The Effects of Thrust Uncertainty and Attitude Knowledge Errors on the MMS Formation Maintenance Maneuver

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ABSTRACT

The Magnetospheric Multiscale (MMS) Mission will use a formation of four spinning spacecraft to study the Earth's magnetosphere. The science objectives of MMS require a near-regular tetrahedron formation to be maintained with side lengths ranging from ten kilometers to several thousand kilometers at orbit apogee. To reduce spacecraft complexity and cost, the current mission concept assumes MMS can achieve its formation goals through open-loop orbit control from the ground, rather than in-flight, closed-loop formation control that has been the subject of recent study. Significant analysis has been performed to provide optimal reference orbit and relative orbit designs. However, the feasibility of achieving these orbits, and maintaining them for an extended period of time in the presence of real world errors and perturbations has not been investigated. In particular, attitude knowledge and control errors, which may have a negligible effect on orbit control for conventional missions with spinning spacecraft, can contribute significant errors to the MMS orbits.

In this work, a 6 degree-of-freedom (DOF) simulation is developed and used to analyze the effects of realistic errors on formation maintenance maneuver accuracy. Several realistic considerations including a finite-burn model, attitude perturbations, and thrust uncertainty are studied. The primary objective is to quantify the effects of realistic attitude and orbit control, knowledge, and actuator errors on the formation geometry by observing representative maneuver errors of a single spacecraft.

INTRODUCTION

The Magnetospheric Multiscale (MMS) mission is a multi-spacecraft mission with the primary objective being to study magnetic reconnection, charged particle acceleration, and turbulence in the selected regions of Earth's magnetosphere. These processes govern the energy exchange throughout the universe and are essential to aid our understanding of the solar system (Ref. 1). Most of the previous missions studying the Earth magnetosphere have been single spacecraft missions. There are obvious limitations in studying the highly dynamical plasma processes with a single measurement in space and time. The recent advances in formation flying technology enable us to use multiple spacecraft to take simultaneous measurements within the prescribed proximity for observing the temporal and the spatial effects of the plasma dynamics. The European Space Agency's (ESA) Cluster II mission is a multi-spacecraft mission studying the magnetosphere (Ref. 2). MMS will examine a different region of the magnetosphere, and will provide higher spatial resolution for observing plasma activity on a smaller scale. The science returns from Cluster II and MMS will complement each other.

The formation control technique MMS is considering is an open-loop approach, which requires all the trajectories and maneuvers to be planned a priori on the ground. The formation will be achieved through optimal trajectory planning and accurate maneuver controls.

The mission achieves its science objectives by selecting the reference trajectory that maximizes the formation dwell time spent in the select portion of the orbit. Once the reference trajectory is designed, the relative orbits for the remaining three spacecraft are chosen based on the quality factor of the tetrahedron formation, which is a function of both size and shape (Ref. 3). The final selection of the relative orbits would primarily be based on the longest sustaining acceptable formation, defined by the scientists, without any maintenance maneuver interventions.

There are three mission phases for MMS. The Phase I reference orbit is 1.2 Re x 12 Re, the Phase II reference orbit is 1.2 Re x 25 Re, and the Phase III reference orbit could be as high as 12 Re x 30 Re. In addition to the initial formation establishment and the routine formation maintenance activities during each phase, the tetrahedron formation would resize between 10 km – 1000 km inter-spacecraft separation distances (tetrahedron side length) to study phenomena of different spatial resolution.

One of the major challenges of the mission is to plan and execute the formation maintenance maneuvers. The size of these maintenance maneuvers varies between 1 mm/s to a few m/s depending on the size of the tetrahedron and the condition of the tetrahedron at the time of the maneuver. The mission concept requires planning all the maneuvers on the ground with custom mission planning software, which would generate the thruster pulsing sequence for individual thrusters to execute in an open-loop fashion. These pulsing sequences could either be time-stamped or, more traditionally, triggered by the sun pulse and then pulsed for a fixed duration. Precise execution of a pre-planned maneuver is critical for the formation to remain stable for an extended period. Any maneuver errors could cause undesirable position drift in just few orbit periods. The effect is even more significant when these errors directly contribute to period mismatching between the spacecraft. Based on previous studies by Carpenter (Ref. 4), minor mismatching in semi-major axis at the end of a maneuver (period mismatching) would cause a secular relative position drift. One example shows a 33 ms period mismatch, which is equivalent to 11 m semi-major axis errors, would cause maximum relative position drift of roughly 1 km in just 3 orbit periods. Therefore, failure to perform maneuvers accurately would require frequent and expensive trimming maneuvers that would drive up the fuel budget and operation cost.

PAST EXPERIENCES

The formation maintenance maneuver's primary objective is to trim small orbit deviations for one or more spacecraft in order for them to achieve their desired absolute states and desired relative states with respect to other spacecraft in the formation. Because of the additional constraints in the relative motions, maintenance maneuvers may be required in any arbitrary direction in the inertial space in order for the formation to be established given the limited maneuver time available. A previous study has shown that the 'slew and burn' scheme, which is used for most three-axis stabilized missions, is not practical for MMS because it would require an enormous amount of fuel for spin axis precession for each maintenance burn (Ref. 5). One effort suggests de-spinning the MMS spacecraft prior to the 'slew and burn' scheme and then re-spinning it back after the orbit maneuver is completed. While the fuel consumption of this scheme has greatly reduced from the simple "slew and burn" scheme, the amount of fuel required for the spin control sets a low upper limit for the number of the maintenance maneuvers MMS can afford. Furthermore, if MMS were to adopt the "de-spin and then re-spin" approach, studies must be conducted to understand the effects of spin maneuvers on the flexible appendages on the MMS spacecraft.

CURRENT MANEUVER SCHEME

For past missions with spinning spacecraft, the common maneuver strategy is to assume the spacecraft would have enough angular momentum to counteract any environmental and system torque disturbances. Therefore orbit maneuvers are often planned with the fixed attitude assumption throughout the maneuvers. While the coupling effects between the forces and torques do exist, missions with spinning spacecraft generally have loose requirements for both the attitude and the delta-V maneuvers, so the fixed attitude assumption is generally acceptable. Missions with more stringent requirements would generally resort to three-axis stabilized spacecraft.

MMS is challenging because the spinning motion is required for extending the wire booms for electromagnetic field measurement, yet the formation flying requirements require MMS spacecraft to have the attitude control and orbit control requirements similar to three-axis stabilized spacecraft. Unlike what is traditionally done for maneuvering a spinning spacecraft, and unlike the slew and burn scheme which consumes an enormous amount of fuel, an alternative maneuver approach that enables a spinning spacecraft to maneuver in any direction in space is required for the MMS mission. For this work, the spacecraft makes use of eight 1 N, mono-prop hydrazine thrusters. The thrusters are in two groups of four collocated thrusters. Within each group, four thrusters are aligned at exactly 90° apart pointing in the +Z, -Z, +Y, and –Y body axes, as shown in Table 1. The center of one thruster group is located at the outer rim of the spacecraft body, and it is located on the plane containing the spacecraft center of gravity. The second thruster group is located at exactly 180° about the +Y axis from thruster group one, symmetrically across the spacecraft body.

Table 1: Assumed Spacecraft Properties, in Spacecraft Body Axis, for this Analysis

Spacecraft Mass	300	[kg]
Center of Gravity	[0 0 0]	[-]
Spin-Axis	[0 0 1]	[-]
Moment of Inertia	[3000 0 0] [0 3000 0] [0 0 4000]	[kg-m^2]
Nominal Thrust Magnitude	1	[N]
Number of Thrusters	8	[-]
Thrust Direction	[0 0 -1] [0 0 1] [0 1 0] [0 -1 0] [0 0 -1] [0 0 1] [0 1 0] [0 -1 0]	[-]
Torque Direction	[0 1 0] [0 -1 0] [0 0 1] [0 0 -1] [0 -1 0] [0 1 0] [0 0 -1] [0 0 1]	[-]

This thruster arrangement allows the spacecraft to maneuver in the axial directions with continuous thrust using four axial thrusters. The tangential thrusters support both the spin maneuvers and the translational maneuvers in the lateral directions. Two torqueless pairs of thrusters would maneuver the spacecraft in the lateral directions by operating in pulse-mode. For the spacecraft to carry out an accurate maneuver in the lateral direction, the thruster pulse phasing angle, the thrust pulse-width, and the location of the center of gravity must be well defined.

Pulse-Width Selection

The tangential thrusters are responsible for performing the component of delta-V on the spin plane. They operate in pulsed mode because they only need to be ON when the thrust vectors are in the direction of delta-V. The current simulation allows thrusters to pulse at two different pulsed width settings: 54° pulse angle for coarse maneuvers in the spin plane and 3.6° pulse angle for fine maneuvers in the spin plane. Based on the current thruster specification, spacecraft parameters, and maneuver scheme, a 3.6° pulse angle provides delta-V resolution of 1 mm/s, which is the precision required to establish stable formations. The coarse maneuver enables faster maneuver execution time. A 1 m/s delta-V would take more than two hours for a spacecraft in the fine maneuver mode to complete, but would only take about half an hour for a similar maneuver to carry out by operating in coarse/fine maneuver mode combination.

The coarse maneuver mode increases the delta-V per pulse to ensure the rapid completion of a maneuver, which is desirable for both flight dynamics analyses and for science operations.

Table 2: Approximate Maneuver Duration Using the Current Variable Pulse-Width Scheme

Maneuver Mode Pulse-Width	Fine Mode 0.2 [sec], 3.6°		Coarse Mode 3 [sec], 54°		
Spin Plane dV [m/s]	# of Burns	Duration [s]	# of Burns	Duration [s]	Approx Total Maneuver Time [s]
0.001	1	8			8
0.005	4	41			41
0.010	8	81			81
0.015	12	122			122
0.020	16	163	1	14	163
0.025			2	17	180
0.050			3	35	197
0.100			7	70	232
0.500			35	348	511
1.000			70	696	859
2.000			139	1393	1555
3.000			209	2089	2252

For maneuvers that involve lateral motion, the tangential thrusters start pulsing at a pulse-width of 3 s or 54°, until the delta-V falls within 0.02 m/s, when the fine maneuver mode would take over to ensure the end velocity to be within 1 mm/s of the target velocity. Table 2 shows the estimated maneuver durations for a spacecraft to reach its target lateral delta-V under this two-maneuver mode framework. The axial thrusters, on the other hand, operate in continuous mode to achieve any axial components of the delta-V. They burn continuously until the target delta-V falls within 1 mm/s. As a result, the maneuver duration is often limited by the lateral maneuver duration.

SIMULATION IMPLEMENTATION

The objective of the simulation is to quantify the effects of errors in thrust magnitude, thrust direction, and attitude knowledge on the maintenance maneuvers. These results are primarily for establishing baseline attitude requirements. The following section briefly covers 1) The structure of the maneuver simulations, 2) The different types of errors scenarios, and 3) The parameters on which maneuver performance can be based.

Overview

A closed-loop maneuver targeting simulation is used to generate the time-stamped thruster pulsing sequence. Once the closed-loop time-stamped pulsing sequence is generated, an open-loop version of the simulation simulates the maneuver according to the pulsing sequence without any additional control logic. There are four error scenarios. Thrust magnitude and direction uncertainty/error is introduced to the open-loop simulation as random errors. Attitude knowledge errors, including 0.1° pitch angle error, 0.1° spin-phase error, and nutation angle errors, are introduced to the simulation as unanticipated initial conditions.

Initializing the simulation with unanticipated initial conditions is equivalent to introducing constant knowledge bias to the system, which can be considered the worst-case knowledge error scenario.

For each of the error scenarios, one hundred maintenance maneuvers ranging from 1 cm/s to 3 m/s randomly scattered across the northern hemisphere of the spacecraft body, Figure 1, are used as the test cases. These maintenance maneuvers are randomly chosen, in the inertial frame, centered at the spacecraft center gravity. All of the maneuvers start at the periapsis.

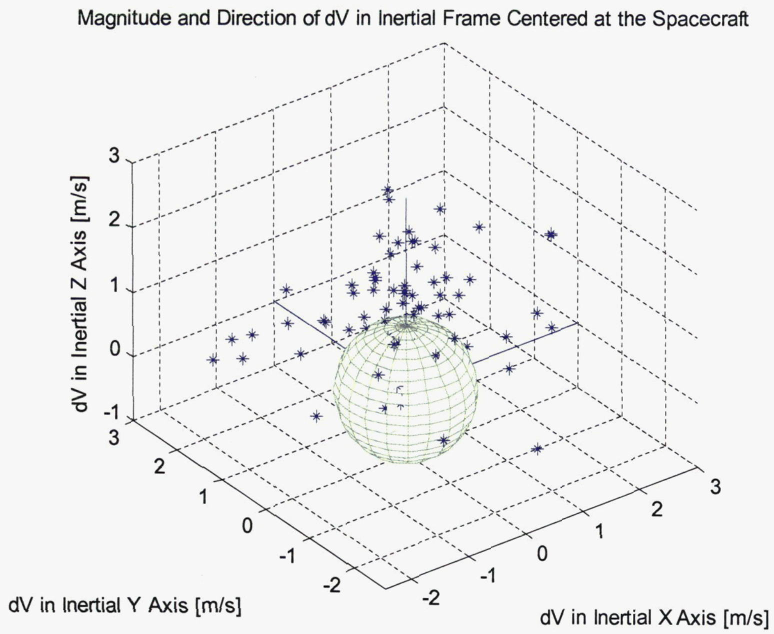

Figure 1: One Hundred Different Maintenance Maneuvers Ranging from 1 cm/s to 3 m/s.

Thrust Uncertainty / Error Modeling

Due to the formation flying requirements of MMS, the pulse characteristics are crucial for accurate maneuver planning. The MMS spacecraft simulation uses a high fidelity thrust profile model. The transient behaviors for thrust buildups and minor fluctuations during a pulse are modeled. A statistical model is used to generate the thrust magnitude as a function of 'time since the thruster valve open signal'. The thrust centroid fluctuation is inherent from the randomized thrust magnitude output. As the spacecraft spins and fires the thruster in the inertial space, a direction error component is introduced. Figure 2 shows a few typical pulse-profiles for a 200 ms pulse. Due to proprietary information consideration, we are restricted from discussing the details of thrust modeling further.

For pulses that are longer than 200 ms, including coarse mode maneuvers and continuous burns, the detailed transient behaviors are replaced by a step function approximation. However, small magnitude fluctuations are added to the nominal thrust level to simulate the thrust uncertainty.

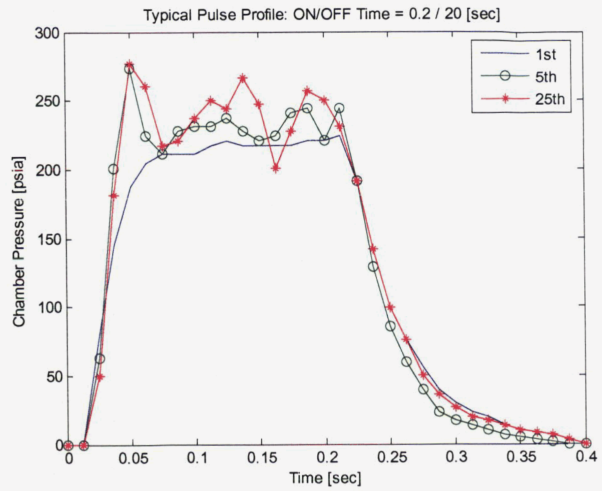

Figure 2: Typical pulse profiles for pulse-width that are similar to MMS's thrusters.

Performance Assessment Parameters

Several parameters are used to assess the effects of the various errors in the system. The spacecraft ephemeris offers a direct way of performance evaluation. By comparing the post maneuver ephemeris with the actual expected states at the end of the maneuver, one can determine the position and velocity errors that have accumulated during the course of a maneuver. Furthermore, it offers a direct measurement for triggering the collision avoidance alert signals when running the multi-spacecraft simulation. However the relative position drift error over time is not immediately realized from the ephemeris discrepancy. While collision avoidance is important, it is also important to assess the maneuver error's effect on sustaining the formation. Relative position drift is dominated by the orbit period, and the orbit period is a function of the semi-major axis (SMA). Therefore SMA is another important parameter for performance evaluation.

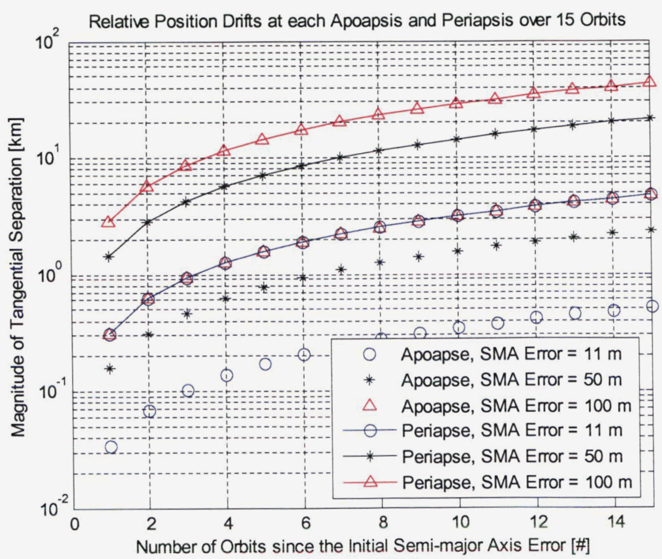

Figure 3: Tangential separation of two spacecraft at the each apoapsis and periapsis for the first fifteen orbits since the initial post-maneuver SMA error.

RESULT

A Monte Carlo simulations of one hundred different maintenance maneuvers ranging from 1 cm/s to 3 m/s scattered across the northern hemisphere of the spacecraft body (Figure 1), show the maximum delta-V errors to be around 0.75 % of what the corresponding position errors are on the order of meters to ten meters for burns larger than 2 m/s. As seen from Figure 4, the worst position error occurs during a 2.6 m/s maneuver, and the corresponding position error is about 12 m. Generally speaking, 1 % delta-V error is within the typical maneuver accuracy. While 0.75 % is under the 1 % boundary, the SMA errors tell a different story. The ratio of SMA errors to the magnitude of the delta-V maneuvers is as high as 50 m in SMA error for a 1 m/s delta-V. This result is more alarming than the position errors and the velocity errors because SMA errors provide a direct measurement for relative drift over time, see Figure 3.

Similar results are found observed from the Monte Carlo simulations for cases with pitch angle error of 0.1° and for spin phase error of 0.1°. From Figure 7 and Figure 8, one can see that the magnitude of position and velocity errors for the two cases are quite similar. This is somewhat expected because small attitude bias errors, whether they are pitch angle errors or phase errors, should not cause significant attitude differences in the inertial frame. The maneuver errors should be inversely proportional to the dot product of delta-V and the spacecraft attitude. But since the delta-Vs are chosen at random, the distributions of errors as a function of the magnitude of delta-V should be similar. The SMA errors for both of the attitude knowledge cases are also similar for the same reason. The SMA errors due to errors in the magnitude of the delta-V are about 50 m SMA error per 1 m/s of delta-V, as illustrated in Figure 9.

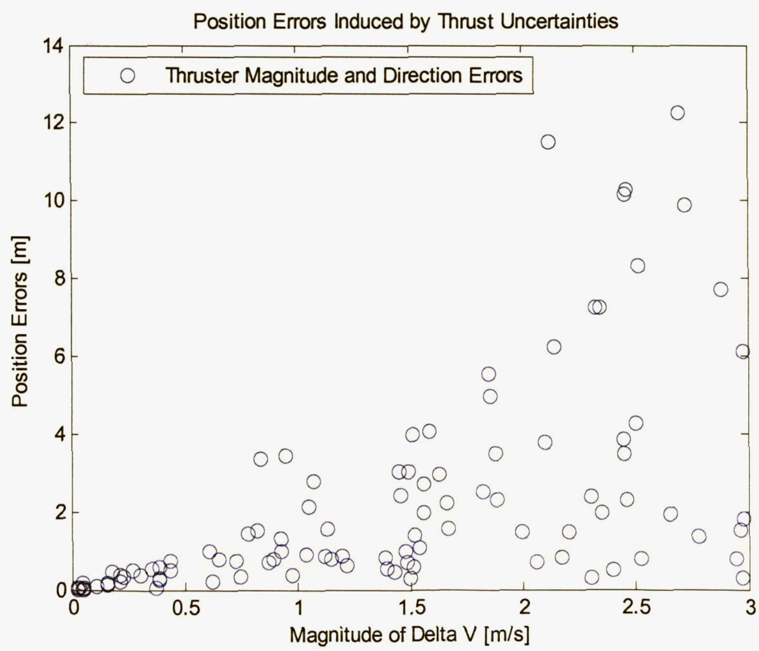

Figure 4: Position errors induced by the thrust errors

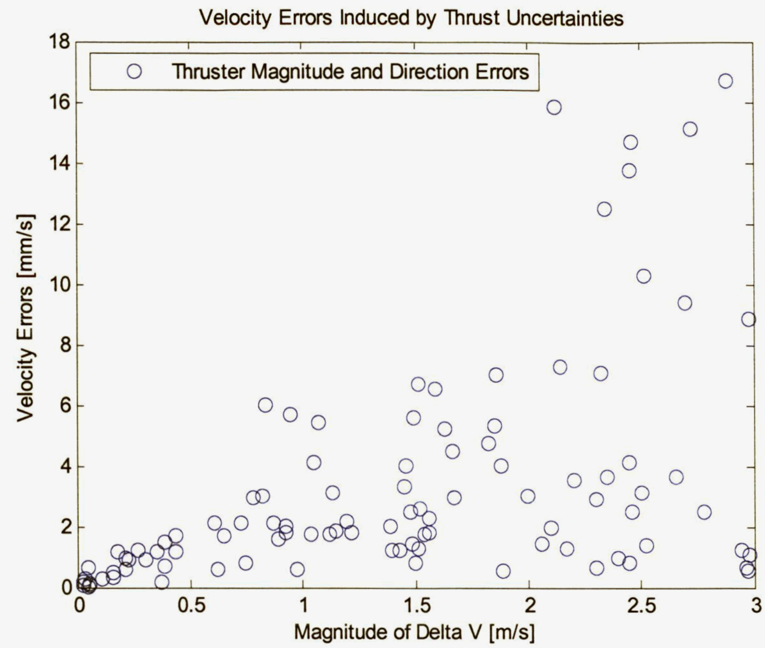

Figure 5: Velocity errors induced by the thrust errors

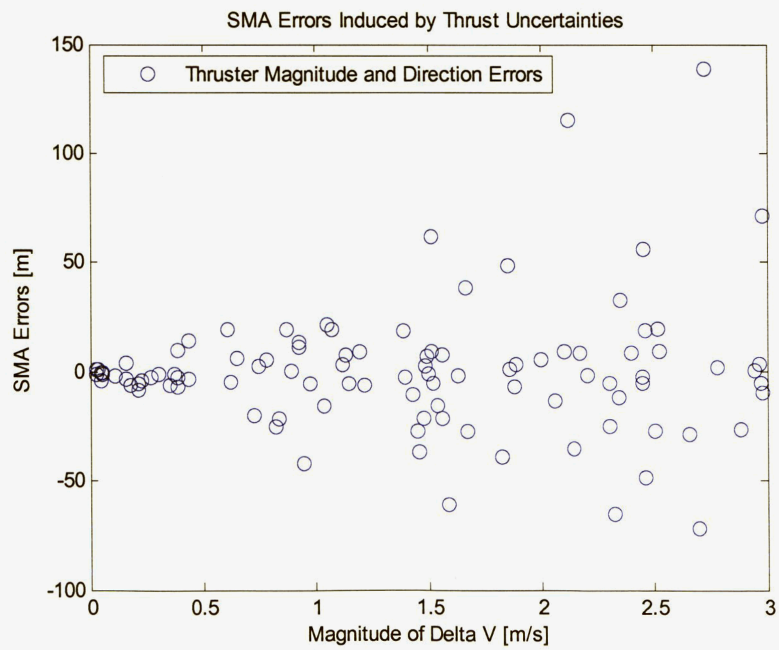

Figure 6: Semi-major axis errors induced by the thrust errors

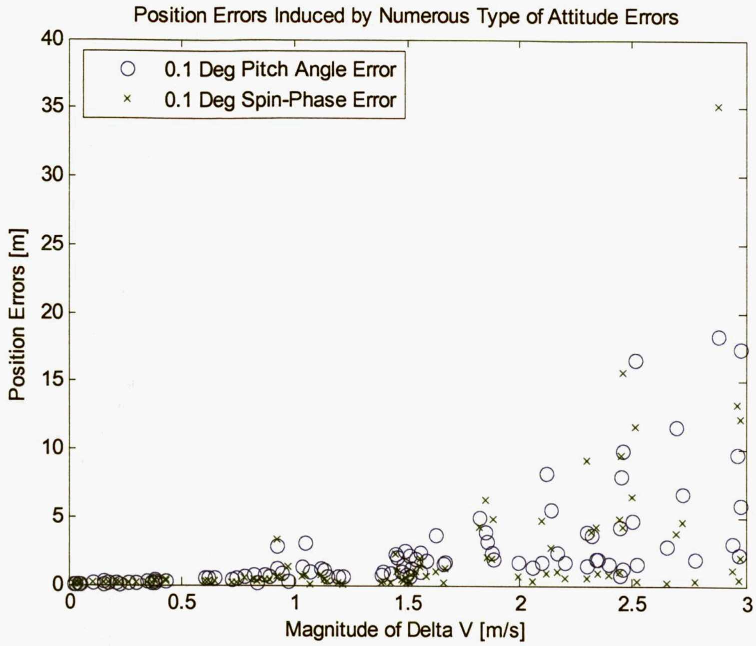

Figure 7: Position errors induced by attitude knowledge errors

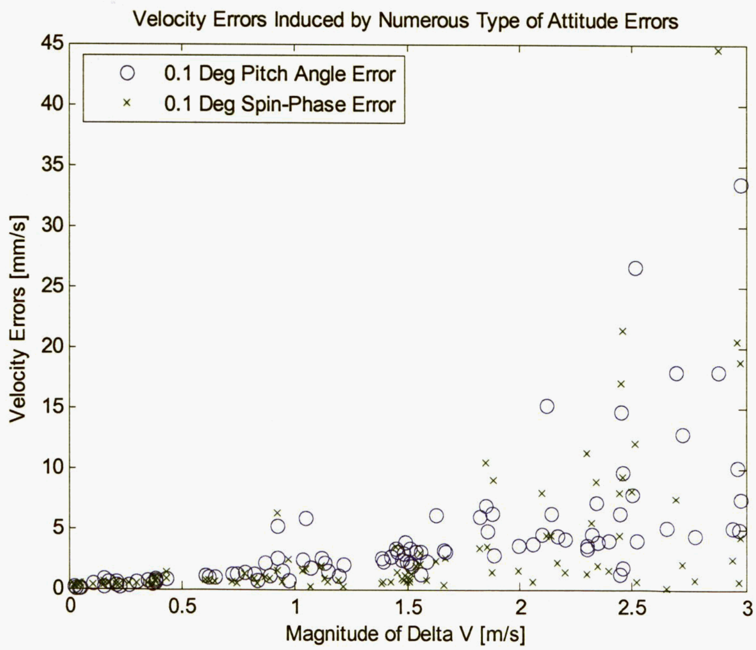

Figure 8: Velocity errors induced by attitude knowledge errors

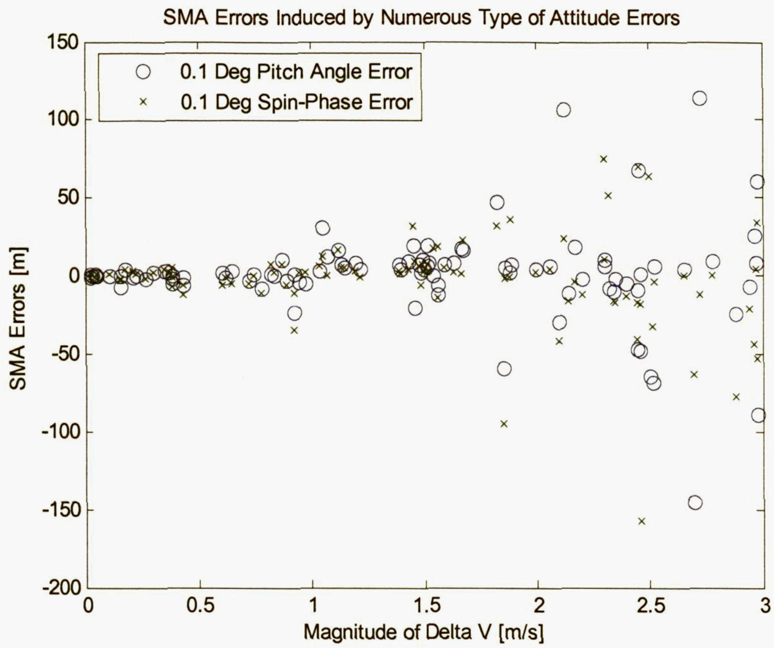

Figure 9: SMA errors induced by attitude knowledge errors

Another set of Monte Carlo simulations is performed for unknown, unanticipated nutation angles. Like previous analyses, one hundred different delta-V maneuvers are planned with the closed-loop maneuver planning software. The time-stamped thruster pulsing sequence from the planning run are executed by an open-loop simulation where unanticipated nutations are included in the spacecraft initial conditions (unanticipated body rate about the non-spin axis.)

Figure 10 and Figure 11 show that while the maneuver errors stay at about the same level as previous results for thrust uncertainties and attitude errors, for nutation angles of less than 0.5°. Position errors are as high as 150 m and delta-V errors as high as 6.4 percent occur for nutations of 1.0°. Similar trends are observed in the SMA errors. For nutation angles larger than 0.5°, SMA errors can be as high as a few kilometers, which is unacceptable. These results confirmed that an excessive level of nutation is not tolerable, and nutation must be managed before and during the maintenance maneuvers through either passive or active means.

It should be noted that the maneuver errors contributed by the unanticipated nutation would be different had the thruster pulses been triggered by the detection of known celestial objects, such as the sun, instead of being triggered by a predetermined timed-sequence. This study adopts the later scheme for convenience, but traditionally the sun pulse triggers maneuvers for spinning spacecraft. For that scheme, sun pulse acts like an attitude feedback to the system during a maneuver, therefore smaller maneuver errors are expected.

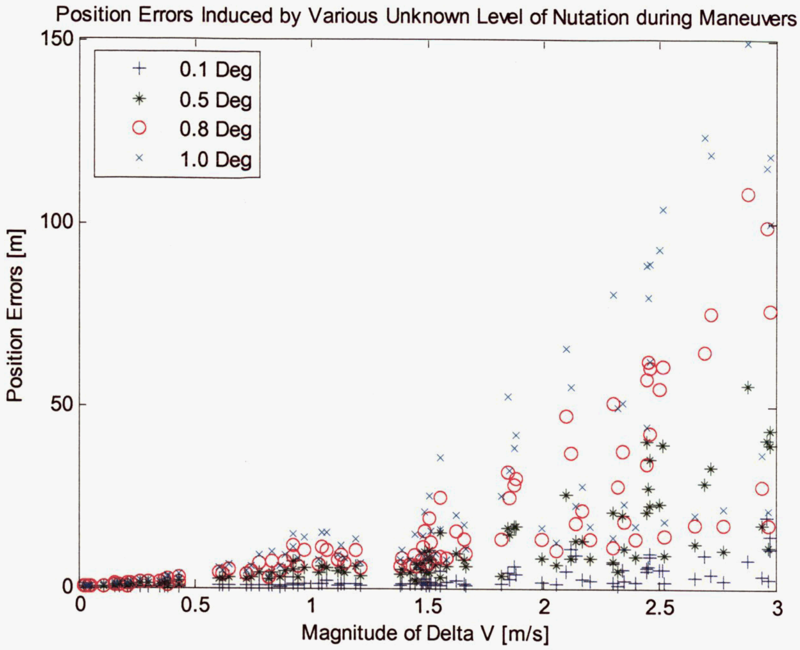

Figure 10: Position errors induced by numerous levels of unanticipated nutation angles

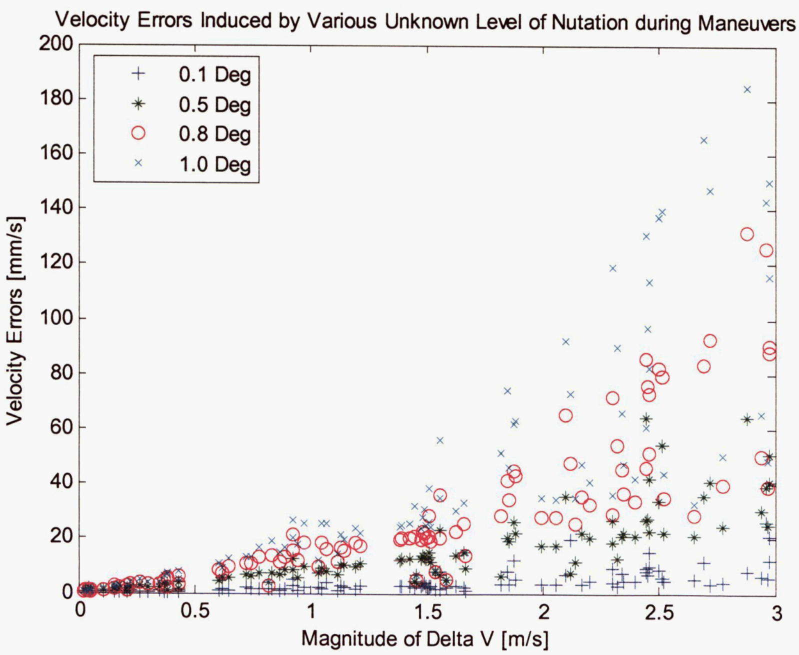

Figure 11: Velocity errors induced by numerous levels of unanticipated nutation angles

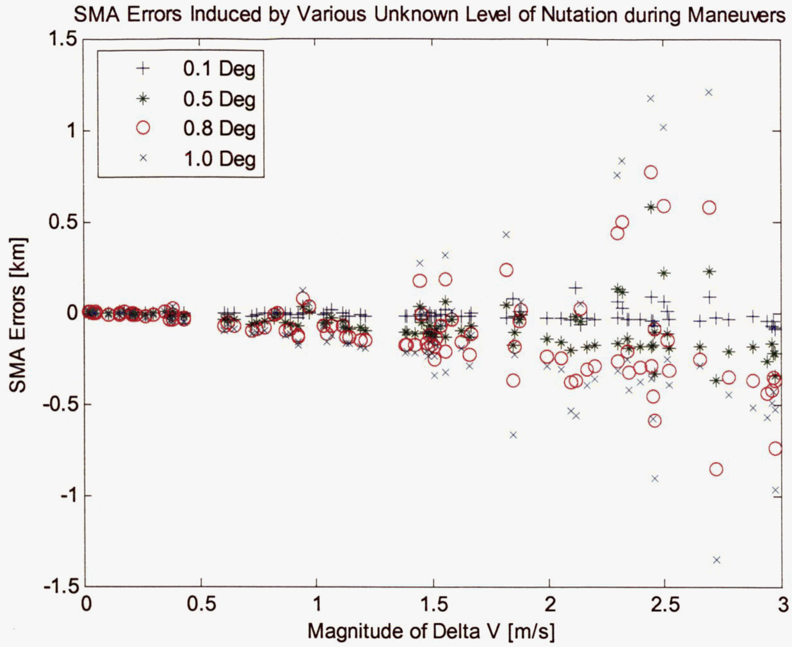

Figure 12: SMA errors induced by numerous levels of unanticipated nutation angles

The simulation results and the maneuver errors corresponding to their particular error sources are summarized in Table 3. While the maneuver errors are tabulated, the acceptable level for these maneuver errors have yet to be defined by the MMS project.

Table 3: Summary of Monte Carlos Simulations Results

	Thrust Errors	Attitude Knowledge Errors [°]		Nutation Angle [°]			
Worst Case Post-Maneuver Errors	Magnitude and Direction	0.1 Pitch Angle	0.1 Spin-Phase	0.1	0.5	0.8	1.0
Position Errors / Magnitude of Delta-V [m]/[m/s]	5.4	6.6	12.2	6.6	19.3	37.6	51.8
Velocity Errors / Magnitude of Delta-V [mm/s]/[m/s]	7.5	11.3	15.5	8.8	26.1	45.7	64.1
Semi-major Axis Errors / Magnitude of Delta-V [m]/[m/s]	54.6	54.0	64.0	65.8	234.6	314.6	500.0

Figure 3, created based on previous studies done by Carpenter (Ref. 4), shows that 11 m of initial SMA error, which causes 33 ms of period differential, would lead to relative drift of 0.1 km and 0.8 km at the apoapsis and the periapsis in just three orbit periods. Furthermore, 50 m of initial SMA error results in 0.5 km and 3 km relative position drift in three orbit periods. Considering that MMS performs science operations near the apoapsis, maintaining the formation near the apoapsis is more crucial. Therefore, 11 m and 50 m of post-maneuver SMA errors may be acceptable for sustaining the formation for 3 orbit periods. But at the same time, choosing the acceptable maneuver errors to be at 50 m would imply the risk of performing a maintenance maneuver as frequent as once every three days, which is hard to manage and realize from an operations and cost consideration. It should also be noted that the relative drift presented in this work is the relative drift of a single spacecraft from its desired trajectory. Whether a formation is acceptable would be based on the relative drift between each of four MMS spacecraft. Therefore, it would be necessary to run a multi-spacecraft simulation before conclusive assessment can be made on the error's effect on the formation.

CONCLUSION

A 6 DOF spacecraft simulation is developed for the MMS mission. A new maneuver scheme and its associated thruster pulsing control logic are also developed. The maneuver simulation consists of two parts: the closed-loop part, which generates the thrust pulsing sequences, and the open loop part which performs the maneuvers by following the thrust pulsing sequences. Thrust uncertainty/error, attitude knowledge error, and nutation error are introduced to the open loop simulation to study the effects of these realistic errors on the MMS formation maintenance maneuvers. While the maneuver execution errors are small judging from delta-V and position errors, the semi-major axis error reveals that many of simulated error sources could be larger than desirable. However, the acceptable level of SMA error has yet to be determined based on the formation requirements and operation concepts. It is uncertain if additional efforts are needed to minimize the error sources. Nevertheless, the simulation results allow baseline requirements to be established, and the simulation is capable of performing future studies.

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