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CONJUNCTION ASSESSMENT FOR THE MAGNETOSPHERICMULTI-SCALE (MMS) FORMATION

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The highly elliptical orbit of the MMS formation-flying mission presents a unique conjunction assessment environment. The MMS spacecraft will spend part of its highly elliptical orbit in a debris-free environment at apogee then transition through densely populated regions in the geosynchronous belt and in low earth orbit (LEO) near orbit perigee. An analysis was performed to characterize the debris environment that MMS will encounter and estimate the number of Risk Mitigation Maneuvers (RMM) that could potentially be required over the mission lifetime. Additionally, an assessment of the GSFC Conjunction Assessment (CA) tool suite was performed to determine its applicability for performing conjunction assessment for the MMS mission.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) has been performing routine Conjunction Assessment (CA) for NASA robotic missions since January of 2005. The majority of missions to date have been in relatively circular orbits resulting in nearly constant debris flux environments. The Magnetosphere Multi-Scale (MMS) formation flying mission, however, is a highly elliptical orbit which will pass through both the geosynchronous (geo) belt and densely populated regions of Low Earth Orbit (LEO). The "NASA Procedural Requirements (NPR) for Limiting Orbital Debris[1]" was updated in August of 2007 to include CA requirements. The policy requires routine conjunction assessment processing for all maneuverable robotic missions that have perigees less than 2000 km or that orbit within 200 km of the geosynchronous belt.

Therefore, it was necessary to determine the impacts of meeting the NPR on the MMS mission. Two problems are specifically addressed in this paper. First, the overall debris environment seen by the MMS spacecraft is characterized to determine the potential number of conjunction Risk Mitigation Maneuvers (RMM) anticipated over the lifetime of the mission. The number of RMM can have significant impact on the fuel budget of the MMS spacecraft. Since the MMS trajectory traverses the geosynchronous altitude twice each orbit, the geosynchronous crossings are also examined to ensure that the MMS mission does not pose a significant risk to any geosynchronous orbital slot.

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Second, the applicability of the existing GSFC Conjunction Assessment System (CAS) 3-D tool to analyzing the risk for conjunctions between the MMS spacecraft is examined. Specifically, the tool is used to compute the probability of collision for multiple revolution encounters when significant process noise may be required to account for maneuver uncertainties and other force model errors. The existing tools that numerically integrate the probability distribution to compute the probability of collision (Pc) are compared to Monte Carlo results.

MMS DEBRIS ENVIRONMENT CHARACTERIZATION

The MMS mission consists of four spacecraft flying in formation to measure magnetosphere phenomena. The reference mission orbit is highly elliptical and occurs in two phases. The first phase has on orbital period of approximately 24 hours with a perigee of 1.2 Earth Radii (ER) and an Apogee of 12 ER. For the second phase of the mission, the apogee will be raised to approximately 25 ER with a corresponding period of approximately 2.8 days.

The highly elliptical orbit of the MMS mission presents a unique conjunction assessment environment. Instead of the relatively constant debris environment experienced by a LEO spacecraft, the highly elliptical MMS spacecraft will spend part of its orbit in a nearly debris-free environment at apogee while transitioning through densely populated regions such as the geo belt and the LEO environment near perigee. The purpose of this analysis is to characterize the overall debris environment that the MMS spacecraft will encounter and estimate the number of conjunction RMM that the MMS spacecraft could potentially be required to perform to avoid conjunctions with debris or other orbiting spacecraft. Additionally, the transition of the MMS spacecraft through the geo belt is analyzed in detail to determine if any repeat encounters with operational geosynchronous spacecraft could occur. If repeat encounter geometry between the MMS constellation and operational geosynchronous spacecraft is found, it may be necessary to change the mission reference trajectory to avoid these encounters. At the very least, coordination between the MMS mission and the geosynchronous operator would be required to mitigate possible conjunctions.

Risk Mitigation Maneuver Frequency

The number of conjunction RMM that might need to be performed by any one spacecraft in the MMS constellation is to be estimated. A typical method for determining the number of RMM anticipated for a mission in development is to look at the historical number of maneuvers required for a spacecraft in a similar orbit. However, since very little history exists for missions similar to MMS, a debris flux ratio method is used. The ratio method determines the debris flux by simulation of the debris environment and the mission trajectory. The flux is determined for both the new mission and a reference, or baseline, regime, which has an extensive operational CA history. The ratio of the two flux values is then used as a scaling factor on the number of RMM known to be required in the reference regime to determine the predicted number of maneuvers for the new orbit.

The Earth Science Constellation (ESC) regime is used as the baseline regime for this study. The ESC regime is sun-synchronous, 700 km orbit. Operational CA has been performed on 11 ESC missions since 2005 and the frequency of maneuvers required in this regime is reasonably well known.

The debris field is modeled using Two Line Elements (TLEs) from the publicly available General Perturbations catalog. The TLEs used for this analysis were downloaded in February of 2008 and represent all publicly available data for debris objects and operational spacecraft tracked by USSTRATCOM. The total number of objects used in this analysis is approximately 13,000.

To determine the steady state debris flux, the MMS reference orbit and all the objects in the catalog are propagated, and all objects passing within 50 kilometers of the MMS spacecraft are recorded. The flux is then calculated as the number of objects penetrating the 50 km sphere per unit of time. The propagation continues until this flux level converges on a steady-state value. This same process is also used to determine the flux for the ESC orbit.

The 50 km sphere size was chosen based on past experience of the GSFC Conjunction Assessment team performing regime characterization analysis. To calculate the debris flux within a reasonable amount of propagation time, enough objects have to penetrate the volume to determine the steady-state flux. Smaller volumes would require longer propagation times.

This analysis assumes that the catalog used adequately represents the debris field during the MMS mission. This assumption is reasonable unless large scale breakups of orbiting objects (on the scale of the Fengyun ASAT event of January 2007) occur between now and the MMS launch. Additionally, only the 24-hour period orbit was considered in this analysis. The approximately 2.8-day orbit of the second phase of the mission will spend considerably more time above the debris field than the Phase 1, 24-hour orbit. Therefore, the 24-hour orbit is considered the worst case scenario for MMS.

Table 1 lists the computed debris flux through the 50 km sphere centered on the ESC and MMS orbits. The debris flux for the MMS orbit is approximately 0.6% of the flux for the ESC regime. The lower flux for the MMS mission is expected because a large part of the MMS orbit is spent above the geosynchronous altitude and most of the debris field is below geosynchronous altitude.

Table 1. Debris Flux for ESC and MMS Orbits.

Orbit	Debris Flux through 50 km Sphere objects per day
EOS 700 km, Sun Synchronous	35
MMS Reference Trajectory	0.2

Table 2 lists the operational impacts to 11 of the ESC spacecraft (Aqua, Aura, Terra, Landsat-5, Landsat-7, EO-1, SAC-C, PARASOL, CloudSat, CALIPSO, ICESat) since routine conjunction assessment operations started in 2005. This operational history translates into approximately 0.18 RMMs per year per spacecraft and 0.1 maneuvers waived-off per year per mission.

The number of RMMs that might be required in the MMS orbit is computed using the fact that the estimated debris flux through the MMS reference trajectory is approximately 0.6% of the flux for ESC type orbits and that ESC orbits have been observed to require 0.18 RMM per year per spacecraft. For an MMS spacecraft over a nominal three year mission lifetime, it is therefore expected that each spacecraft will require a minimal 0.0032 RMM. Therefore, given the uncertainty in the debris environment, it would be conservative to budget fuel for one RMM per spacecraft in the MMS orbit over the nominal three year mission.

This analysis was originally conducted in March 2008[2]. The operational impacts documented in Table 2 include updated events through July 2009. The average numbers presented in Reference 2 were 0.15 RMM per year and 0.05 maneuvers waived off per year. The addition of the more recent operational data does not significantly change the number of RMM per year observed for EOS or the expected number of RMMs expected for MMS.

Table 2. Earth Observing System Operational Impact Due to Debris since January 2005.

Date	Asset	Impact
May 2005	Aqua	Waive-off of routine maneuver
October 2005	Terra	Risk Mitigation Maneuver
December 2005	Aqua	Waive-off of routine maneuver
January 2007	Terra	Waive-off of routine maneuver
January 2007	PARASOL	Risk Mitigation Maneuver
February 2007	SAC-C	Risk Mitigation Maneuver
June 2007	Terra	Risk Mitigation Maneuver
July 2007	CloudSat	Risk Mitigation Maneuver
June 2008	Aura	Risk Mitigation Maneuver
July 2008	Aura	Waive-off of routine maneuver
July 2008	CloudSat	Risk Mitigation Maneuver
October 2008	PARASOL	Risk Mitigation Maneuver
January 2009	Landsat-7	Waive-off routine maneuver
May 2009	EO-1	Risk Mitigation Maneuver

Geosynchronous Belt Transition

Since the MMS formation will be transitioning through geosynchronous altitude on every orbit, the interaction between the MMS orbit and the geo belt must be characterized. The objective is to determine if the MMS spacecraft will repeatedly conjunct with any operational geosynchronous spacecraft. If repeating conjunction geometry is found, changes to the mission orbit may be warranted.

A reference ephemeris for the MMS mission containing both the 24-hour and 2.8-day orbits is interrogated to determine the predicted longitude of the spacecraft at geosynchronous altitude (both ascending and descending). An analysis of these longitudes is then made to determine if the MMS orbit repeatedly crosses the geo belt at any given longitudes resulting in repeated conjunctions with operational geosynchronous spacecraft.

The time history of the longitudes at which the MMS reference orbit crosses the geo belt is shown in Figure 1. Three distinct phases of the mission are seen. Between approximately 10 days and 700 days the orbital period is about 24 hours and the geo belt transition longitudes are uniformly distributed from 0 to 360 degrees. Between approximately 700 days and 800 days the orbit is being raised from a period of about 24 hours to a period of about 2.8 days and the geo belt transition longitude appears random. After 800 days, the 2.8-day orbit is established and again a uniform pattern appears to emerge. A histogram of the longitude distribution is shown in Figure 2. The longitudes are separated into 0.5 degree bins to represent typical geosynchronous longitude station-keeping boxes. Again, the geo belt transition longitudes are fairly evenly distributed. The maximum number of "visits" to a longitude is 11 with the majority of longitudes being "visited" between two and five times.

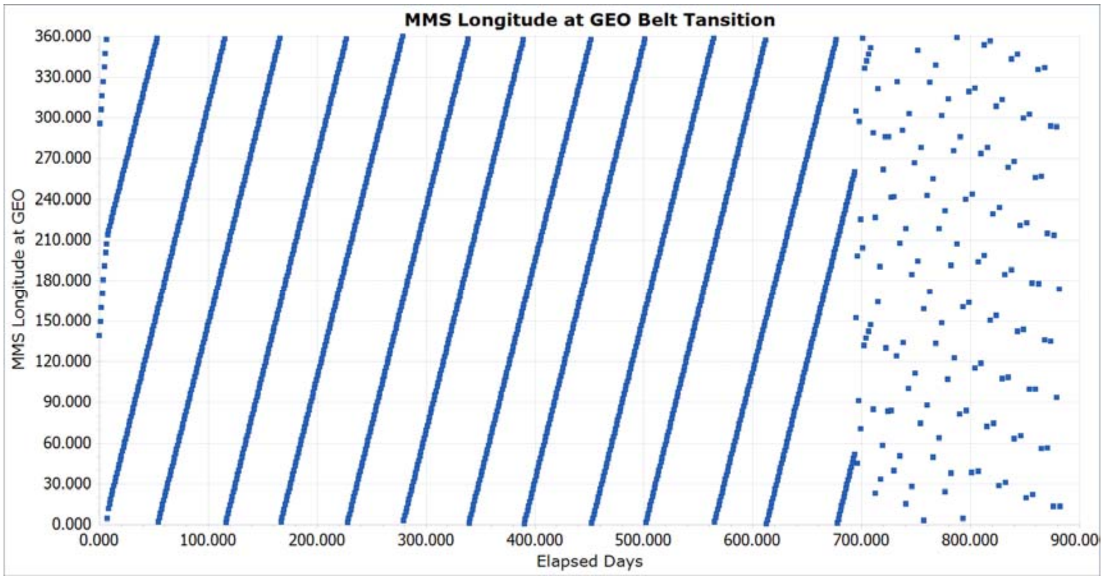

Figure 1. Time History of GEO Belt Crossing Longitudes.

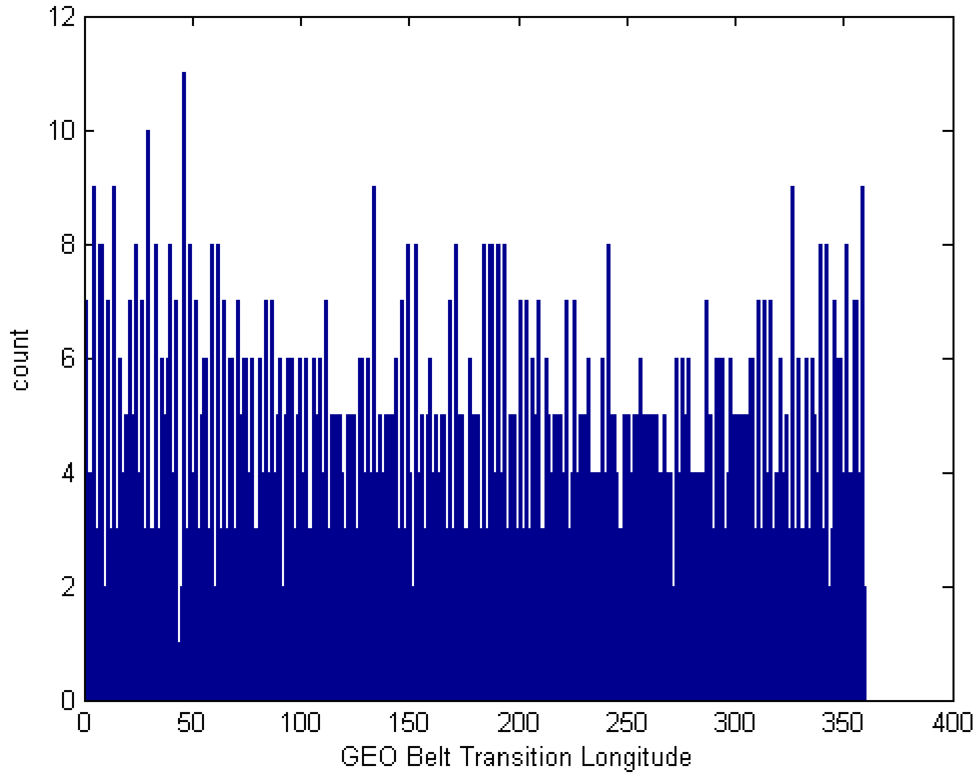

Figure 2. Histogram of GEO Belt Crossing Longitudes.

The results show that the MMS trajectory as represented by the ephemeris transitions through the geo belt with a fairly uniform longitude distribution. Therefore, the MMS reference orbit does not represent a significant threat to any particular object in the geo belt. Conjunctions between the MMS spacecraft and objects in the geo belt can therefore be handled via a routine conjunction assessment process during the operational mission and do not warrant any further pre-mission consideration.

GSFC CA TOOL ASSESSMENT

The GSFC Conjunction Assessment System (CAS) Tool Suite has been documented[3, 4] and has been in use since 2005 to support NASA robotic conjunction risk assessment operations. This tool suite includes the standard 2-D methodology[4] for computing Pc for high speed encounters and a 3-D methodology[4] for computing Pc for low speed, non-linear encounters. Additionally, a Monte Carlo tool is available and is typically used as a “truth” reference. Previous assessments and the vast majority of operational use of the tool suite covers a single event propagated over a short span near the Time of Closest Approach (TCA).

However, MMS is a formation flying mission and the possibility for low relative velocity, multiple revolution encounters is increased, raising additional issues. There was uncertainty as to how the existing tool suite would handle multiple-revolution encounters. Also, given the relatively long orbital period of the MMS orbit and the frequent formation maintenance maneuvers, significant process noise may be required to accurately predict the uncertainty in the orbit for CA purposes. The exact amount of process noise is not known at this time and will be the result of further navigation analysis of the MMS mission. However, previous analysis had questioned whether there is sufficient justification for ignoring process noise in the analytical computation of Pc[6]. The concern was that for extended periods of propagation, the de-correlation of uncertainty due to process noise could result in a greater Pc. The analysis that follows addressed these concerns by attempting to determine if there is a level of process noise that will cause the existing GSFC CAS 3-D tool to provide inaccurate estimates of the collision probability.

The 3-D tool[3] numerically integrates the combined error probability distribution function over the non-linear relative trajectory between two spacecraft. This tool was built to handle the inclusion of process noise in the propagation of the covariance through an encounter. However, since the vast majority of conjunctions observed operationally are brief in nature (encounter times less than one second), the inclusion of process noise has never been needed to accurately model the state errors.

The existing Monte Carlo[7,8] tool randomly samples the state of each spacecraft from its state error covariance. The two state realizations are propagated to their new TCA and if the resulting miss distance is below an input threshold, referred to as the Hard Body Radius (HBR), a "hit" is counted. The number of "hits" divided by the total number of trials is the Pc. The existing CAS Monte Carlo tool had two deficiencies in addressing the MMS problem that required modification. First, the original tool only interrogated the next closest approach between the two randomly sampled states. This limited the tool to use for single, fly-by encounters and was not suitable for multiple revolution encounters. To fix this issue, the tool was modified to search all close approaches within an input time span for violation of the HBR. If any encounter in the time span had a miss below the HBR a "hit" was counted. Second, the propagation of the random states needed to include random accelerations to account for the process noise. The COTS product FreeFlyer was used to build the MC tool and includes the ability to add additional accelerations to the force model used to propagate spacecraft states. This feature made the inclusion of random accelerations in the propagation of the states straight forward. The modified MC tool was compared to the original MC tool to ensure they provided the same answers in the degenerative case – single encounter, no process noise.

To stress the tools and provide an additional point of comparison, the multiple revolution encounter geometry in Reference 6 was used. This orbital geometry creates a relative motion that is a 2×1 ellipse, with semi-major axis of 200 km. There is uncertainty in the initial relative position and velocity of 10 m and 1 mm/sec, with −.95 correlation coefficient between radial position and along track velocity, and between radial velocity and along track position. An exclusion volume with a radius of 50 meters was used. The results from the 3-D Tool and the MC tool for various levels of process noise over a seven orbit period are shown in Figure 3.

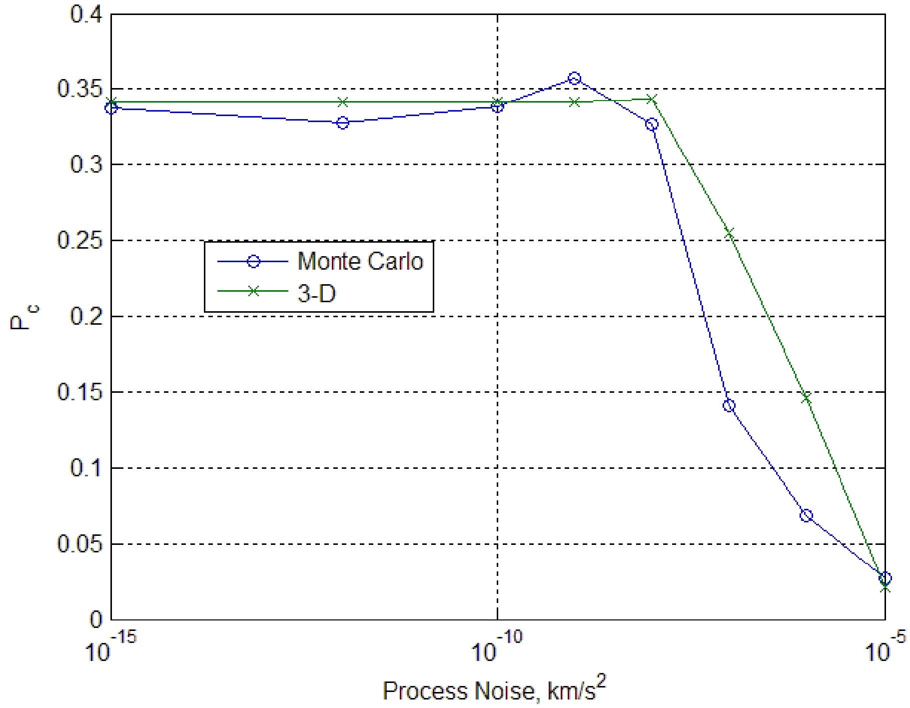

Figure 3. Comparison of Monte Carlo and 3-D Tool

Qualitatively, the results are as expected. When larger values of process noise are used the probability density becomes less and the resulting probability decreases. The results show a very favorable comparison between the Monte Carlo and 3-D tools even when significant process noise is included. The MC results demonstrate that the addition of process noise can cause slight increases in the probability of collision that were not reflected in the 3-D tool. However, since operational CA decisions are typically made based on the "orders of magnitude" level of the Pc, the increase in probability observed in this case is not significant. In all but one case (Process Noise = 1e-6), the MC and 3-D methods yield the same order of magnitude results. The single discrepancy between the MC and 3-D tool for a process noise of 1e-6 is interesting and still needs further investigation. Qualitatively, it is clear that the gradient of the Pc versus Process Noise curve is very steep at this point, and the discrepancy between the MC and 3-D method may not be surprising.

A further comparison of the 3-D and Monte Carlo tools was performed by using the tools to duplicate the Survival Probability history shown by Carpenter[6]. Survival Probability is defined as one minus the Pc. The orbital geometry creates a relative motion that is a 2×1 ellipse, with semi-major axis of 200 km. There is uncertainty in the initial relative position and velocity of 10 m and 1 mm/sec, with −.95 correlation coefficient between radial position and along track velocity, and between radial velocity and along track position. An exclusion volume with a radius of 50 meters was used and a 3 milligee/sec$^{1/2}$ process noise is added. The results are shown in Figure 4. The 3-D Tool results are shown by the solid line and the Monte Carlo results are shown by the circles. To aid the comparison to Reference 6, the results are presented as Survival Probabilities. Both tools show good agreement with the results of Reference 5.

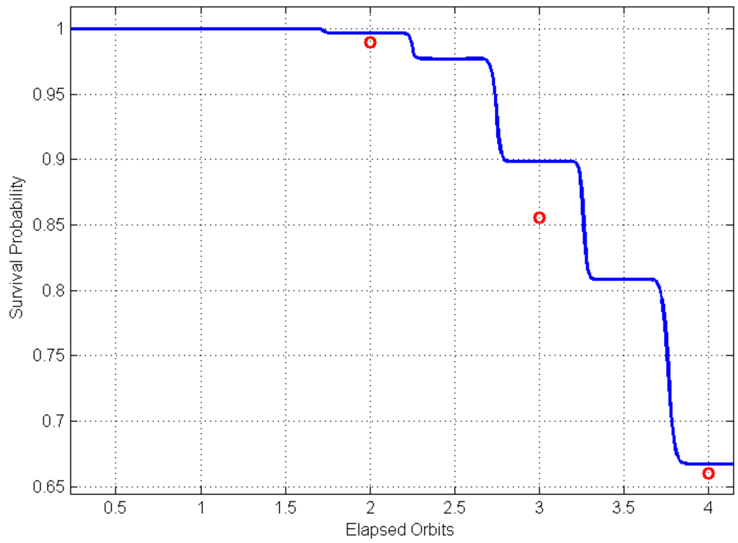

Figure 4. Survival Probability results for realistic formation flying example using 3-D Tool and Monte Carlo

The agreement between the existing CAS 3-D tool, the modified MC tool, and the independent results in Carpenter[6] show that the CAS 3-D tool is capable of determining the Pc for multiple revolution encounters in the presence of process noise. It should be noted that in Conjunction Assessment operations all available tools should be used to determine the risk level. Since the 3-D method has been shown to provide consistent results when compared to the MC and can be executed more quickly than MC methods, the 3-D tool would be sufficient to serve as a first indication of probability threat for low speed encounters for the MMS mission. However, Monte Carlo methods should also be used to validate any assessments that indicate a high collision risk.

CONCLUSION

The highly elliptical MMS mission orbit represents new challenges to routine conjunction assessment analysis and operations. As opposed to circular orbits which see a relatively constant debris flux, the MMS orbit will transition through regions with almost no orbital debris and through highly dense regions such as LEO and the geo belt. This paper has shown that the overall debris flux seen by the MMS spacecraft will be extremely small compared to the sun-synchronous regime. By comparing the well understood sun-synchronous environment to that anticipated on MMS, an estimate of the number of RMM was determined to conservatively be around 1 per spacecraft over the three year mission lifetime. It has also been shown that the existing 3-D tool in the GSFC CAS Tool Suite is capable of determining the probability of collision for multiple revolution encounters in the presence of process noise and will be capable of supporting CA operational analysis for the MMS mission.

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