38 Re. GEONS was initialized from a Navigator point solution and achieved convergence shortly after perigee. The following table details significant on-board navigation events after a Navigator cold-start.

Table 1. Orbit Radius of Navigator Power-Up Events (In-bound flank; in Earth Radii)

	Navigator to full power	**First GPS acquired**	**First point solution**	**GEONS initialized / converged**
MMS4	12.85	12.70	12.38	11.594 / 1.81 (Out-bound)
MMS1	11.65	11.39	10.74	10.714 / 1.97 (Out-bound)
MMS2	10.27	10.02	9.82	9.639 / 2.14 (Out-bound)
MMS3	8.70	8.41	8.36	8.344 / 2.53 (Out-bound)

8. CONCLUSIONS

Now that the MMS spacecraft are in their extended mission, they will encounter a handful of extremely long eclipses during most years. Since these eclipses are considerably longer than the spacecraft and their instruments were designed for, it was unlikely that all systems would survive unscathed unless special measures were taken. These measures include orbital maneuvers to alter the phasing of MMS relative to Sun and Earth; a tilt of the spacecraft to increase the solar illumination on the instrument deck; powering down all scientific instruments and certain spacecraft systems; and extensive heater operations. Using this approach, all four MMS spacecraft and their instruments survived the long eclipses in Aug. 2019 unscathed, which serves to confirm the preparatory modeling and analysis that had been carried out. Based on this experience and the further predictions of these models, the outlook for future years of the extended mission appears bright.

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BIOGRAPHIES

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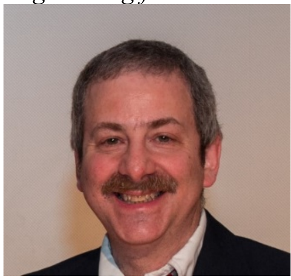
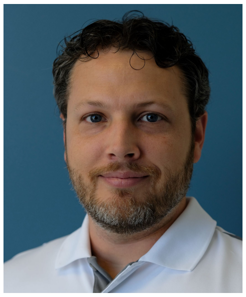


Neil Ottenstein *received a PhD in Theoretical Nuclear Physics from University of Maryland at College Park in 1990. He has been working as a Goddard Space Flight Center contractor for nearly 30 years, first with CSC and then a.i.solutions, inc. He has been the contractor flight dynamics operations lead for MMS since before the 2015 launch and has worked on numerous other missions including SDO, LRO, WIND, POLAR, XTE, STEREO, FAST, LANDSAT-7, IMAGE and several GOES. He received a 2018 NASA Agency Exceptional Engineering Achievement Medal and a 2017 Robert H. Goddard Engineering Award for his work on MMS.*

Eric Palmer *received his B.S. degrees in Mechanical and Aerospace Engineering from West Virginia University. After spending five years performing flight dynamics operations and analysis for the Aqua, Aura, and Terra missions as well as analysis for the Afternoon constellation, he joined the MMS mission. He worked to develop and test flight dynamics operations* *tools prior to launch and has supported operations and analysis from launch through to the current extended mission.*



Christopher Riley *received a M.S. in Space Systems Engineering from Johns Hopkins University in 2019 and a B.S. in Mechanical Engineering from University of Wisconsin, Madison in 2004. He has 14 years of spacecraft operations and analysis experience on NASA missions including with MMS, Advanced Composition Explorer (ACE), and Wind satellites as well as with the Space Shuttle.*

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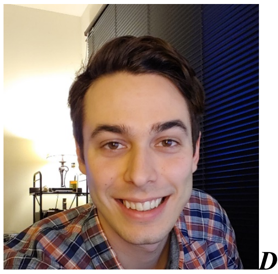

Dominic Godine *graduated from Virginia Tech with an Aerospace Engineering degree in 2013, and has worked in satellite operations for Raytheon for a classified government customer. From 2016 to 2018 he was part of the Magnetospheric Multiscale mission flight dynamics team. From 2018 until the present he has worked in the Space Products Division of a.i. solutions supporting the development and distribution of FreeFlyer software.*