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CONJUNCTION ASSESSMENT TECHNIQUES AND OPERATIONAL RESULTS FROM THE MAGNETOSPHERIC MULTISCALE MISSION

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This paper describes the results that have been obtained to date concerning conjunction assessment between the MMS spacecraft during formation flying. Two main mechanisms can lead to intra-MMS conjunctions: execution errors in the maneuvers that set up the formation, and missed burn contingencies. Both of these effects have been experienced over the course of the MMS mission, particularly when flying at the small formation size of 7 km. Methods for detecting such events will be discussed, as well as two types of maneuver that have been developed to deal with them.

INTRODUCTION

The NASA Magnetospheric Multiscale (MMS) mission is flying four spinning spacecraft 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 have been flown in tetrahedron formations of varying dimensions in order to perform magnetospheric science measurements. In the first phase of the mission, these measurements were taken on the dayside of the Earth, in a Region of Interest surrounding the apogee of the MMS orbit (radius 12 R_E). The goal during Phase 1 was to observe the magnetospheric reconnection events that are expected to occur near the bow shock where the solar wind impinges upon the magnetosphere. Measurements during the later Phase 2b, after apogee radius has been increased to 25 R_E, will be taken in the magnetotail[3], 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.

This paper will describe the results that have been obtained to date concerning conjunction assessment (CA) between the MMS spacecraft during formation flying, complementing the formation flying discussion of a companion paper[4]. MMS navigation is performed on-board using a weak-signal GPS-based system[5]: this allows signals to be received even when MMS is flying above the GPS constellation, producing a highly accurate determination of the four MMS orbits using the Goddard Enhanced Onboard Navigation System (GEONS). This data is downlinked to the MMS Mission Operations Center (MOC) and used by the MOC Flight Dynamics Operations Area (FDOA) for maneuver design and conjunction assessment. Maneuver commands are then uplinked to the spacecraft and executed autonomously using an on-board accelerometer-based controller[6], with the ground monitoring the burns in real time.

Reference 7 described the formation flying results that were obtained during the earliest portions of the mission, referred to as Phases 0, 1a and 1x. Subsequent to this, MMS entered into science collection

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during its second dayside passage, termed Phase 1b. A significant factor for this phase from the flight dynamics and CA points of view was that the science team requested that MMS fly in as small a formation as possible: this was motivated by the science data that was collected concerning magnetic reconnection during Phase 1a. This data showed that the electron diffusion region associated with a reconnection event was typically smaller than the smallest formations (scale size 10 km) that were flown during Phase 1a. As a result, there were cases where three of the MMS spacecraft flew through an electron diffusion region, but never all four, as would be ideal for science. However, the original mission specification was that MMS be capable of flying in formation scale sizes from 10 km to 160 km during Phase 1; all maneuver-related systems were designed with this goal in mind. It was therefore not a trivial task to be able to fly in formations smaller than 10 km. The MMS flight dynamics team consequently had to carry out extensive analysis and testing to determine the smallest safe formation scale size: this was determined to be 7 km, which was deemed fully satisfactory by the science team.

This new minimum formation size was driven predominantly by conjunction-related questions, which will be detailed in the paper. Firstly, if one maneuver in the set that puts the spacecraft into formation is waved off, a conjunction can arise unless the maneuvers are carefully designed to avoid this difficulty. This is a consideration for the design of any formation, but is exacerbated by flying at the small formation size. Secondly, the small execution errors produced by the on-board delta-v controller can give rise to differences between the periods of the MMS orbits, and therefore to drift rates between the spacecraft. The subsequent set of formation maneuvers must consequently be scheduled before this drift can lead to an uncomfortably close approach. This has led to a typical interval between maneuvers for 7 km formations of 2-4 weeks, as opposed to 4-5 weeks for larger formations. These more frequent maneuvers cause some time to be lost for science, since the maneuvers take place in the science Region of Interest (RoI), and instruments have to be turned off when burning. However, the science team felt that this tradeoff was certainly acceptable.

The paper describes the various tools that have been developed by the MMS flight dynamics team for conjunction assessment, and describes how they are used. Results obtained to date are then discussed, illustrating the differences between the small and larger formation cases. In particular, several CA-related events that occurred during formation flying during Phase 1b, at the small 7 km formation size, are discussed in detail. Finally, two types of avoidance maneuvers are described that have been designed for the case where a conjunction is predicted to occur before regular formation maneuvers can be scheduled.

MMS CONJUNCTION ASSESSMENT APPROACH

There are two types of decision errors an operator can make when faced with a close approach (with acronym again CA: the appropriate meaning in any given case will be clear from the context always): (1) deciding to maneuver when in fact the CA would not have resulted in a collision (a false alarm), and (2) deciding not to maneuver when the CA will actually result in a collision (a missed detection). In order to control both false alarm and missed detection rates, Carpenter and Markley[8] proposed a Wald Sequential Probability Ratio Test (WSPRT) for CA. This reference showed that for CA, the WSPRT reduces to a simple odds ratio involving a collision probability that makes use of predicted relative state information derived from a complete history of observations preceding the conjunction, along with a prior probability of collision representing the inherent base risk of the particular conjunction, e.g. due to the prevailing debris environment. As described in Reference 8, the WSPRT likelihood ratio, Λ_k, associated with a set of observations collected over a time interval $\{t_1,t_2,...,t_k\}$ depends on an odds ratio: the odds associated with the probability of collision computed from all available observations, $P_{c|k}$, normalized by the odds associated with the prior probability of collision, $P_{c|0}$, representing the background risk of a particular conjunction:

$$\Lambda_k = [(1- P_{c|k})/ P_{c|k}]\,[P_{c|0}/(1 - P_{c|0})] \qquad (1)$$

For the WSPRT, the likelihood ratio is compared to upper and lower thresholds which are computed from target rates of missed detection and false alarm. If Λ_k is greater than the upper limit, the CA is dismissed, whereas if Λ_k is less than a lower limit, a CA alarm is issued, and a CA maneuver will be considered. As Reference 8 shows, this test can be reformulated to compare $P_{c|k}$ directly to alarm and dismissal probability thresholds, P_c^A and P_c^D.

As References 9 and 10 and describe, CA screening forms a key component of MMS maneuver design. Two key questions are: will maneuver execution errors lead to an undesirably high probability of a CA, or will a missed burn contingency result in one? A preliminary maneuver design is first run through a screening tool that checks the minimum miss distances that occur in the event of any missed burn, or combination of missed burns: if this minimum is below a safe threshold, the maneuvers must be redesigned.

Following this test, nominal MMS spacecraft states and a distribution of a priori maneuver errors are used to generate sample trajectories for a Maneuver Targeting Tool (MTT). In this process, 100 (or sometimes 250) sample trajectories of the MMS spacecraft are propagated using a low fidelity model which includes simulations of a formation maneuver set. Such a set consists of two maneuvers by each of three spacecraft; the fourth MMS takes the role of non-maneuvering reference. The results are then analyzed in order to determine the overall feasibility and efficacy of the maneuver design. A failing grade from this inspection results in a redesign of the planned operations, while a pass moves on to the next step. Next, a Constellation High Fidelity (CHiFi) tool is run in a Monte Carlo mode known as Casino to propagate an ensemble derived from the designed initial state, maneuver execution error, and navigation error, to the time of the first maneuver. At this point, the first and second moments of the quantities of interest are used to infer a Gaussian distribution for the state of each spacecraft. With these assumptions and moments, random variables with appropriate statistics are then considered in the Brute Force Monte Carlo (BFMC) scheme: the standard MMS implementation considers 75,000 cases. At the planned time of the second maneuver, this process is repeated.

If any interval with a non-zero hit count is detected, random variables are again generated from the Gaussian assumptions derived at the end of the Casino runs and act as training samples for the calculation of Polynomial Chaos Expansion (PCE)-based collision probabilities at each time step of the aforementioned interval, as Reference 9 describes. If the two computed collision probabilities fail to agree to within their respective confidence intervals, a maneuver redesign would be considered (although this has never yet occurred). Otherwise, the maximum probability within the interval and across the two methods is used to compute the unique $P_{c|0}$ value for that particular encounter, and recorded in a "Watch List."

For all times at which BFMC failed to record a non-zero collision probability, a 50% confidence limit is assumed to serve as a proxy giving $P_{c|0} = 2.2749 \times 10^{-6}$. For the MMS WSPRT, which targets a false alarm rate of 1/20 and missed detection rate of 1/1000, this $P_{c|0}$ results in alarm and dismissal values for the zero events detected case of $P_c^D = 2.3947\text{x}10^{-9}$ and $P_c^A = 4.5451\text{x}10^{-5}$. Since MTT would have rejected any formations with unsafe close approaches that its 100 samples detected, there is effectively an upper limit on $P_{c|0}$ that corresponds to a P_c^A of approx. 0.5/100, which corresponds to $P_{c|0} = 2.5144\text{x}10^{-4}$.

Note also that, once the maneuvers have been performed and post-maneuver navigation solutions are available from the spacecraft, a process of calculating the probability of collision corresponding to the observations up to and including time t_k, that is, $P_{c|k}$, is carried out after each perigee pass as part of the CAFA tool suite (see below), in a manner essentially similar to the BFMC/PCE process just described.

MMS CONJUNCTION ASSESSMENT TOOLS

Plots of inter-satellite ranges (ISRs) between the six pairs of MMS spacecraft are a very useful tool for evaluating CAs, as will be seen in examples discussed later in the paper. In addition, two more sophisticated types of plots are also used for MMS conjunction assessment. These plots, produced by what are known as the MMS Conjunction Assessment Functional Area (CAFA) suite of tools, will now be described. The inputs to both of these tools (and indeed the data that is used to generate ISR plots) are the "restart states", or state estimates, for the spacecraft that are produced by the MMS GEONS navigation system[6]. This system makes use of GPS signals to determine the MMS orbit: since the bulk of this orbit lies above the GPS constellation, the most complete data is obtained around perigee, when the MMS spacecraft fly through the main lobes of the GPS satellites. The preferred inputs to the CAFA tools are therefore the restart states that correspond to a post-perigee communications pass.

Relative Motion Situational Awareness Tool

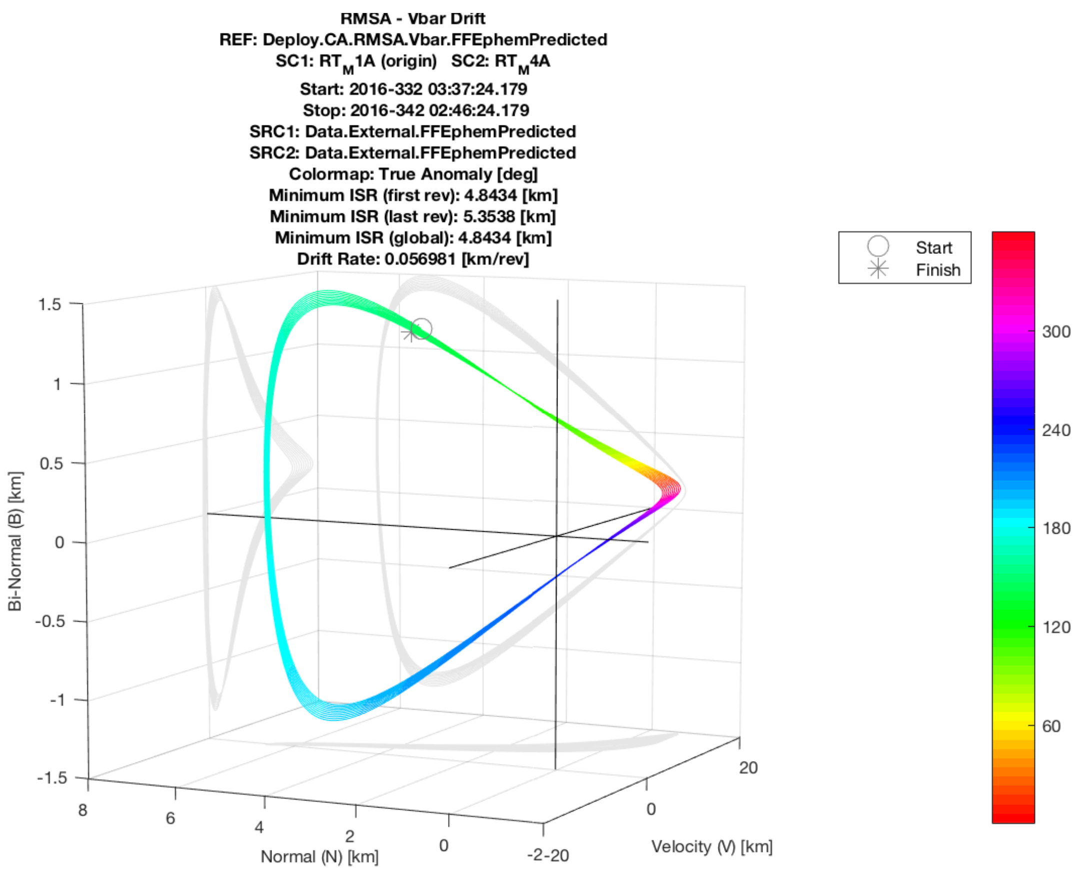

Figure 1: MMS Inter-Satellite Relative Motion in VNB Frame for a 7 km Formation. The color scale indicates true anomaly in degrees, so that warm colors correspond to perigee.

The Relative Motion Situational Awareness (RMSA) tool is a means of displaying the relative motion between each pair of MMS spacecraft. These states are then propagated out for 10 orbits, with no further maneuvers applied, and the relative motion of the spacecraft plotted in 3-D in terms of a coordinate system, centered on one of the spacecraft and with axes along its orbital velocity vector (V), the orbit normal (N), and the binormal direction B that completes the right-handed VNB triad. (For a circular orbit, B would be aligned with the local radius vector; this is generally not the case, however, for the highly eccentric MMS orbit.) The resulting plot is of the type shown in Figure 1; in addition, the mean drift rate per rev is given, as are the minimum ranges on the first and last orbits. This plot helps to provide insight into the possible relative motion of this pair of MMS spacecraft. In particular, since a small difference in semi-major axis (SMA) between the two orbits (a common manifestation of maneuver execution errors) predominantly leads to drift along the velocity axis, the N and B motion shown in the RMSA plot tends to be more "robust" than that along V: this helps in understanding how the relative motion will likely evolve over time.

Snapshot Tool

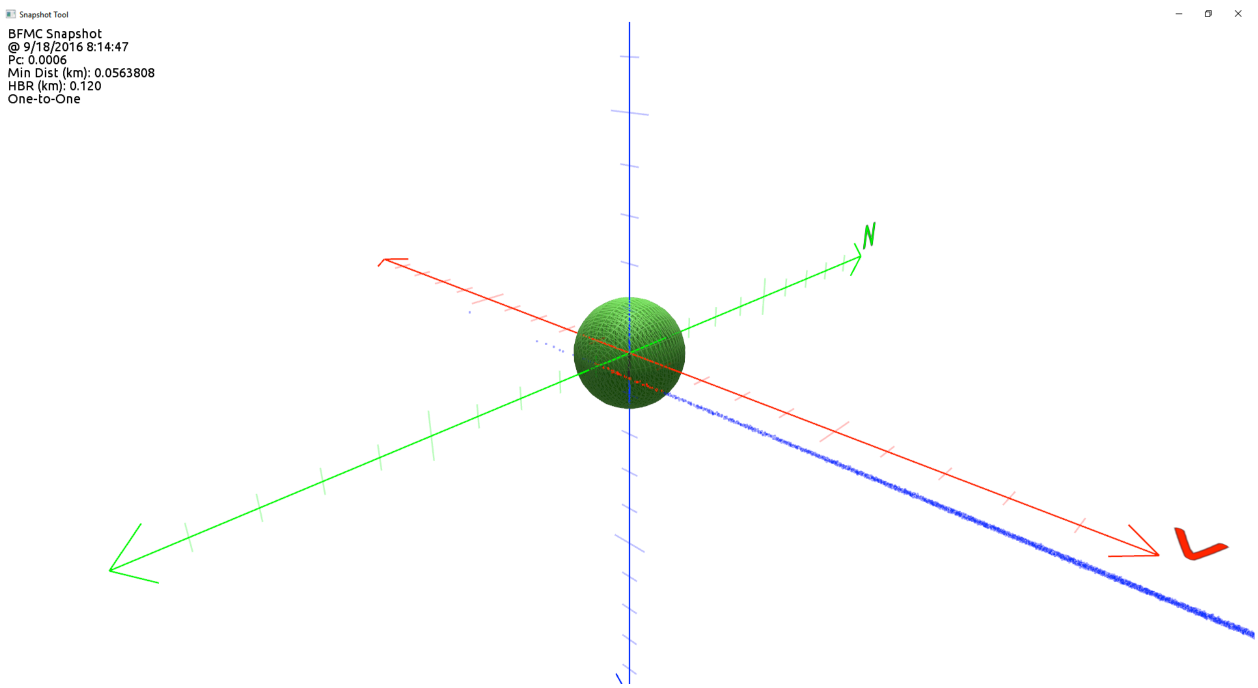

Figure 2: MMS Snapshot Tool Output for an Example Conjunction. In this case, the point cloud is largely along and below the V-axis, and points falling inside the HBR are colored red.

The Snapshot Tool is a platform-independent application which allows the user to view a 3D representation of close approach scenarios. The visual, as Figure 2 depicts, shows a hard-body radius (HBR) sphere around one spacecraft, and a BFMC point cloud of propagated close approach states for the other spacecraft relative to it in the VNB reference frame of the reference satellite. In the case of MMS, with its 60 meter wire booms, the HBR is taken as 120 m to reflect the extent of both spacecraft combined. The tool gives the probability of collision (Pc), the minimum distance to any of the states (not necessarily the minimum distance for the case with the highest probability of collision), the time of the close approach scenario, and the Pc calculation method (one-to-one [75,000 BFMC cases] or all-to-all [$75{,}000^2$ cases]).

Snapshot plots are produced under two circumstances: in the first, when a non-zero probability of collision is computed, this CA event is entered onto the watch list, as described previously. The second circumstance is when the minimum range falls below some user-defined threshold, e.g. 300 m. If the point cloud associated with this event does not penetrate the HBR, there will be a zero probability of collision, and so the event will not appear on the watch list. However, situational awareness is improved if the user is aware of such close flybys: they are therefore put onto a separate "events list", and snapshot plots generated.

AVAILABLE CONJUNCTION AVOIDANCE MANEUVER DESIGNS

The preferred approach to dealing with a predicted conjunction between two MMS spacecraft is to bring forward (i.e., perform early) the next scheduled formation maneuver set. However, in the event that there is insufficient lead time between the detection of the conjunction and the predicted CA, two types of avoidance maneuvers have been designed. Fortunately, neither of these has yet been required to be performed "in anger" to mitigate a CA; however, the second, trim, type has been demonstrated to prolong the lifetime of a formation. Details of these two maneuver types will now be given.

Dodge Maneuver

The Dodge maneuver was developed before launch as a pre-planned technique for dealing with conjunctions between either two MMS spacecraft, or between an MMS and a Resident Space Object (RSO). RSO conjunctions typically occur down near the MMS perigee, as most other spacecraft in intersecting orbits are at altitudes down near the MMS perigee. MMS-to-MMS conjunctions would also typically be expected to occur down in this regime, and in particular at true anomalies in the vicinity of 90 or 270 deg. The reason for this is that conjunctions are most likely to occur where the orbit planes of the two MMSs cross: since out-of-plane separation is maximized around apogee, where the formation shape is optimized for science collection, this puts the plane crossings around 90 and 270 deg. The four MMS orbits are designed to prevent conjunctions by ensuring that there is separation either along-track or radially at the plane crossings: however, a botched burn could lead to an unintended close approach. If this is recognized far enough ahead of time, it could be dealt with by bringing forward a regular Formation Maintenance (FM) maneuver set. However, this approach is not feasible if the conjunction is only identified shortly before the Time of Closest Approach (TCA): it is for this purpose that the Dodge maneuver was designed.

The Dodge is a single burn by a single spacecraft, one of the CA pair. In some cases, there may be freedom to select which of these two MMSs should dodge; however, for cases where the CA results from a botched burn by one spacecraft, it would presumably not be able to maneuver again so soon, requiring that the other CA spacecraft be the dodger. The Dodge Δv (fixed at 0.5 m/s magnitude) lies in the orbit plane, and is designed to shift the position of the maneuvering MMS by the largest amount possible at the CA location, which is taken to be at 270 deg true anomaly. (The 90 deg case gives more time between Dodge and CA, and so is somewhat more benign: a Dodge that gives sufficient separation at 270 deg will do even better at 90 deg.) The original Dodge implementation applied the maneuver at a fixed true anomaly of 200 deg; however, the code was subsequently generalized to allow the Dodge position to be selected arbitrarily, for instance to match available communication contacts. For the more usual case where there is a considerable time between the maneuver and the conjunction, a burn along the velocity vector would maximize the change in semi-major axis (SMA), and hence period, and hence along-track separation. However, in the dodgy case, the relatively small lead time between Dodge and conjunction implies that the separation at the TCA can actually be maximized by burning in a different direction, giving not only a SMA-related along-track shift, but also a "direct" radial shift. The Dodge maneuver achieves the maximal separation possible for a given burn magnitude by optimizing burn direction as a function of the selected burn true anomaly.

MMS has not yet had to carry out a Dodge maneuver, as most conjunctions are identified long enough beforehand to deal with them using a normal FM set. However, software is in place to dodge if it is ever required in the future.

Trim Burn

It was often found while flying at small formation sizes in Phase 1b that one particular spacecraft pair (to be precise, MMS1 and MMS4) often drifted slowly towards each other. The resulting danger of a conjunction then required that a Formation Maintenance (FM) maneuver set be carried out in order to "reset" the formation. In several cases, this had to be done earlier than it had originally been planned to maneuver, which led to disruption to science collection (since the FM2 maneuvers all occur in the science RoI) and additional fuel use. The underlying reason for this inter-satellite drift is that execution errors in the preceding FM set led to the semi-major axes (SMAs) of the MMS1 and MMS4 orbits being somewhat different, leading to different orbital periods and hence a slow drift rate.

The trim burn was designed during the Phase 1b small formation flight period in order to avoid this difficulty. This is a single burn by one of the spacecraft in the drifting pair, and is designed to null the SMA difference between it and the other drifting MMS. Burns to change SMA are typically applied along the orbital velocity vector, as this is the most efficient direction. However, the SMA difference to be corrected was typically small, on the order of 10 m, and the required burn size to correct this with a burn along the velocity would be too small to be feasible. In fact, the MMS closed-loop Delta-v controller, although performing extremely well and greatly exceeding its performance specifications, cannot accurately generate maneuvers smaller than about 0.05 m/s. Consequently, the trim burn uses the MMS open-loop "checkout mode" to apply a small Δv along the spin axis of the spacecraft: so long as this is not aligned with the orbit normal (which only occurs twice per orbit), there is a component of Δv along the orbital velocity vector, and consequently the desired small change in SMA can be produced.

A trim burn was carried out on Dec. 28, 2016 and was very accurate at nulling a 10 m SMA difference between MMS1 and MMS4. (See Reference 7 for further details on the trim burn.) The burn location was selected to avoid a spin axis/orbit normal alignment, and was positioned outside the science RoI: there was therefore minimal disruption to science operations. The total fuel consumption was approximately 3 grams, as opposed to on the order of 0.2 kg for a typical FM set. This trim was successful at accomplishing its objective of greatly reducing the drift rate between MMS1 and MMS4, so allowing the next FM set to be delayed by a week, as desired.

CONJUNCTION ASSESSMENT EXAMPLES AND SMALL FORMATIONS

A significant factor for the second MMS dayside pass (Phase 1b) from the flight dynamics (and especially conjunction assessment) point of view was that the science team requested that the spacecraft fly in as small a formation as possible: this was motivated by the science data that was collected concerning magnetic reconnection during Phase 1a. As described above, this data showed that the electron diffusion region associated with a reconnection event was typically smaller than the smallest formations that were flown during Phase 1a.. The MMS flight dynamics team consequently had to carry out extensive analysis and testing to determine the smallest safe formation scale size: this was determined to be 7 km, which was deemed fully satisfactory by the science team.

This new minimum formation size was driven predominantly by the execution errors produced by the on-board delta-v controller: if this system had not been exceeding its specifications, flying at 7 km would not have been possible. An implication of flying in smaller formations is that more frequent maneuvering is usually required. The typical interval between maneuvers for 7 km formations was in the range 2-4 weeks, whereas it has been 4-5 weeks for the larger formations. These more frequent maneuvers, as discussed above, were often triggered by two spacecraft drifting too close together.

An additional factor that helps to dictate the smallest feasible formation size was not fully recognized before a conjunction that occurred in November 2016, near the end of Phase 1b. This is that, in the event that one spacecraft is not able to carry out one of its FM burns, it ends up on an orbit that is quite different from its intended final formation orbit. There is therefore the risk that there will be a close approach between the non-maneuvering spacecraft and one of the other three. This is what occurred during the November conjunction, when MMS3 was not able to execute its FM2 burn, due to a missing station contact. It is possible to prevent such contingency cases from leading to excessively close approaches by redesigning the FM sequence: this approach uses the freedom to change the order in which the spacecraft carry out their FM1 and FM2 burns. However, designing a small formation that was not only robust enough to maneuver execution errors to avoid frequent FMs, and could tolerate all possible missed-burn contingencies without leading to close approaches, was found to be extremely challenging. A viable solution was always found, but at the expense of significant workload for the flight dynamics team.

September 2016 Event

As a preliminary to entering into a series of 7 km formations as desired by the MMS science team during Phase 1b of the mission, the spacecraft were maneuvered from the 40 km Phase 1x formation into a 10 km formation on Sept. 1, 2016. It was initially desired that this formation persist for three weeks before a new set of maneuvers would be carried out to enter the first 7 km formation. However, the restart states downlinked after the first perigee following the maneuvers made it clear that a slow closing rate existed between MMS1 and MMS4, and that waiting for three weeks would have led to an undesirably small range between the two spacecraft. In fact, the corresponding snapshot plot (Fig. 2) shows that the cloud of all possible BFMC cases intersect the hard-body radius of the other spacecraft, indicating a non-zero probability of collision. Consequently, it was decided to bring forward the next maneuver set by one week: this kept the range between MMS1 and MMS4 above 1.5 km.

October 2016 Drift Case

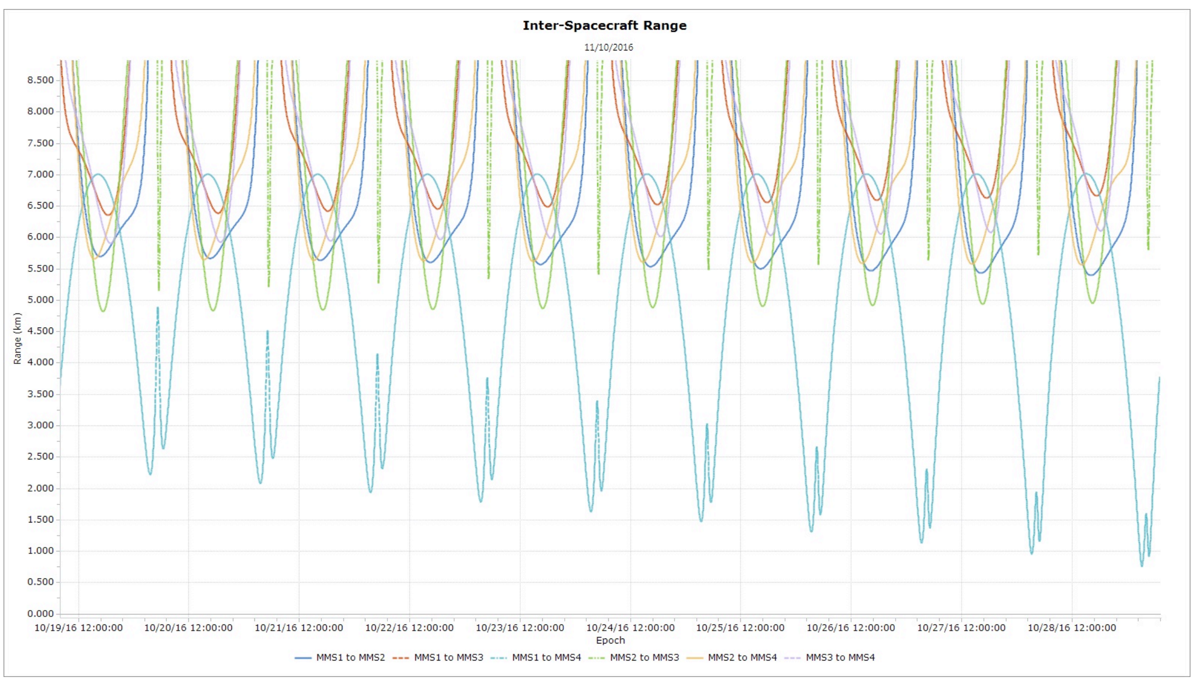

Figure 3: MMS Inter-Satellite Range Plot for Oct. 2016 Drift Case.

It was found that the particular geometry of most of the series of 7 km formations that were flown tended to lead to this same type of slow drift between MMS1 and MMS4: Figure 3 shows an ISR plot for a 7 km formation that was flown in Oct. 2016. The ubiquity of this drift was a result of the fact that the two spacecraft were nearly directly out-of-plane from each other at apogee, which allows them to come uncomfortably close when their orbital planes cross at true anomalies approx. 90 and 270 deg. In the nominal formation, i.e. in the absence of execution errors, the MMS1/MMS4 range remains safe;

however, a small amount of SMA difference between the two orbits can set up a slow drift. In the interests of saving fuel, the MMS Formation Design Algorithm (FDA) uses the original formation as the seed for the formation that is maneuvered into, leading to the geometry persisting. Eventually, for the final 7 km formation in Jan. 2017, the FDA was reset to instead choose a new, randomly-generated orientation: this used considerably more fuel to enter into, but overcame the prevalent MMS1/MMS4 drift condition.

An alternative way to deal with this drift is to apply a trim burn as described earlier. Figure 4 illustrates the result obtained for a simulated trim to deal with the Oct. 2016 drift case of Figure 3: it can be seen that there is essentially zero drift rate between the spacecraft following the burn. It should be noted that this trim was not actually carried out, as the implementation of the trim in the MMS ground system was still being finalized. However, as already discussed, one was carried out on Dec. 28, 2016, with good results.

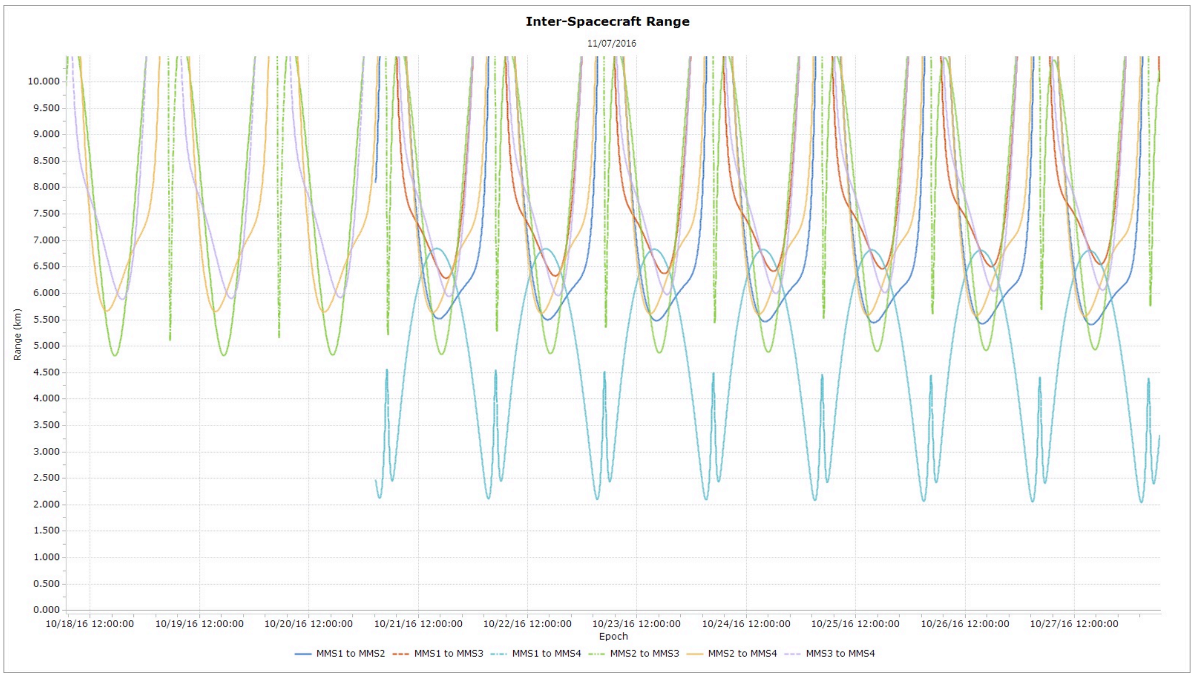

Figure 4: MMS Inter-Satellite Range Plot for Oct. 2016 Drift Case After Simulated Trim Burn.

November 2016 Event

On MMS, a pair of maintenance (FM1, FM2) or resize (FR1, FR2) maneuvers for any one spacecraft can be considered as a rendezvous pair, where the first burn transfers the spacecraft from its position in the existing formation to its desired location in the new formation, and the second burn modifies its velocity to ensure that it continues to track the new formation geometry. The Nov. 2016 CA case was the result of MMS3 spacecraft missing its FM2 in a set of maneuvers designed to maintain a 7 km formation. Since MMS maneuvers are performed while the spacecraft is in contact with a ground station, the loss of a contact prevents the corresponding burn from being carried out. That is what occurred on Nov. 17: the contact that had been scheduled for the MMS3 FM2 was preempted, with little notice, to allow for higher-priority coverage of a launch. Once the MMS operations team was made aware of this fact, very shortly before the FM1 passes, an attempt was made at short notice to “pre-load” the FM2 maneuver on-board MMS3 at the end of its FM1 contact, so allowing it to perform its FM2 “in the blind”. However, this procedure had not been fully tested, and was not successful. Consequently, the end result was that MMS3 missed its FM2 burn: see ‘x’ in Figure 5 (all times noted are in UTC).

Following the missed maneuver, FDOA staff started planning a pair of make-up maneuvers to bring MMS3 back into formation with the other three spacecraft after a delay of a few revs. The procedure that was used for this maneuver design was similar to that which was put in place after a missed burn event in Dec. 2015: see Reference 4 for further details. A final check, at~5 PM local, of the design of the make-up burns was to examine inter-satellite range plots so as to ensure that there was no close approach between MMS3 and any other MMS in the interval between its catch-up maneuvers. It was indeed observed that no unduly close approaches occurred over this period: the closest pass was a little under 3 km. However, it was noted with some consternation that a close pass of below 500 m would occur at ~4:30 AM local between MMS2 and MMS3 (see Fig. 6), with this taking place before the first of the make-up burns. This was therefore not caused by the catch-up maneuvers, and so could not be "designed out" by modifying these: it was a direct result of MMS3's missed FM2. Usually, such CA cases are identified prior to the final planning of the complete FM maneuver set, and the FMs redesigned to prevent a missed burn from giving rise to a CA. However, this time the CA report generated by FDOA came short of identifying this case due to a software error. (This has since been corrected.) Therefore, existence of the CA was not appreciated until less than 12 hours before its predicted time.

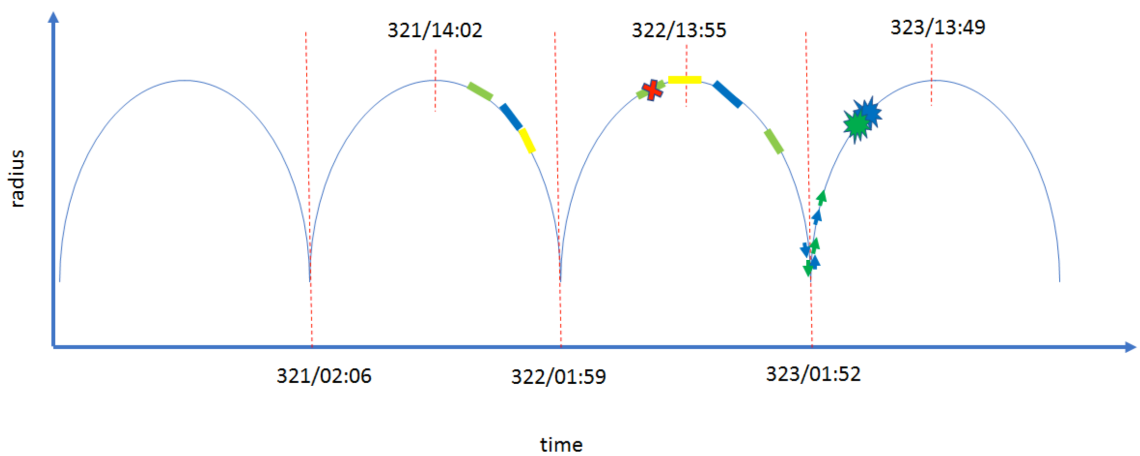

Figure 5. Schedule of Contacts for MMS3 and MMS2 Approaching CA Time.

At this point, towards the end of an already long day, the decision was made to begin designing two alternative CA mitigation maneuvers: one Dodge and one trim burn. If selected, the Dodge would have been executed at a new DSN contact on the ascending orbit flank; if the trim were proceeded with, it would have taken place during one of the existing Tracking and Data Network Satellite (TDRS) post-perigee contacts. These locations were selected bearing in mind the position high on the ascending flank of the predicted CA (see Figure 5). As finally designed, either maneuver would have increased the minimum separation between MMS2 and MMS3 by several hundred meters. However, the decision as to whether to actually proceed with either of these mitigation maneuvers would be taken during a telecon that started at 10 PM local: this was timed so as to start with a discussion of the pre-perigee GEONS navigation data (Figure 5), then proceeding to data from the first post-perigee restart states later in the telecon. There was insufficient time to consider the second post-perigee restart states (typically the best data since, as the MMS spacecraft go through perigee, the maximum possible number of GPS signals are detected) in the maneuver decision process, as the trim burn would actually have been carried out during one of these passes.[4]

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[4] Note that pre-perigee solutions usually refer to the data generated from the telemetry downloaded during the first TDRS real-time contacts. However, on this day, time was the essence to make any decision. Therefore, the OD solution for MMS3 was based on the preceding DSN contact that was put in place following its missed maneuver contact; the OD solution for MMS2 was based on the SN contact. In the paper, this set is referred to as the Pre-

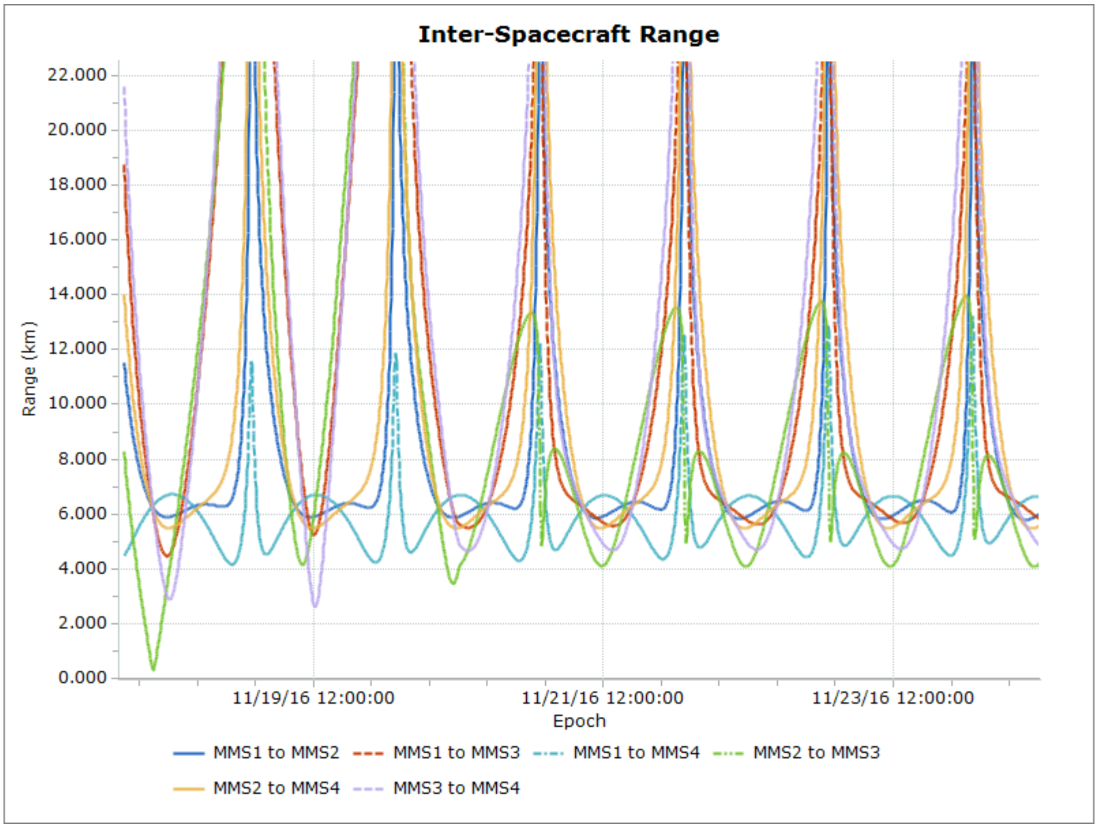

Figure 6: MMS Inter-Satellite Range Plot for Nov. 2016 Missed Burn Case.

The following plots compare the results obtained for these various sets of restart states. In all cases, although an ISR below 500 m was observed from the RMSA plots (this is the miss distance for the nominal orbits, with no error cloud superimposed), a zero probability of collision was computed from the BFMC runs, and no alarm was generated on the watch list. To provide additional insight into the situation, snapshot plots (of a later version not available at the time of the Nov. 2016 CA) have also been generated based on the BFMC results.

Figure 7 shows the RMSA plot for the pre-perigee data set; the corresponding minimum ISR value is 315 m. Figure 8 then shows the snapshot plot for these restart states. In this case, the minimum miss-distance reported is 172 m (shown with the yellow line). However, the distribution of one-to-one ISR solutions (displayed as the blue cloud) needs to be also considered to estimate the mean of the min miss-distance. Considering that the central body is 120 m (shown as the green globe) and each axis is scaled to 1000 m, the length of the cloud is roughly 120 m and thus the mean minimum distance will be approx. 232 m (172 m + 60 m).

Perigee set. Likewise, what is referred to here as the first Post-Perigee set uses the MMS3 OD solution resulting from its pre-perigee TDRS contact, and the MMS2 OD solution based on the first post-perigee TDRS contact.

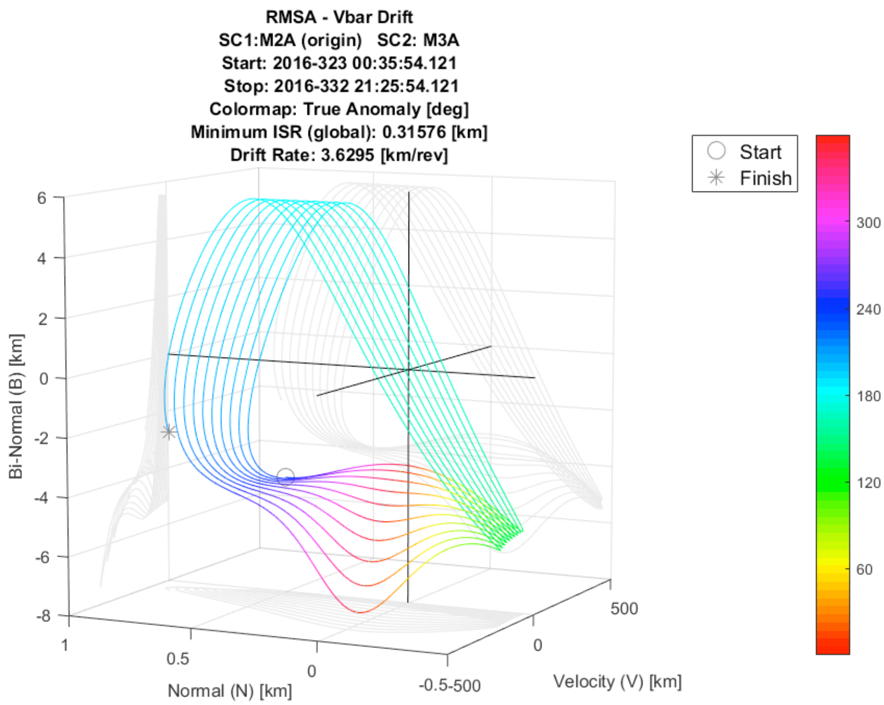

Figure 7. RMSA Plot for Pre-Perigee Restart States.

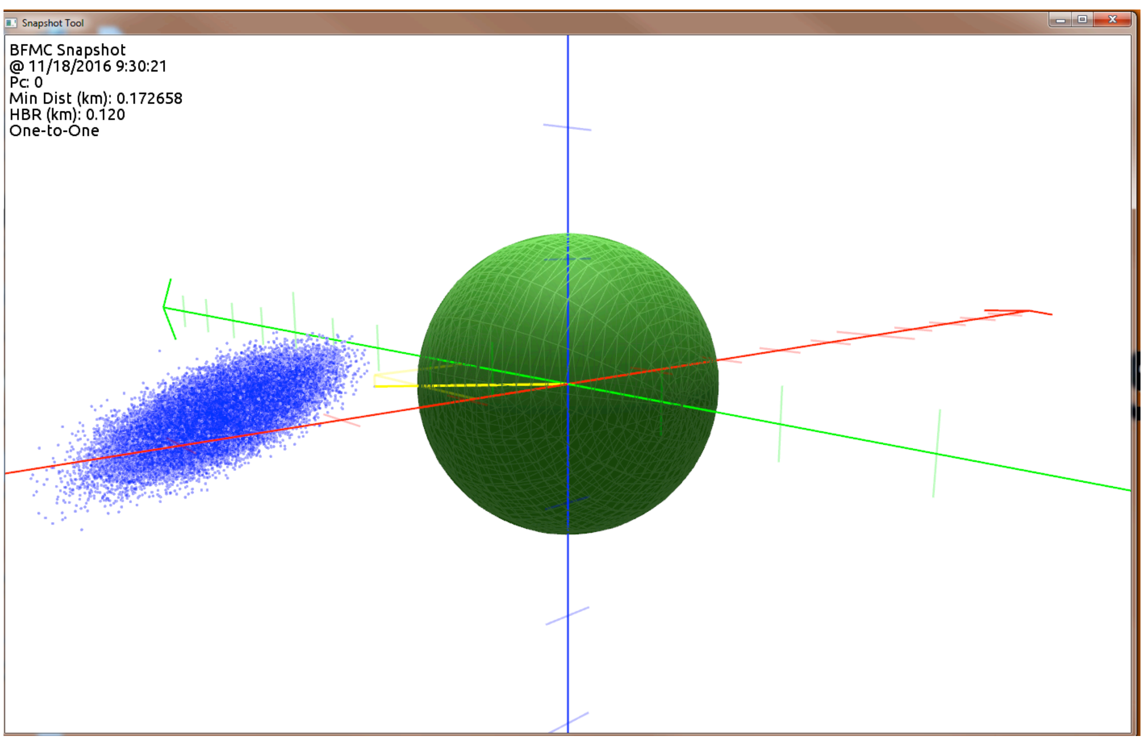

Figure 8. Snapshot Plot for Pre-Perigee Restart States.

Next, CAFA was similarly run on the Post-Perigee 1 set of restart states. Figure 9 shows the RMSA plot and the ISR is now reported to be 375 m. The snapshot plot for the post-perigee 1 set (see Figure 10) displays similar features to those seen above, with a minimum miss distance of 271 m, and distribution length at 80 m. The resulting mean miss distance is then computed to be 311 m (271 m + 40 m), or somewhat greater than that indicated from the pre-perigee data. Given this improvement in miss distance and the fact that a zero probability of collision was still computed by the BFMC tool, the decision taken at the end of the telecon was that a CA mitigation maneuver was not required. Indeed, MMS3 and MMS2 passed by one another tightly but safely.

On the following day, CAFA was also run, after the fact, on the second post-perigee OD solutions, since this is the best data available. This further confirmed an increasing ISR estimate: see Figures 11 and 12. The new minimum ISR value was computed from the RMSA plot to be 388 m. From Figure 12, the snapshot plot gives a minimum miss distance of 300 m and distribution length at 50 m: the resulting mean miss distance is 325 m (300 m + 25 m). The best estimate for the miss distance was eventually determined to be 320 m, based on the definitive ephemeris. This can be seen, not to agree precisely with the value produced by the RMSA plot, which does not include the effects of position uncertainties. However, it agrees well with the value obtained from the Post-Perigee 2 snapshot plot, confirming that the data that was used to make the decision not to maneuver was indeed credible.

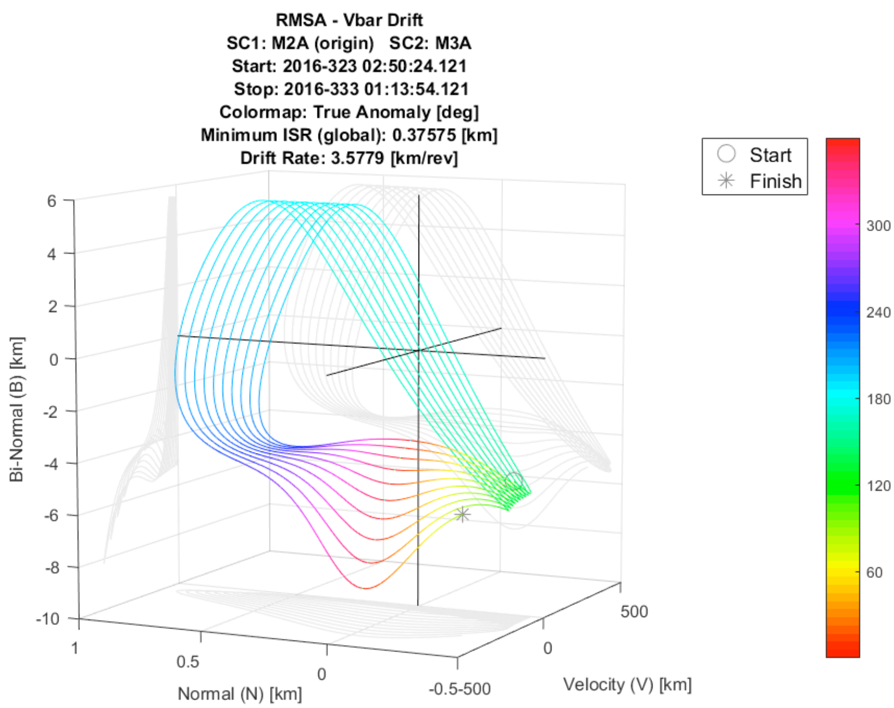

Figure 9. RMSA plot for Post-Perigee 1 Restart States.

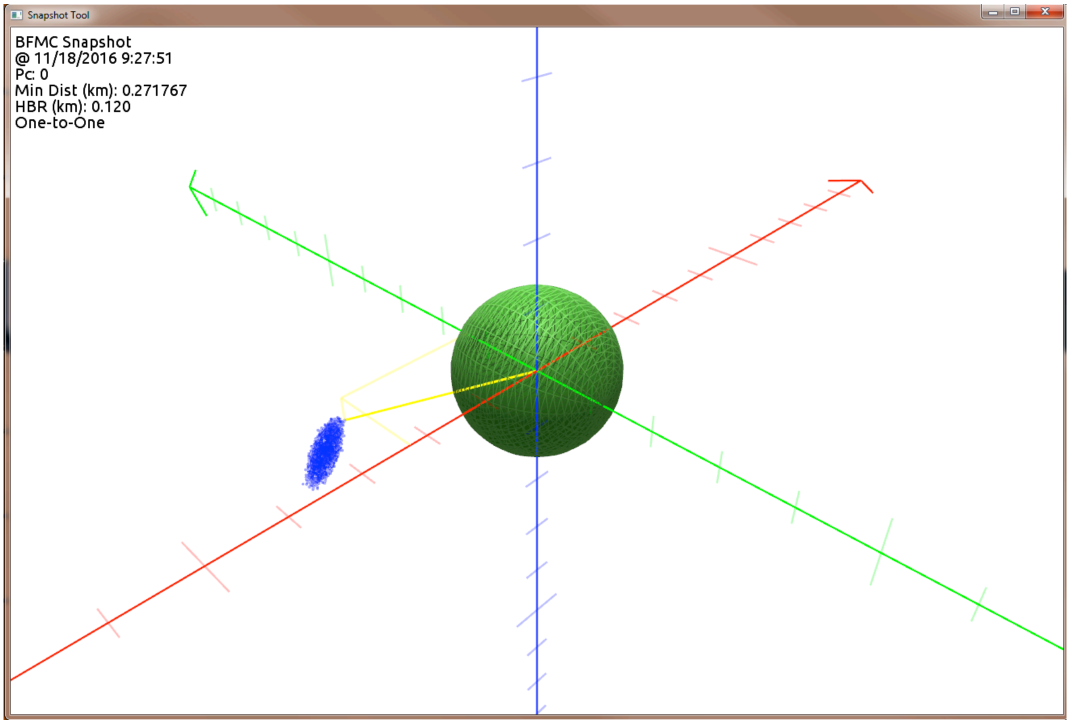

Figure 10. Snapshot Plot for Post-Perigee 1 Restart States.

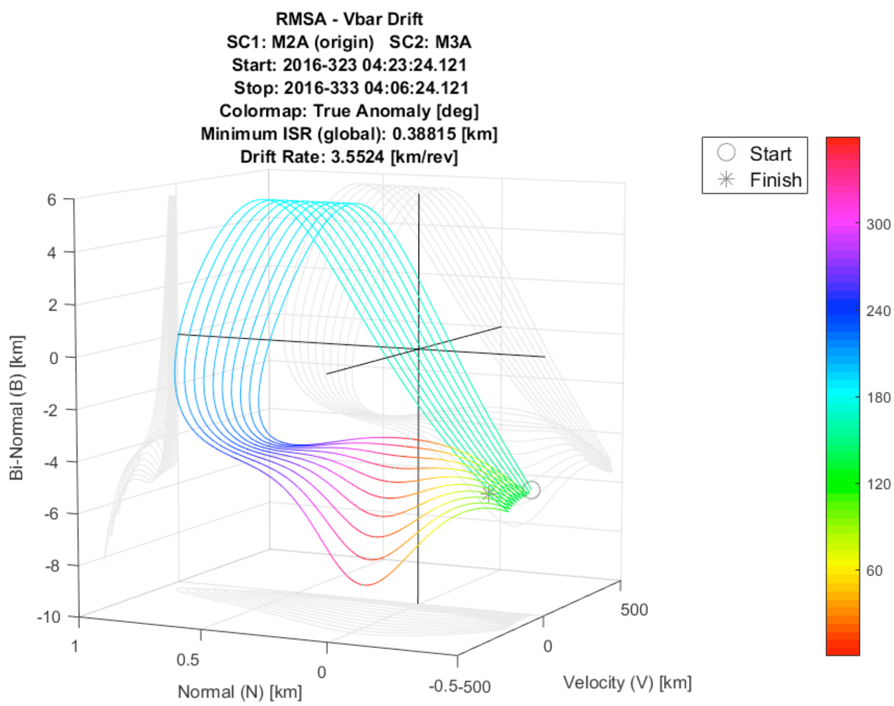

Figure 11. RMSA Plot for Post-Perigee 2 Restart States.

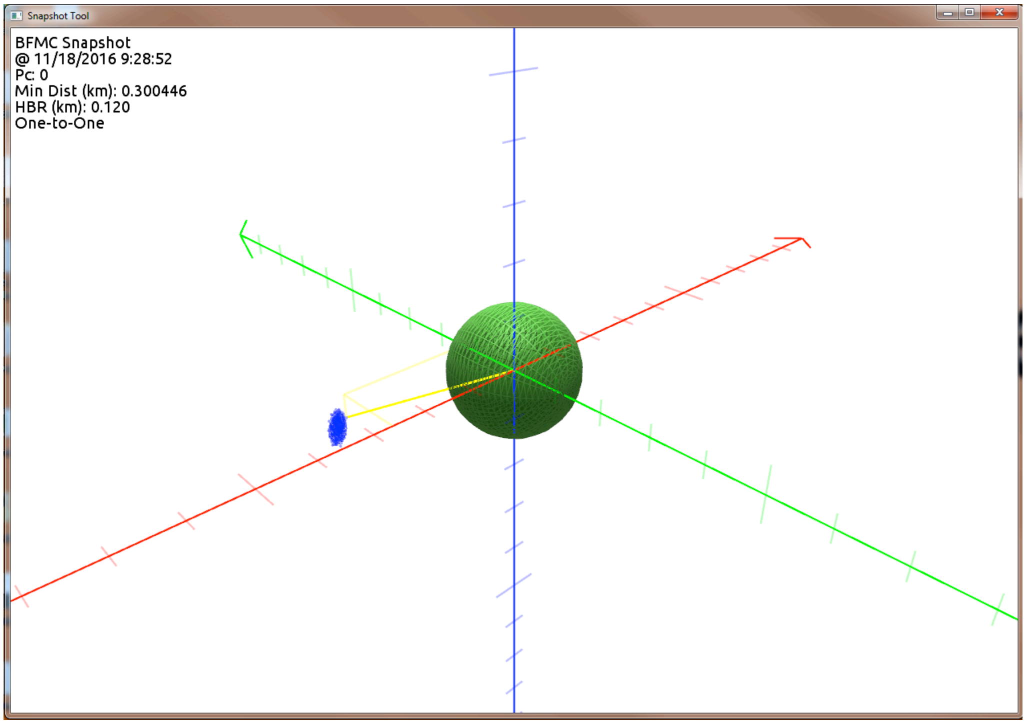

Figure 12. Snapshot Plot for Post-Perigee 2 Restart States.

CONCLUSIONS

Extensive operational experience has been obtained during the MMS mission concerning conjunction assessment during formation flying. Two main mechanisms can lead to intra-MMS conjunctions: execution errors in the maneuvers that set up the formation, and missed burn contingencies. Both of these effects have been experienced over the course of the MMS mission, particularly when flying at the small formation size of 7 km. Methods for detecting such events were discussed in the paper, and illustrated by examination of several events that occurred during the Phase 1b 7 km formation flight regime. Finally, two types of collision avoidance maneuver that have been developed were described also.

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