

# LAUNCH WINDOW OPPORTUNITY ASSESSMENT FOR THE MAGNETOSPHERIC MULTISCALE MISSION

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The Magnetospheric MultiScale (MMS) Mission is a tetrahedral formation mission designed to study magnetic reconnection in the Earth's magnetosphere. To sample these regions of interest, the MMS mission will be divided into two main science phases: Phase 1 and Phase 2 with  $1.2 \text{ Re} \times 12 \text{ Earth Radii (Re)}$  and  $1.2 \text{ Re} \times 25 \text{ Re}$  orbits, respectively. This paper focuses on quantifying the MMS yearly launch window opportunities defined by the associated science and operating parameters and constraints. In addition to the seasonal variation limitation, the MMS reference orbit design has other restrictions such as conflicting requirements between science goals and engineering constraints. This paper will present the MMS launch window opportunity assessment method, assessment results, and an analysis of the orbit perturbation effects on various science and engineering constraints. The impact of initial launch conditions on the implementation of NASA spacecraft disposal requirements will also be considered.

## INTRODUCTION

The Magnetospheric MultiScale (MMS) Mission is a tetrahedral formation mission designed to study magnetic reconnection in the Earth's magnetosphere.<sup>1</sup> The plasma-physical processes of reconnection and particle acceleration occur in two main regions of Earth's magnetosphere: the day side magnetopause and the night side magnetotail. To sample these regions of interest, the MMS mission will be divided into two main science phases: Phase 1 and Phase 2 with  $1.2 \text{ Re} \times 12 \text{ Earth Radii (Re)}$  and  $1.2 \text{ Re} \times 25 \text{ Re}$  orbits, respectively, which are initially inclined at  $28.5 \text{ deg}$  with respect to the Earth's equator. These highly eccentric orbits are designed to provide long time periods in the science region of interest, which is centered at apogee.

This paper focuses on quantifying the MMS launch window opportunities defined by the associated science and operating parameters and constraints. The objective of this study is to verify that the MMS mission has at least 6 months per year of available launch opportunities and to quantify the viable launch seasons and blackout periods within a year of launch. To identify the viable end-to-end reference orbit trajectories about which to initialize the tetrahedron formation, the available injection right ascension of the ascending node (RAAN) and argument of perigee (AOP) were scanned throughout a year starting with a nominal launch date. Each reference trajectory was evaluated to determine if the science and engineering constraints were satisfied dur-

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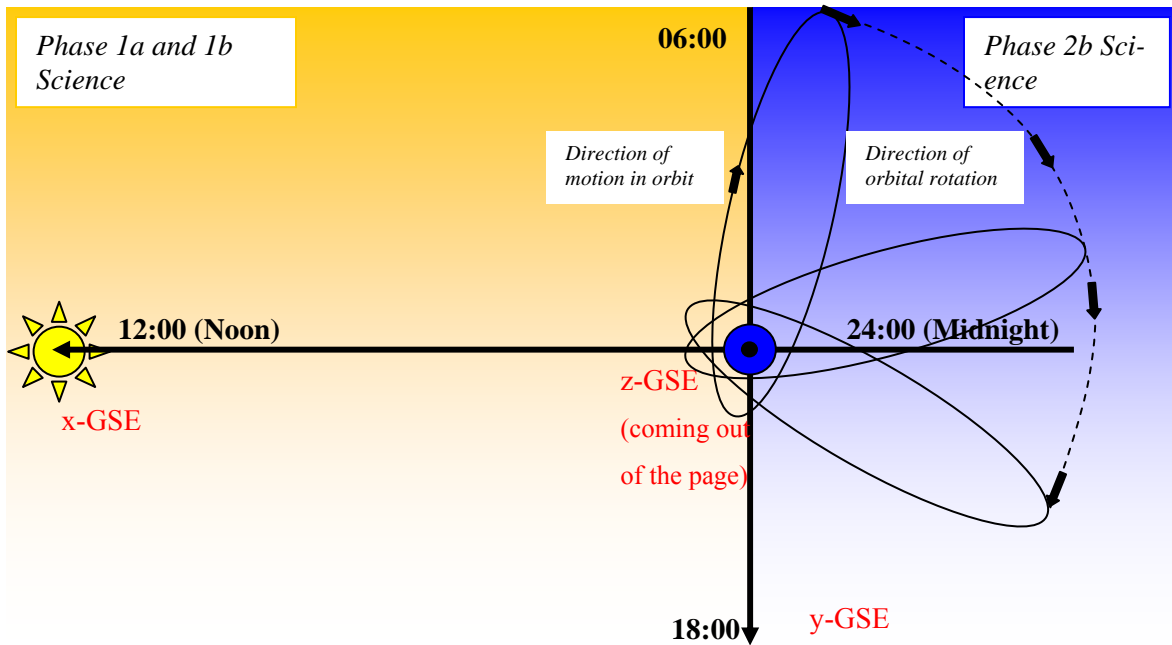
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ing each phase of the mission lifetime. This reference orbit will be used as a starting point to design the MMS formation.

After a brief description of the MMS mission phases and constraints are provided, the reference orbit launch window assessment methodology and assessment results are discussed. Subsequently, an analysis of the orbit perturbation effects on various science and engineering constraints is presented. Finally, the impact of initial launch conditions on the implementation of NASA spacecraft disposal requirements is considered.

### MMS MISSION PHASES AND CONSTRAINTS

The MMS science phases and regions-of-interest are defined in the Geocentric Solar Ecliptic (GSE) rotating reference frame. The science phase start and end locations are given in terms of the orbit apogee vector GSE time (or Clock angle) convention ranging from 00:00 to 24:00 as shown in Figure 1. The GSE x-axis is defined as the unit vector from Earth-to-Sun and the GSE z-axis is aligned with the North Ecliptic Pole. The GSE y-axis completes the right-handed triad. The MMS orbit apsidal line precesses clock-wise in the GSE frame. The GSE time is defined counter-clockwise in the GSE frame as shown in Figure 1.



**Figure 1. GSE Frame Schematic**

The first mission phase (Phase 0) is the launch and commissioning phase. The commissioning duration is 120 days. The MMS spacecraft are launched into 185-km perigee height with 12 Re apogee radius orbits, which requires the spacecraft to perform a series of 5 perigee raise maneuvers starting on mission Day 4 to raise their perigee radius to the desired mission value of 1.2 Re. The injection inclination is 28.5 deg. The argument of perigee (AOP) is varied and the right ascension of the ascending node (RAAN) is selected such that at the end of the commissioning the spacecraft line of apsides is at the specified GSE time (between 17:00 and 19:00).

The first day side science phase (Phase 1a) starts at a GSE time between 17:00 and 19:00. Phase 1a is followed by a night side phase (Phase 1x) with no defined science requirements. Phase 1x starts at a GSE time of 06:00. The next day side science phase (Phase 1b) starts at GSE time of 18:00. Phase 2a consists of a series of 8 maneuvers to raise apogee from 12 Re to 25 Re.<sup>2</sup> Phase 2b is a night side science phase which starts no later than the time at which the x-GSE component of the apogee vector reaches -10 Re as it precesses into the night-side region. The total mission duration after the commissioning phase is two years.

The MMS trajectories have to satisfy the following set of engineering and science constraints during their mission lifetime:

- The maximum shadow duration during the first two weeks after launch is equal to or less than one hour.
- Phase 1a Apogee GSE Latitude between GSE time of 10:00 and 14:00 must be between  $\pm 20$  deg.
- Phase 1b Apogee GSE Latitude between GSE time of 10:00 and 14:00 must be between  $\pm 25$  deg.
- Phase 2b Neutral sheet dwell time must be equal to or larger than 100 hours (not including time spent in shadow)
- Maximum umbra duration for any given 20-hour window during the mission must be less than 216 min
- Maximum of (umbra + 50% penumbra) duration for any given 20-hour window must be less than 231 min
- Minimum perigee height is 900 km.

All the MMS phases (from launch to disposal) along with their associated engineering/science requirements were considered in the MMS launch window opportunity assessment and subsequent analyses presented in the following sections.

## **MMS LAUNCH WINDOW OPPORTUNITY ASSESSMENT**

In this section, an overview of the MMS launch window opportunity assessment method is first presented. Then, the main models and assumptions are provided. Finally, the launch window opportunity assessment results are discussed.

### **Assessment Method**

For a given launch day, each trajectory was fully determined by a given injection AOP and RAAN. First, a coarse AOP/RAAN scan was performed on the first and fifteenth of each month starting August 2014 and ending September 2015. The AOP was scanned from 0 to 355 deg in steps of 5 deg and the RAAN was varied for this analysis such as to obtain a Phase 1a GSE start time between 17:00 and 19:00 in steps of 0.2 hours. A 0.2-hr increase in GSE Phase 1a start corresponds to about 3 deg in RAAN. Then, a finer scan was performed for the months of August and September 2014, where the full scan was performed every 4 days. For each day, only the viable range of AOP was scanned with a finer GSE phase 1a start time step size of 0.1-hr to find additional opportunities in the month of August 2014, which is the current target month for the MMS launch.

As described in Table 1 and later used to illustrate launch window opportunities in Figure 2, candidate launch window trajectories are assigned a color indicating whether a mission constraint has been violated by that trajectory. If a trajectory violates any mission constraint it is shown in red with the following keyword indicating which constraint was violated:

- **Lp2** = maximum shadow during the first two weeks after launch.
- **ns** = neutral sheet constraint
- **mu** = maximum umbra duration constraint
- **mu50** = maximum(umbra+50% penumbra) constraint
- **1a** = Phase 1a latitude constraint
- **1b** = Phase 1b latitude constraint

In addition, the constraint violations are given some margins in which the trajectory, even though not preferred, might be deemed an acceptable launch date. Those trajectories are shown in yellow with keywords identical to the red constraint violations but preceded with the letter “y” for “yellow”. If a given trajectory satisfies all the identified constraints, it is colored in green. If a trajectory significantly violates the Phase 1a or Phase 1b latitude requirements, it is colored black.

**Table 1. Current Green-Yellow-Red Limits for Each Constraint**

Constraint	Green	Yellow	Red
Phase 1a Latitude (deg)	$lat_{max} \leq 20$ and $lat_{min} \geq -20$	$20 < lat_{max} \leq 25$ or $-25 \leq lat_{min} < -20$	$lat_{max} > 25$ or $lat_{min} < -25$
Phase 1b Latitude (deg)	$lat_{max} \leq 25$ and $lat_{min} \geq -25$	$25 < lat_{max} \leq 30$ or $-30 \leq lat_{min} < -25$	$lat_{max} > 30$ or $lat_{min} < -30$
Dwell Time in the Neutral Sheet (hours)	$\geq 100$	$80 \leq t_{NS} < 100$	$< 80$
Maximum Shadow Duration during the first two weeks after launch (minutes)	$\leq 60$	$> 60$ and $\leq 120$	$> 120$
Maximum Umbra Duration (minutes)	$\leq 216$	$> 216$ and $\leq 276$	$> 276$
Max Shadow (Umbra+50%Penumbra) Duration (minutes)	$\leq 231$	$> 231$ and $\leq 291$	$> 291$

Figure 2 shows a sample of the color-coded launch date summary for August 1, 2014. Each row corresponds to an injection argument of perigee value ranging from 0 deg to 355 deg in steps of 5 deg. Each column corresponds to a Phase 1 GSE start time ranging from 17:00 to 19:00 in steps of 0.2 hour.

2014_0801											
	17	17.2	17.4	17.6	17.8	18	18.2	18.4	18.6	18.8	19
0	ns/	y1b/ns/	y1b/ns/	y1b/ns/	y1b/ns/	y1b/ns/	1b/ns/	1b/ns/	1b/ns/	y1a/1b/ns/	y1a/1b/ns/
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30	Lp2/	Lp2/	Lp2/	y1a/Lp2/	y1a/Lp2/	y1a/yLp2/	1a/	1a/			
35	Lp2/ymu/yr	Lp2/ymu/yr	y1a/Lp2/	y1a/Lp2/	y1a/Lp2/	y1a/Lp2/	1a/Lp2/	1a/yLp2/			
40	Lp2/mu/mt	Lp2/ymu/yr	y1a/Lp2/yr	y1a/Lp2/yr	y1a/Lp2/yr	y1a/Lp2/yr	1a/Lp2/				
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55	Lp2/mu/mt	Lp2/mu/mt	y1a/Lp2/mt	y1a/Lp2/mt	y1a/Lp2/mt	y1a/Lp2/mt					
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Figure 2. Sample Launch Window Analysis Color-Coded Launch Date Summary (August 1, 2014).

## Assumptions and Models

All the reference trajectories were generated using a *FreeFlyer*<sup>®</sup> script modeling all phases of the mission discussed above as well as the disposal phase (as an option). *FreeFlyer*<sup>®</sup> is a commercial-off-the-shelf (COTS) software application for use in satellite mission analysis, design and operations.\* After the reference trajectories were generated, they were post-processed to check whether they satisfied the engineering and science constraints discussed in the previous section. The following assumptions were made: (1) the force model includes a JGM2 4x4 Earth Geopotential and Sun and Moon third body forces. The atmospheric drag force is included only for the commissioning phase and the disposal phase, (2) the spacecraft is a spinner with attitude controlled such that the spin axis is tilted 2-deg from the North Ecliptic toward the Sun and aligned with the Sun-Earth line throughout the entire mission; and (3) all maneuvers are modeled as impulsive maneuvers (based on Keplerian computation) and projected in the axial and radial thruster directions to compute the total delta-V per maneuver. Generally, the spin plane is inclined by some degree to both the ecliptic plane and the orbit plane.

## Assessment Results

As the GSE frame evolves with respect to the MJ2000 (Mean of J2000) equator frame, the MMS reference orbit launch window opens and closes throughout the year. Figure 3 shows a high-level overview of the green/yellow/red/black regions throughout the year. The first and the fifteenth of each month are presented starting in August 2014 and ending in September 2015. For each launch date, the x-axis represents the Phase 1a GSE time start ranging from 17:00 to 19:00 in steps of 0.2 hour and the y-axis represents the injection AOP ranging from 0 deg to 355 deg in steps of 5 deg.

Figure 3 indicates the ‘limited opportunity’ months are August 2014, February 2015, and August 2015. The ‘high opportunity’ months are November 2014 and May 2015. There is a 6-month symmetry due to the GSE frame rotating at about 1 deg/day where the launch opportunities are shifted by 180 deg in argument of perigee for the same launch day six months later. The limited opportunity months are separated by 6 months as are the high opportunity months. Consequently, use of this symmetry allows the results of the first 6 months of the year to quantify the available opportunities for the following six months. There are 10 months with available opportunities from August 2014 to August 2015. Note that a finer scan in argument of perigee and Phase 1a GSE start time might uncover ‘green’ launch scenarios for the currently ‘limited opportunity’ months.

The neutral sheet dwell time is one of the most constraining requirements with a large amount of red launch cases caused solely by not meeting the 80 hours minimum value. In addition, meeting the neutral sheet dwell time constraint conflicts with satisfying the maximum shadow constraint because the neutral sheet region is also located in the Earth shadow region. The Moon shadows, which are penumbras only, do not greatly affect the maximum shadow duration except when they occur near apogee.

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\* <http://www.ai-solutions.com/freelyer/>

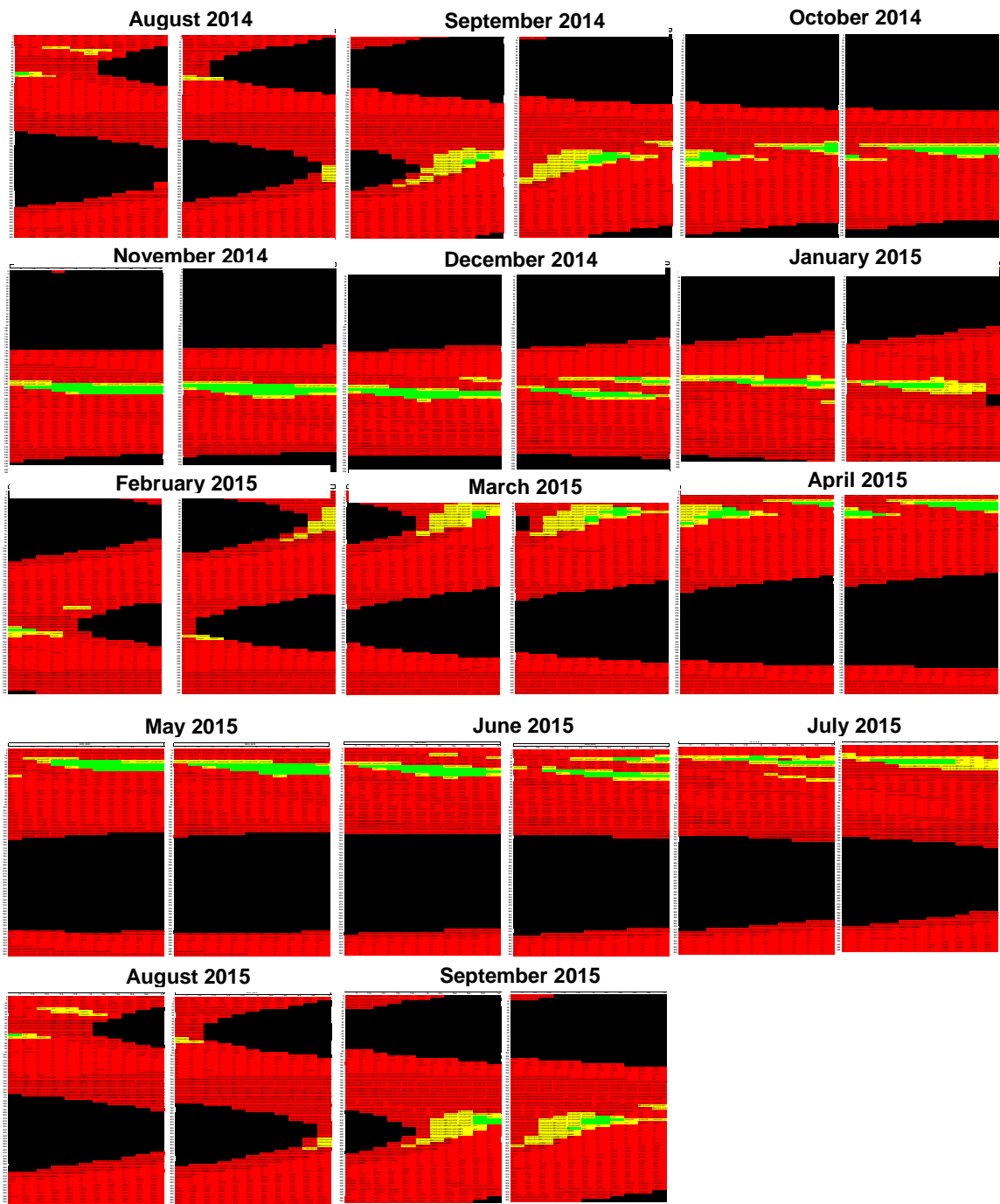


Figure 3. August 2014-September 2015 Launch Window Analysis Overview.

## **ORBITAL GEOMETRY AND PERTURBATIONS EFFECT ON SELECTED MISSION PARAMETERS**

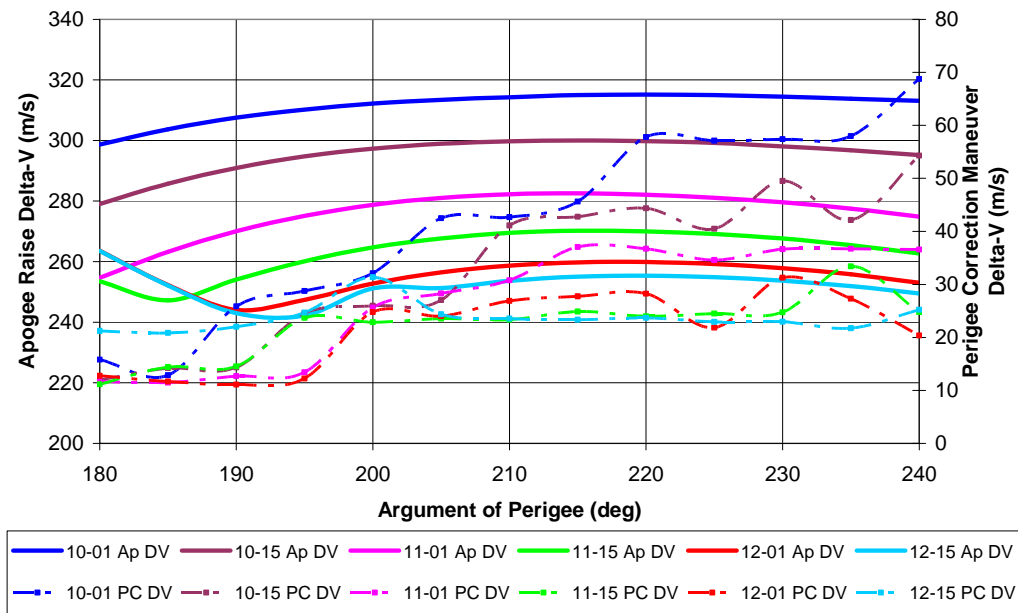
Another factor in choosing a nominal launch opportunity is the effect of orbital perturbations on the mission constraints and the propellant needed to correct for the induced changes. The highly eccentric MMS orbit is very sensitive to perturbations such as the Earth's oblateness and the gravitational pull from the Sun and Moon, which affect perigee altitude throughout the mission. This section focuses on three major parameters: mission delta-V requirements, maximum shadow duration, and time spent in the neutral sheet region. Six launch dates (the 1<sup>st</sup> and the 15<sup>th</sup> of October, November and December in 2014) were chosen to determine trends in the three selected mission parameters over a given available launch season. The first subsection will focus on the effect on the mission maneuvers and the second subsection will present the effect on the neutral sheet and maximum umbra duration parameters.

### **Effect on Mission Maneuvers**

There are three types of maneuvers considered in the reference trajectory: the perigee raise maneuvers during commissioning to go from 1.03 Earth Radii to 1.2 Earth Radii, the apogee raise maneuvers during Phase 2a to raise apogee from 12 Earth Radii to 25 Earth Radii and the perigee correction maneuvers that occur whenever the perigee height drops below 900-km. The perigee correction maneuver delta-V mainly varies with the Sun/Moon perturbations effect on the orbit during Phase 2b.

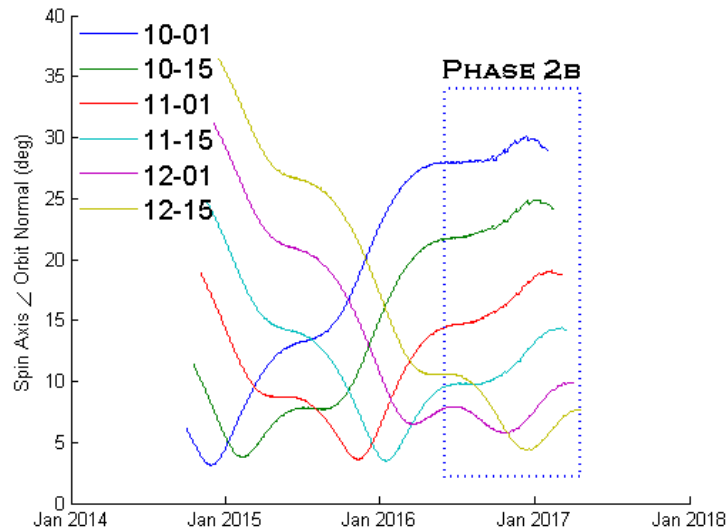
Figure 4 plots the apogee raising total delta-V (Ap DV) and the total perigee correction delta-V (PC DV) as a function of the argument of perigee for each selected launch date. As seen in Figure 4, the perigee correction delta-V increases with argument of perigee values. The increase is the highest in October with delta-V ranging from approximately 15 m/s for an argument of perigee of 184 deg to nearly 70 m/s for an argument of perigee of 240 deg. There is little variation of the apogee raising delta-V across argument of perigee (~ 20 m/s). The main variation is observed across the different launch dates and is driven by the evolution of the spin axis to orbit normal angle value during Phase 2.

### Critical Mission Maneuver Summary



**Figure 4. Apogee Raising and Perigee Correction Delta-V**

Figure 5 shows the angle between the spacecraft spin axis and the orbit normal vector for the six launch dates investigated. As the launch season progresses, the angle between the spin axis and the orbit normal decreases during Phase 2. This allows the spacecraft to use primarily the radial thrusters to perform the in-plane maneuvers.

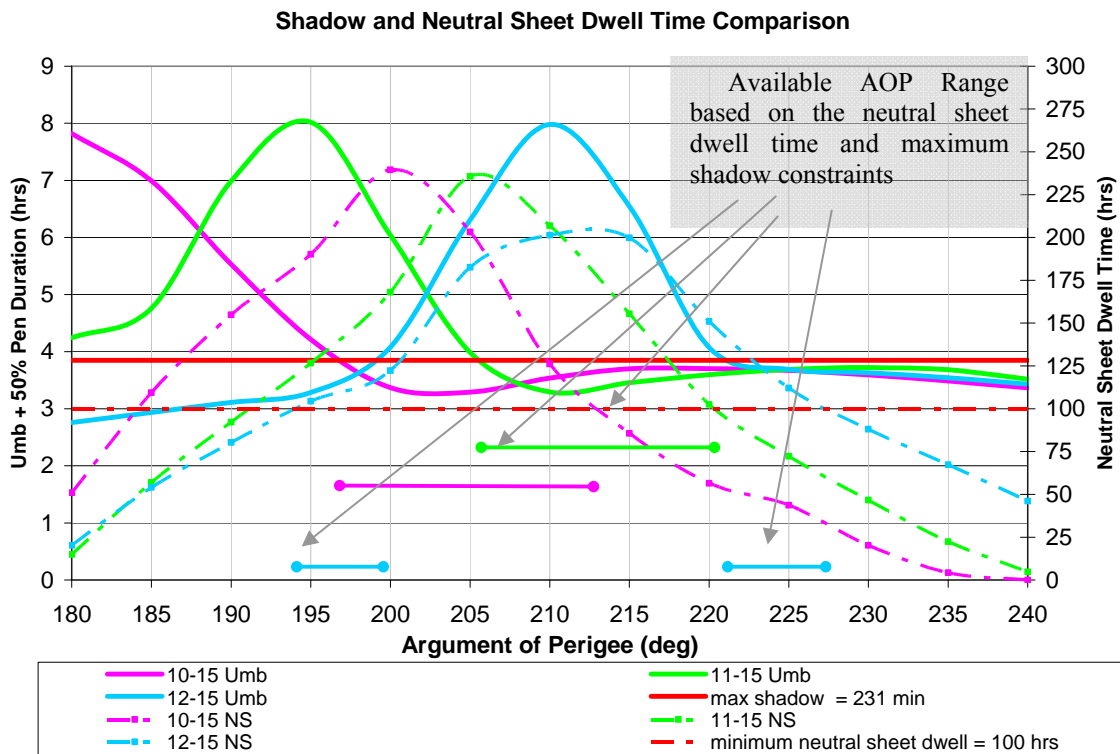


**Figure 5. Angle between S/C Spin Axis and Orbit Normal**

Overall, the total mission delta-V is mainly affected by the orientation of the spin axis with respect to the orbit plane. The perigee maintenance delta-V is also very sensitive to the Sun and Moon perturbations on the perigee height. This effect is also observed on the duration of the MMS uncontrolled disposal, which is discussed in the next section.

**Effect on Neutral Sheet Dwell Times and Maximum Shadow Duration**

Figure 6 plots the neutral sheet dwell time (NS) and maximum shadow duration (Umb) as a function of the argument of perigee. The best configuration for the MMS mission is to have maximum neutral sheet time with minimum shadow duration. In other words, it is best to have the peak of the neutral sheet evolution align with the trough of the maximum shadow evolution as is the case for the October and November scenarios. In December, the maximum neutral sheet dwell time corresponds to the maximum shadow region which starts limiting the available launch cases for MMS.



**Figure 6. Maximum Shadow and Neutral Sheet Dwell Time**

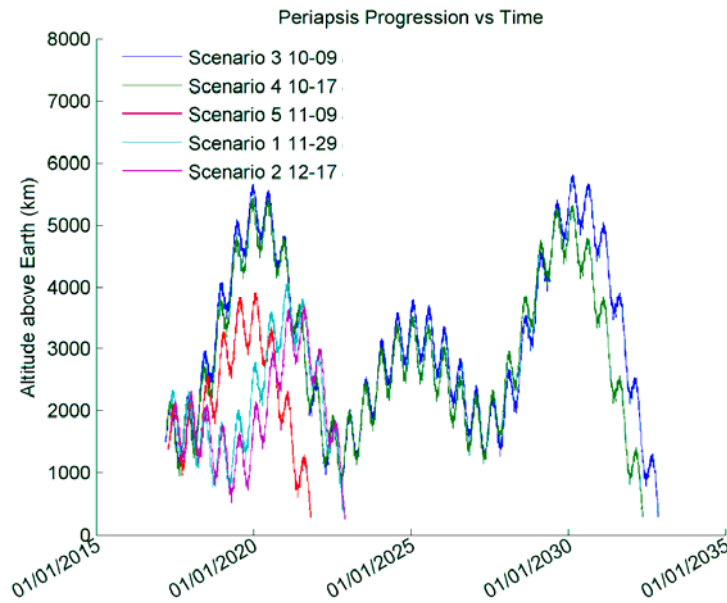
**ORBITAL PERTUBATIONS EFFECT ON MISSION REENTRY DURATION**

At the end of the mission, in compliance with the NASA Procedural Requirements 8715.6A, the spacecraft must be reentered into the Earth’s atmosphere within 25 years. The end-of-mission conditions vary significantly with the initial launch conditions due to variations in the Sun and Moon perturbations on the reference orbit. Several different launch scenarios were studied in an effort to span different end-of-mission conditions. For this analysis, the launch scenarios were selected such as to span a wide range of perigee evolution and end-of-life values. All valid launch cases for the October-December 2014 period were investigated and the launch scenarios

with the minimum and maximum end-of-life perigee values were selected. In addition, three more scenarios were chosen with various numbers of perigee maintenance maneuvers.

Nominally, the reference orbit analysis does not include the atmospheric drag force (except for the commissioning phase) due to its smaller effect on the orbit as compared to J2 or the Sun and Moon third body forces. However, during the disposal phase drag becomes a major perturbation effect. The Jacchia Roberts atmospheric drag model is used in this study during this phase. The Jacchia-Roberts atmospheric model accurately reflects the NASA 1976 Standard Atmosphere model from 90 km to 126 km, and from 126 km up to 1000 km. For this study, the spacecraft are to be considered reentered when their perigee altitude drops below 80 km above the Earth’s surface.

Figure 7 shows the perigee altitude progression during the disposal phase for the selected launch cases. The Sun and Moon perturbations cause long and short oscillations that are nearly in phase for each launch case.



**Figure 7. Disposal Periapsis Altitude (Uncontrolled Reentry) for the Selected Launch Scenarios.**

Table 2 summarizes the reentry epochs as well as the disposal durations for each scenarios. The reentry phase does not include any disposal maneuver. For the scenarios investigated, the MMS reference spacecraft were found to reenter the Earth’s atmosphere well within limits set forth by NPR 8715.6A. The longest reentry duration was about 16 years for the cases studied. The main effects that drive the natural orbit decline are the long and short period cycles of the Sun and Moon perturbations.

**Table 2. Dates of spacecraft reentry**

Scenario	Mission End	Reentry Epoch (Without Maneuver)	Lifetime until Reentry*
October 17, 2014	March 17, 2017	May 12, 2032	15y 2m**
December 17, 2014	May 22, 2017	Nov 22, 2022	5y 6m
November 29, 2014	May 1, 2017	Nov 22, 2022	5y 6m
October 9, 2014	March 11, 2017	Nov 5, 2032	15y 8m
November 9, 2014	April 10, 2017	Oct 22, 2021	4y 6m

\* Time before spacecraft's minimum altitude drops below 80 km above Earth's surface

\*\* y = years, m = months

## CONCLUSION

A launch window analysis was performed that investigated viable MMS reference orbit launch opportunities for an entire year span from August 2014 to September 2015. For a given launch day, each trajectory was fully determined by a given injection argument-of-perigee and right ascension of ascending node. Using the latest assumptions and requirements, the 'limited opportunity' months were August 2014, February 2015 and August 2015. The 'high opportunity' months were November 2014 and May 2015. The neutral sheet dwell time is one of the most constraining requirements with a large number of red launch cases caused solely by not meeting the 80 hours minimum duration. In addition, meeting the neutral sheet dwell time constraint conflicts with satisfying the maximum shadow constraint because the neutral sheet region is also located in the Earth shadow region.

Other factors to be considered when choosing a nominal launch opportunity are the orbit perturbation effects on various science and engineering constraints induced by initial launch conditions. The highly eccentric MMS orbit is very sensitive to perturbations such as the Earth's oblateness and the gravitational pull from the Sun and Moon, which affect perigee altitude throughout the mission. Mission delta-V requirements, neutral sheet dwell time, and maximum shadow duration were considered for various launch dates. It was found that the total mission delta-V is mainly affected by the orientation of the spin axis with respect to the orbit plane. However, the perigee correction delta-V is sensitive to the Sun and Moon perturbations on the perigee height. This effect is also observed on the duration of the MMS uncontrolled disposal. The best configuration for the MMS mission is to have maximum neutral sheet time with minimum shadow duration as is the case for the October and November scenarios. In December, the maximum neutral sheet dwell time corresponds to the maximum shadow region which starts limiting the available launch cases for MMS.

For the scenarios investigated, the MMS reference spacecraft was found to reenter the Earth's atmosphere well within the 25-year limits set forth by NPR 8715.6A. The longest reentry duration was about 16 years for the cases studied.

It is obvious that there are many more parameters involved in modeling the reference orbit that could influence the results presented in this paper. Additional trade space analysis will be performed (for example increasing the mission perigee value) as the pre-mission design and analysis work matures. Future work will also focus on developing a method to find an optimal reference orbit based on multiple criteria such as minimum delta-V requirement, maximum neutral sheet dwell time and minimum shadow duration.

## **REFERENCES**

<sup>1</sup> C. Gramling, "Overview of the Magnetospheric MultiScale Formation Flying Mission", AAS-09-328, Astrodynamics Specialist AAS Conference, Pittsburgh, PA, August 2009.

<sup>2</sup> C. Roberts, J. Tichy and C. Gramling, "Apogee Raising for the Magnetospheric MultiScale Formation Flying Mission", AAS-09-329, Astrodynamics Specialist AAS Conference, Pittsburgh, PA, August 2009.