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(Preprint)

GLOBAL POSITIONING SYSTEM NAVIGATION ABOVE 76,000 KM FOR NASA'S MAGNETOSPHERIC MULTISCALE MISSION

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NASA's Magnetospheric Multiscale (MMS) mission, launched in March of 2015, consists of a controlled formation of four spin-stabilized spacecraft in similar highly elliptic orbits reaching apogee at radial distances of 12 and 25 Earth radii (RE) in the first and second phases of the mission. Navigation for MMS is achieved independently on-board each spacecraft by processing Global Positioning System (GPS) observables using NASA Goddard Space Flight Center (GSFC)'s Navigator GPS receiver and the Goddard Enhanced Onboard Navigation System (GEONS) extended Kalman filter software. To our knowledge, MMS constitutes, by far, the highest-altitude operational use of GPS to date and represents a high point of over a decade of high-altitude GPS navigation research and development at GSFC. In this paper we will briefly describe past and ongoing high-altitude GPS research efforts at NASA GSFC and elsewhere, provide details on the design of the MMS GPS navigation system, and present on-orbit performance data from the first phase. We extrapolate these results to predict performance in the second phase orbit, and conclude with a discussion of the implications of the MMS results for future high-altitude GPS navigation, which we believe to be broad and far-reaching.

BACKGROUND

High altitude GPS research and development

The GPS system was designed and optimized for users near the surface of the Earth. This user base includes all spacecraft in Low-Earth Orbit (LEO). GPS receivers for LEO missions are now standard spacecraft navigation components. At altitudes above about 3000km, the signal environment start to change as the mainlobe of the directional GPS transmit antennas may no longer point

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toward the user. Above the GPS constellation, the only mainlobe signals visible to the user are those that spill over the limb of the Earth. These signals can be still be reasonably strong for a user at Geosynchronous Earth Orbit (GEO), for example, but are only sparsely available. A receiver capable of acquiring and tracking weak signals could, in principle, take advantage of the more numerous, but much weaker, transmitter side lobes as shown in Figure 1.

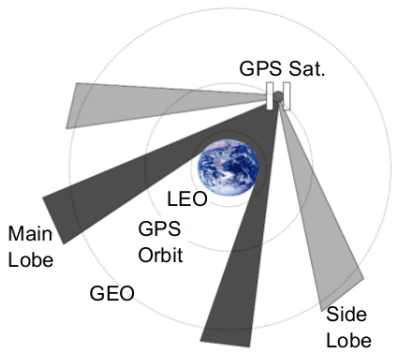


Figure 1: High altitude reception of GPS signals

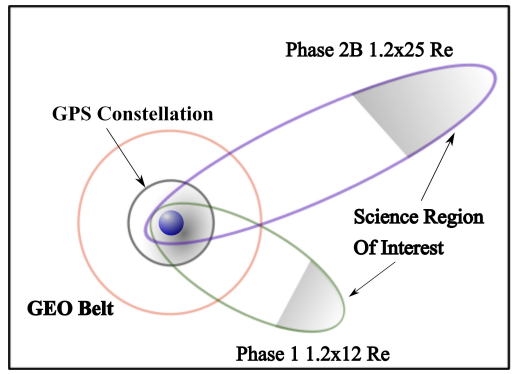


Figure 2: MMS Phase 1 and Phase 2b orbits

Research and development into high-altitude GPS navigation has been ongoing for more than a decade. Numerous analytic and hardware-in-the-loop simulation studies have investigated GPS receiver architectures for high-altitude missions and navigation performance achievable at GEO, Highly Eccentric Orbit (HEO) and even on cislunar trajectories. Navigation engineers at NASA GSFC have been particularly active in this area conducting analyses and simulation studies,[1–3] developing specialized GPS receivers and software[4,5] (including the Navigator GPS receiver and GEONS filter software used on MMS), and leading efforts to protect and characterize the signals available for high-altitude users.[6,7] The PhD dissertation of Moreau was a significant milestone in this work.[8]

The first on-orbit high-altitude GPS experiments were carried out in the late 1990 to early 2000's by putting modified LEO receivers on HEO satellites to examine receiver performance and the practicality of tracking and processing sidelobe signals.[9–12] While limited sidelobe reception was demonstrated on some of these experiments, high performance navigation was not achieved. Analysis at GSFC of GPS tracking data from the AMSAT-OSCAR 40 experiment noted significant differences in the transmit patterns of the different blocks of GPS satellites.[11] This helped motivate an

effort led by GSFC engineers to define the GPS Space Service Volume (SSV) user base and develop specifications on signal availability and strength up to GEO altitude.[6] This effort continues today, with results from the MMS mission supporting the case.[13]

The first published use of *operational* high altitude GPS-based navigation was presented in Reference 14, in which a U.S. Government GEO spacecraft with a transponder relayed GPS signals to the ground, where they were processed with a receiver. Recently, a similar configuration as in Reference 14 was used to demonstrate autonomous navigation at GEO using a GSFC Navigator receiver running GEONS. This demonstration was part of the GPS transmit Antenna Characterization Experiment (ACE), which has also provided a full characterization of the on-orbit GPS transmit antennas including sidelobes in support of high-altitude navigation.[7]

Recently a number of high altitude capable GPS receivers have reached maturity. In 2012, Surrey Satellite Technology Ltd. flew a specialized high-sensitivity receiver, the SGR-GEO, on-board the GIOVE-A Galileo demonstration satellite, orbiting just above the GPS constellation at 23,000 km, and numerous GPS sidelobes were tracked.[15] Airbus Defense and Space offers two receivers that can target HEO applications: the MosaicGNSS[16] and the newer LION Navigator (not related to the GSFC Navigator).[17] The GSFC Navigator is operational on MMS, and a modernized version is in active development. The Navigator design was licensed to Moog-Broadreach around 2010, who has developed reduced Size, Weight and Power (SWaP) receivers based on the NASA technology. One of these receivers was demonstrated on-orbit for the AFRL ANGELS GEO mission in 2014,[18] and a single-board version, the NavSBR, has been developed for the AFRL EAGLE program.[19] The ESA Proba-3 HEO mission plans to use a RUAG Podrix receiver.[13] Launching in 2017, NASA/NOAA's GOES-R mission plans to use GPS for primary navigation at GEO using a General Dynamics Viceroy-4 receiver.[20] With this new technology availability, the next few years promise many more satellites navigating by GPS above the GPS constellation.

To our knowledge, however, NASA's MMS mission, launched in March of 2015, flying a GSFC Navigator, has demonstrated the first operational use of high-altitude GPS-navigation on a civilian spacecraft. At its current Phase 1 apogee distance of 76,000 km, almost twice the distance of the GEO belt or about 1/5th of the way to the moon, the MMS mission also claims a record for the

highest operational use of GPS, and gives a clear demonstration of the benefit to navigation that can be achieved by processing GPS sidelobe signals. Furthermore, in the mission's second phase, apogee will be doubled to more than 160,000 km.

In the rest of this paper, we describe the MMS mission, its GPS navigation system and mission requirements, and present results from the first phase of the mission, including how the performance was validated against an independent orbit determination scheme. Next we predict the performance in the second phase, and examine the benefit of sidelobe tracking by reprocessing the MMS flight data with sidelobe signals eliminated. Finally, we draw conclusions and speculate on the impact of the MMS results for future missions.

MMS Navigation System Design

MMS is a Solar Terrestrial Probe mission funded by NASA's Science Mission Directorate Heliophysics Division. It will study the phenomenon of collisionless magnetic reconnection and particle acceleration in the electron diffusion of the Earth's day side magnetopause and night side neutral sheet in the magnetotail.[21] MMS science relies on three-dimensional measurements made by a formation of four nearly-identical spin-stabilized satellites carrying a total suite of 100 instruments. The spacecraft are controlled to maintain a tetrahedron within the science Region of Interest (ROI), whose scale-size, or nominal leg lengths, are varied from 10 km to 400 km. The nominal two-year mission includes two distinct science collection orbits, Phase 1 and Phase 2b.* As shown in Figure 2, the Phase 1 orbit is a 1.2×12 Earth radii (RE) ellipse with ROI above 9 RE (at the day-side magnetopause) and the Phase 2b orbit is a 1.2×25 RE ellipse with ROI above 15 RE (at the night-side magnetotail).[22] Figure 3 shows the stacked launch configuration of the MMS spacecraft just prior to encapsulation in the Atlas V launch vehicle fairing.

In the late 1990s, an early MMS study identified through covariance analysis that ground tracking alone could not support MMS formation flying requirements unless a crosslink ranging system were added. Since no off-the-shelf crosslink system existed, pre-Phase A studies were initiated to seed the development of such a system. One of the early outcomes of the study was that an integrated GPS receiver would significantly simplify the system design. The study identified multiple potential

*Phase 2a is an apogee raising sequence.

suppliers including an in-house option based on the Navigator and GEONS. Independent studies by GSFC flight dynamics analysts had, by this time, determined that on-board navigation was necessary to support the operational cadence of the mission, and could deliver superior performance to almost any ground-based Orbit Determination (OD) scenario. Ultimately, the in-house option was selected, resulting in a Navigator+Crosslink+GEONS navigation system. This system would process GPS pseudorange and crosslink range and Doppler measurements, and enable each satellite to estimate its absolute state and the relative state to the rest of the MMS constellation. As analysis and simulations were refined and the mission design evolved, in particular with removal of a planned 10×50 RE "Phase 4" orbit, the navigation team determined that requirements could be met with GPS-based navigation alone. Just prior to the MMS Preliminary Design Review, it was determined that, with a minor descope of science requirements, a significant cost and risk reduction could be achieved by removing the crosslink component of navigation sytem, which was nearing completion of its early prototype qualification testing. This left the Navigator with embedded GEONS filter as the final operational navigation system for MMS.

The key MMS on-board OD requirements, highlighted in Table 1, were designed to ensure that the Flight Dynamics team would be able to safely and accurately maintain the range of nominal formation sizes throughout the mission. The first two requirements listed in the table are the most critical: the MMS navigation system must determine the spacecraft Semi-Major Axis (SMA) to within 50 m (above 3 RE and outside maneuver recovery periods) 99% of the time in Phase 1, and to within 100 m, with the same qualification, in Phase 2b. Determination of the orbit SMA to acceptable levels is, in general, more challenging than that of the orbit plane orientation and shape and, critically, error in SMA knowledge largely determines the growth rate of propagation errors.[23] The error in the predictive states (as well as maneuver execution errors) drive the required frequency of maneuvers. The SMA knowledge requirement is derived from a mission level goal of constraining the time between formation maintenance maneuvers to be greater than two weeks, and ideally more than a month. To a large extent, the remaining requirements in the table are subordinate to the SMA requirements, and were developed to ensure the hardware-in-the loop and Monte Carlo simulations met them with sufficient margin.

Table 1: Key On-Board Orbit Determination Requirements

Description	Requirement
Phase 1 Semi-major Axis Estimation Requirement	50 m above 3 RE (99%)
Phase 2b Semi-major Axis Estimation Requirement	100 m above 3 RE (99%)
Orbit Position Estimation Requirement	100 km Root Sum Square (RSS) (99%)
PPS Distribution Accuracy	325 µs
Minimal Tracked Signal Level	-175 dBW
Maximum Spin Rate	3.7 Revolutions Per Minute (RPM)
Maximum Time to Attempt Acquisitions on All Visible Satellites	300 s
Dynamic Range	15 dB
Measurement Noise On L1 Pseudorange	30 m (3σ)

Navigator GPS

NASA GSFC has been developing GPS receivers for on-board navigation with a focus on above-the-constellation applications since the 1990's. The first receiver, called PiVoT, was based on a popular commercial GPS chipset with software modified to enable HEO operation, and was used primarily in laboratory simulations.[4] The Navigator GPS receiver program was initiated in the early 2000's with the main goal of achieving efficient operation in above-the-GPS-constellation orbits. To meet this challenge, the receiver design included a powerful signal acquisition engine to enable rapid, autonomous, unaided acquisition to a threshold carrier-to-noise spectral density (C/N_0) level of 25 dB-Hz,* a level that lets it directly acquire and track many GPS transmitter sidelobe emissions at GEO altitude and beyond. Additionally, the Navigator incorporated specialized flight software, including the GEONS filter, to enable robust navigation when fewer than four signals were present, and the receiver hardware was designed to withstand the harsh environment of high-altitude orbits. Further details of the general receiver design are given in Reference 5.

The first on-orbit demonstration of the Navigator was on the 2009 Hubble Space Telescope Servicing Mission 4 as part of the Relative Navigation Sensor experiment, where basic functions were demonstrated, and a unique reflected GPS sampled dataset was collected that is still the subject of active research.[24] Navigator is the primary GPS sensor for NASA's GPM mission, launched in February 2014. The receiver technology was incorporated into the Honeywell receiver developed for the Orion capsule to enable fast signal reacquisition upon emergence from the plasma-induced radio blackout during re-entry, a capability that was successfully demonstrated on Orion EFT-1 in

*For the MMS-Navigator, a C/N_0 level of 25 dB-Hz, as reported by the receiver, corresponds to a received power level at the antenna output port of approximately -178 dBW.

December 2014. The full Navigator design has been licensed to Moog-Broad Reach (MBR) and Space Vector Corporation, and MBR has developed improved SWaP versions for AFRL's ANGELS and EAGLE programs and NASA's NICER mission. The Next Generation Navigator is currently in development at GSFC with goals of supporting modernized GPS and GNSS signals, and reducing SWaP. An early version of this receiver was deployed for the GPS ACE program.[7]

MMS-Navigator In this subsection we describe some details specific to the MMS-Navigator. First, the fact that the MMS spacecraft spin at three Revolutions Per Minute (RPM) adds a significant challenge. Spacecraft design constraints precluded the use of omnidirectional or hemispherical antennas placed on the top and bottom of the spacecraft. Instead, four GPS antennas were placed around the perimeter, and the receiver was designed to hand-off from one antenna to the next.[*]The need to achieve full sky coverage while spinning constrained the antenna design and peak gain. For example, on a three axis stabilized spacecraft operating above the GPS constellation and processing weak signals, a specialized nadir-pointed high-gain antenna could be used to improve received signal levels. Additionally, each receiver derives all frequencies from a dedicated Ultra-Stable Oscillator (USO) with minimal random fluctuations (1×10^{-11} Hadamard deviation at 1 sec and 1.4×10^{-11} at 24 hrs), over temperature (3×10^{-11} per °C), and other environmental effects. The USO specifications were driven by the need to meet navigation and (initially tighter) timing requirements, in particular, under an operational mode (no longer planned for use) where the GPS radio frequency circuits would be shut off above 3 RE.

Altogether, the MMS GPS hardware consists of a total of eight GPS receiver electronics boxes: two per spacecraft, bolted together as a primary/redundant pair. Each receiver has a dedicated USO made by Frequency Electronics, Inc., four GSFC custom design antennas, and four front-end electronics from Delta-Microwave, Inc. The receivers were all built and tested at GSFC by a relatively small team of engineers and technicians. Pictures of the MMS GPS hardware are shown

[*]The antenna handoff technique for MMS allocates a pair of correlators to each signal being tracked. A traditional Phase-Locked Loop (PLL)/Delay-Lock Loop (DLL) controls the primary correlator to track the signal of interest. The secondary correlator's code generator is synchronized to the primary DLL to maintain code lock, while a secondary PLL, periodically resynchronized to the primary, attempts to acquire independent phase lock on the "next" antenna. Due to the spin-stabilization of the spacecraft, the signals rise and set on each antenna in a fixed sequence, so the next antenna is known given the current. Hardware constraints precluded the use of more than two correlators per channel, and, while alternate pre-correlation techniques were considered, the described approach was determined to provide adequate performance in simulation, and now on-orbit.

in Figure 4.

Figure 3: Launch configuration of the MMS spacecraft

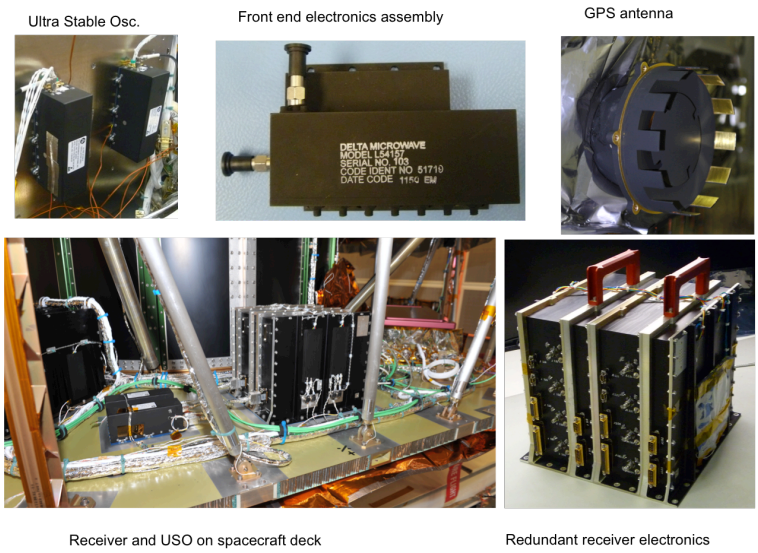


Figure 4: MMS GPS hardware components

Goddard Enhanced Onboard Navigation System (GEONS)

GEONS is a high-heritage software package developed at GSFC for on-board OD. It implements a factorized-covariance Extended Kalman Filter algorithm with a fourth or eighth order Runge-Kutta integrator and realistic process noise models. GEONS has the ability to estimate multiple spacecraft absolute and/or relative position and velocity vectors, clock states, drag coefficient correction, Solar Radiation Pressure (SRP) coefficient correction, and measurement biases. The core dynamic models include up to 30×30 Joint Gravity Model-2 geopotential, non-spherical solar and lunar potential, solar system body point masses, Harris-Priester atmospheric density, SRP, measured accelerations, and an impulsive delta-V maneuver model. It can handle numerous measurement types including GPS/WAAS differenced and undifferenced pseudorange and carrier phase, differential corrections from multiple sources, Ground Station range and Doppler, Crosslink, Celestial object line of sight, and X-ray Pulsar pulse phase and frequency.

GEONS is the evolution of a long history of onboard orbit determination software developed at GSFC. The work leading to GEONS began with ground-based experiments on Landsat 4, Landsat 5 and the Cosmic Background Explorer in the 1980s. These led to a series of experiments on-board the Extreme Ultra Violet Explorer in the 1990s, which formed the basis for systems that have per-

formed operational OD on Terra since 1999.[25] The GPS measurement processing was developed for the Lewis mission[26] and used on Earth Observer-1, and GPS processing, especially for high-altitude missions, has been a focus of recent GEONS research and development.[27,28] GEONS has remained under active development and has been extensively licensed to the US aerospace industry and academia.

For MMS, GEONS is configured to estimate absolute position and velocity vectors, clock bias, rate, and acceleration. The integrator is configured with a 10 second step size. The dynamics model uses a 13×13 geopotential, solar and lunar point masses, SRP with spherical area model, and drag. It processes GPS L1 C/A undifferenced pseudorange observables provided by the Navigator GPS receiver at a 30 second period. Accelerometer data is provided from the attitude control system at a 10 second period during maneuvers. The accuracy of the accelerometer data has been shown on-orbit to be sufficient to support typical maneuver execution errors (target SMA change vs. resulting estimated SMA change) of less than one percent.

MMS GPS TESTING

Several years of hardware and software testing were invested to ensure the requirements in Table 1 could be reliably met. Hardware simulations were run with the Navigator receiver to show that the unit was able to meet the requirements over multiple orbits given a fixed set of initial conditions. The resulting performance statistics, such as acquisition and tracking thresholds, measurement noise, and number of signals tracked, were provided to the Flight Dynamics team who used them to build a software model of the Navigator. This model was used in conjunction with the GEONS software to perform Monte Carlo simulations and ensure the requirements were met over a broad range of conditions. Detailed hardware test results were presented in Reference 29, and the Monte Carlo simulation results were presented in Reference 30. While these studies demonstrated that all requirements would indeed be met, it has become apparent that significant conservatism was built into the models and on-orbit results have exceeded performance expectation.

ON-ORBIT RESULTS

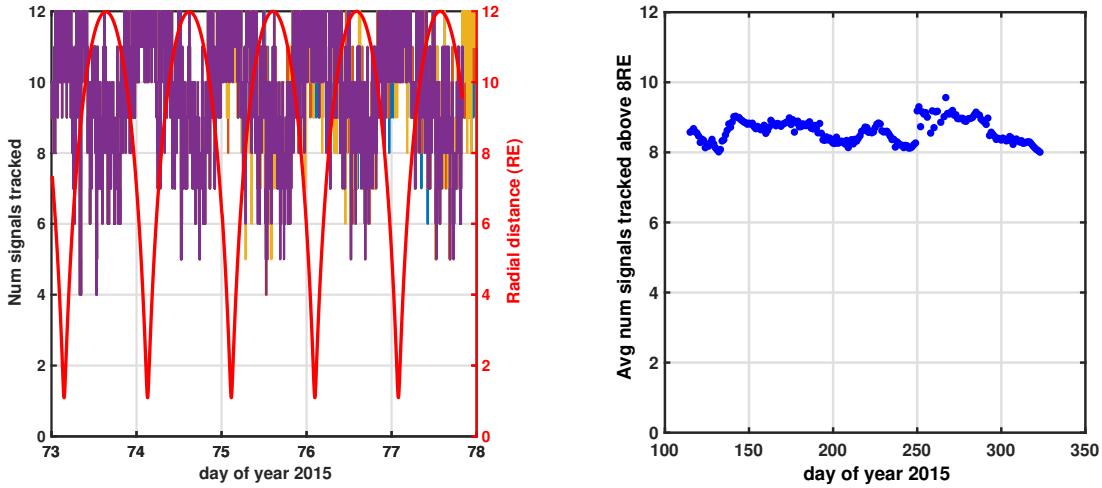
On March 12, 2015, the MMS spacecraft experienced a flawless launch out of Cape Canaveral on an Atlas V-421 rocket. After several hours, as the spacecraft moved towards apogee, each of the GPS receivers was powered up and almost immediately began acquiring signals. Within a few minutes, the receivers had nearly filled their 12 tracking channels and were generating point and filtered solutions, all above the GPS constellation. In the next section, we present results from early mission operations focusing on two distinct time frames: the first few orbits, and a quiescent period during the navigation certification campaign around day 136 of 2015. The performance up to the writing of this paper has remained consistent with these results.

Receiver performance

Figure 5a shows the number of signals tracked and orbital radius from the first three full orbits of the MMS mission on days 73 through 77 of 2015. Individual traces for each of four spacecraft are plotted on the same axis. Due to highly consistent tracking performance, the traces nearly lay on top of one another. Perhaps the most striking result is that each receiver is able to track, on average, more than eight signals in the region above the GPS constellation and, at times, even 12 signals at the 12 RE apogee. At perigee, the receiver is limited to 12 signals by the number of channels available in the hardware. Figure 5b shows a long term trend of the average number of signals tracked by each receiver at distances greater than 8 RE. Each data point on the graph is the average number of signals tracked during the portion of each orbit above 8 RE, where the average is taken across measurement epoch and across all four receivers.

The excellent visibility above the GPS constellation is due to Navigator's ability to track weak GPS transmitter sidelobe signals. Figure 6 shows a time series of the reported C/N_0 of the tracked signals on day 136 of 2015, which is typical. The cluster of signal tracking arcs below 35 dB-Hz are sidelobe signals, which can be seen to make up the vast majority of all signals tracked above the GPS constellation.

While the source geometry becomes seriously degraded at high altitude, the large number of signals tracked means that the receiver is able to compute point solutions at almost all times in the MMS Phase 1 orbit. One benefit of this fact is that, if necessary, the receiver is able to reinitialize the



(a) Number of signals tracked with orbital radius over the first 4 full orbits of the MMS mission from days 73 through 77 of 2015

(b) Long term average number of signals tracked above 8 RE

Figure 5: Number of signals tracked

GEONS filter at almost any point in the orbit. Figure 7 shows the difference between the GEONS filtered state and the point solution along with the GDOP overlaid in red for MMS observatory 1 (MMS1) on day 136 of 2015. Note perigee occurs around seven tenths of the way into the day.

Figure 8a shows the GEONS position and velocity RSS (1σ) covariance diagonal "formal errors" and Figure 8b shows the GEONS clock bias and rate (1σ) root-variance from day 73 through 77 of 2015. The filter fully converges after one complete orbit and, thereafter, the maximum RSS position formal errors reach 12 m at apogee, and the maximum RSS velocity formal errors peak to 3 mm/s near perigee, otherwise remaining below 1 mm/s. The clock rate covariance remains between 3-4 mm/s due to the tuning of the filter for the MMS USO.

Figures 9a and 9b show the GEONS pre-measurement-update observed-minus-predicted pseudo-range residuals, i.e., filter innovations, from day 136 of 2015 plotted as a function of time and true anomaly, respectively, with different colors denoting separate GPS satellites. The residuals are zero mean throughout the orbit, with standard deviations ranging from a few meters at perigee to about ten meters at apogee. This is as-expected since the signals are weaker at apogee, but importantly, there do not appear to be any significant systematic biases, suggesting that the sidelobe signals are providing valuable information to the filter.

In preflight GPS hardware-in-the-loop simulations, the filter 1σ formal error was always found

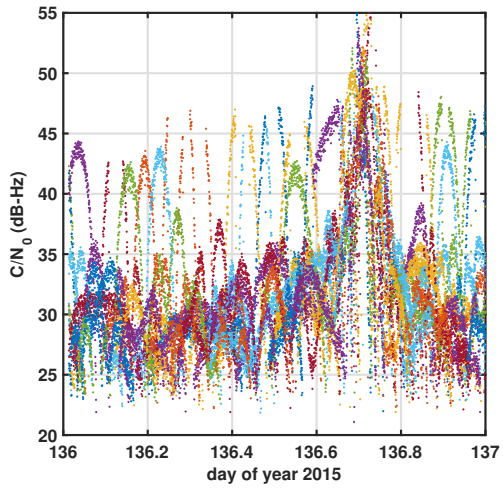


Figure 6: Received C/N_0 for MMS1 on day 136 of 2015 showing sidelobe tracking

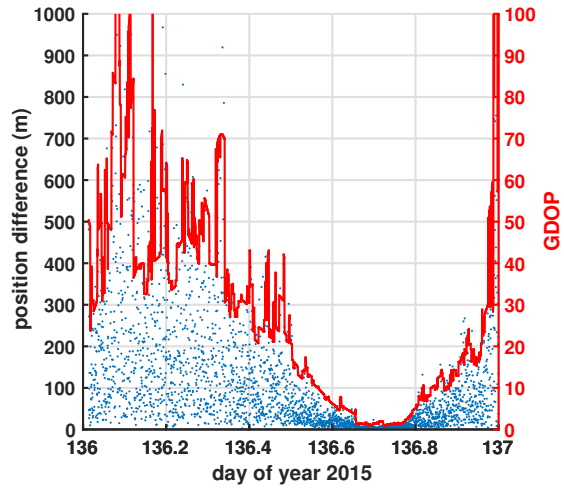
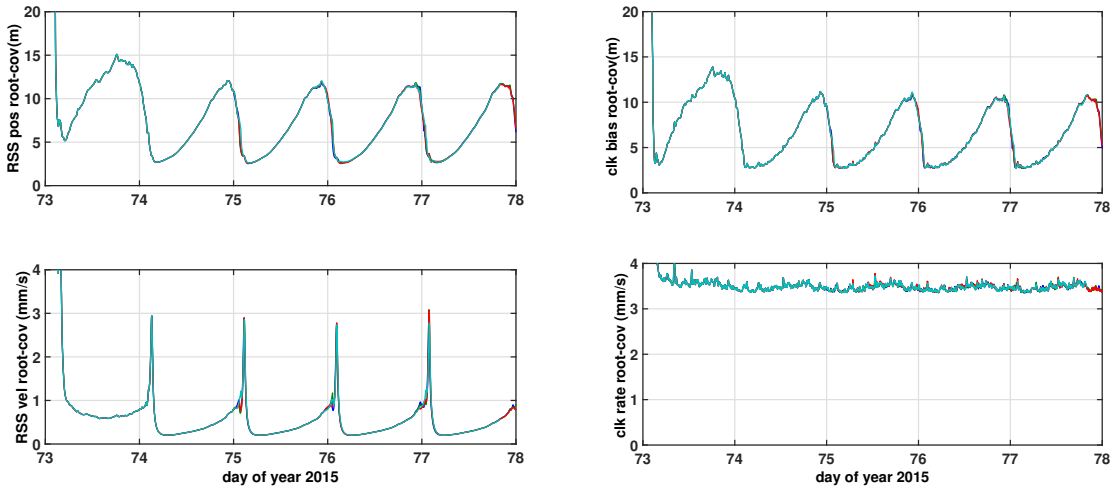


Figure 7: Point solution and filtered solution RSS position differences with GDOP

to be a conservative upper bound for the actual errors (see Reference 29), so it may be reasonable to speculate that the actual errors for MMS on-orbit are, likewise, significantly smaller than these formal errors, but lacking a truth position to compare against, the actual errors are unknown. The following discusses how the filter performance was validated against an independent OD solution during a quiescent navigation commissioning period using an independent OD process.

Navigation certification

References 31 and 32 give detailed discussions of the use and performance of GEONS on MMS. In particular, Reference 32 describes results from a certification campaign that occurred during the first nine weeks of the MMS mission. During this period, the GSFC Flight Dynamics Facility (FDF) performed daily ground-based OD solutions based on two-way range and Doppler tracking from Tracking and Data Relay Satellite System in the vicinity of MMS perigees, and near-continuous two-way Doppler tracking from the Deep Space Network throughout the remainder of the MMS orbits. The highlight of the certification campaign was a three-day window from day 133 through 136 of 2015, when all other spacecraft commissioning activities ceased, so as to provide a quiescent window for OD calibration. The FDF used definitive attitude products and communications antennas center-of-mass offsets to remove the signature of the MMS spacecrafts' three RPM spin rate from the tracking data. The FDF then processed these "de-spun" data using the filter-smoother in Orbit Determination Toolkit from Analytical Graphics, Inc. to provide an independent radiometric



(a) RSS position and velocity

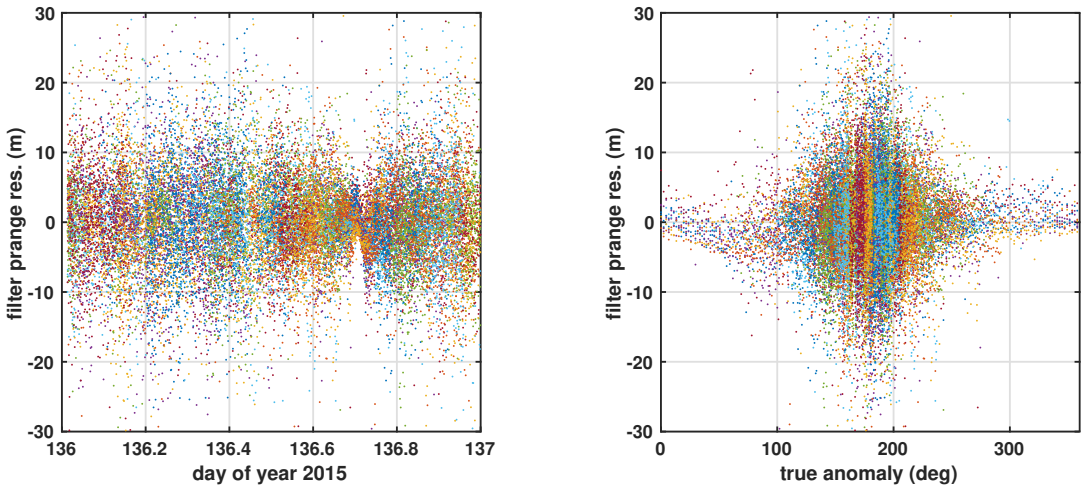
(b) clock bias and rate

Figure 8: GEONS 1σ formal error (covariance) over the first 4 full orbits of the MMS mission from day 73 through 77 of 2015. Results from each of the MMS satellites are shown, but the traces lie nearly on top of one another, due to highly consistent tracking performance.

OD reference solution.

Figure 10 provides a typical result, from MMS1, for one view of the comparison between GEONS and the FDF reference. The four plots in the left column of the figure show time series differences between the solutions. Each color denotes a separate orbit. The right column period-folds each of the orbits onto the same one degree mean anomaly grid. The time series plots also show daily values of the mean difference, and its 99% confidence interval, while the period-folded plots show a mean and confidence interval computed across a bin at each mean anomaly grid point. The upper three plots in each column show differences in position vector components, expressed in a Frenet frame whose first basis is the reference velocity direction (V), second basis is the reference orbit normal direction (N), and whose third basis (B for "bi-normal") completes a right-hand triad. The fourth plot shows the SMA difference.

The time series differences in Figure 10 clearly illustrate the non-stationary statistical moments, which the time-series statistics fail to capture. The one-degree mean anomaly bins of the period-folded differences appear to track the non-stationary moments much better. The statistical variability of the differences is expected due to the highly elliptical MMS orbit, and the strong variability of the information content in both the FDF and GEONS solutions. For the FDF solutions, the fact that only Doppler tracking is available for most of the orbit means that orbit errors are not well



(a) vs. time (b) vs. true anomaly (180° apogee, 0° perigee)

Figure 9: GEONS pseudorange residuals during day 136 of 2015

constrained outside of the perigee region. For GEONS, even though an average of about 9 GPS signals were tracked throughout the apogee region, GDOP values often reached well over 100. Another difference between the solutions is that the FDF solutions used daily definitive values of the Earth Orientation Parameters (EOP) to rotate Earth-fixed quantities such as GPS ephemerides and gravity coefficients into the J2000.0 frame, while GEONS used an EOP prediction from the previous week. Also, GEONS used the GPS broadcast ephemeris, while FDF used *post facto* precise ephemerides from the International GPS Service.

Table 2 summarizes the performance of the OD calibration. One may compare these results to the driving navigation requirements which Table 1 lists. The absolute orbit positioning requirement of 100 km, which is needed for locating science observations, appears to be met with significant margin. The SMA requirement of 50 m for Phase 1, which is needed for formation flying, would also appear to be met with substantial margin. If one accepts the conclusion, suggested by evidence presented in Reference 32, that that most of the difference between the GEONS and the FDF solutions derives from errors in the FDF solution, then it would appear that performance margins are even higher. Reference 32 discusses additional performance metrics, including sub-meter level consistency among SMA differences between GEONS solutions for the four MMS spacecraft, predictive-definitive overlap comparisons, and others that further support the conclusion that GEONS is determining the SMA of the MMS orbits to the meter level throughout the orbit. It is no-

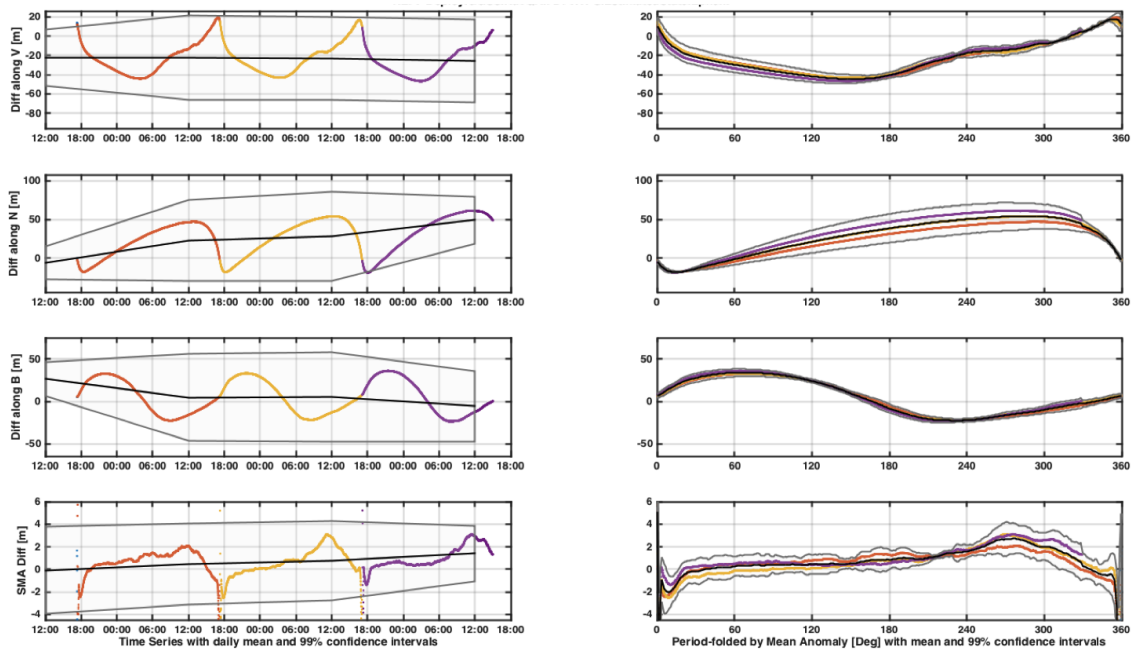


Figure 10: Position Component and SMA Differences between Onboard GPS OD and Ground-based Independent Radiometric OD, with Empirical Confidence Intervals, for MMS1. The left column shows time series differences; the right column shows period-folded differences.

table that GEONS is achieving such accuracy without the use of sophisticated measurements, such as carrier phase differences, and with relatively modest dynamic model fidelity. The conclusion

Table 2: GEONS Performance Summary (all units are meters)

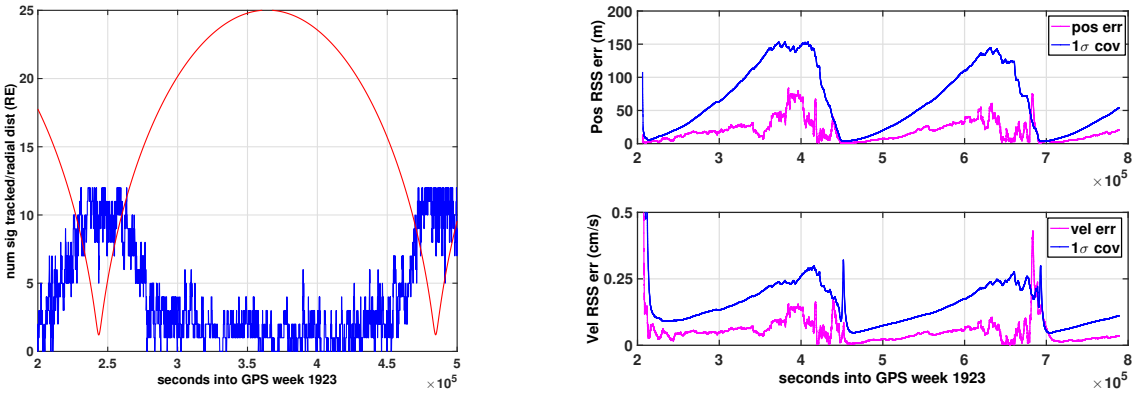
Quantity Differenced from FDF OD	MMS1	MMS2	MMS3	MMS4
RSS Position (Worst Case)	65	50	50	25
SMA (Max of 99% CI Above 3 RE)	4	5	6	4

is that GPS navigation performance in Phase 1 is meeting requirements with significant margin. This excellent performance has allowed for faster than expected maneuver recovery in same orbit, reduced frequency of formation maintenance maneuvers (4-5 weeks between, versus the 2 week baseline), and early use of the onboard solution for communication system acquisition data, all leading to smoother and simpler operations for the flight dynamics team.

Predicted Performance in MMS Phase 2b

In the winter of 2017, the MMS mission will perform a series of maneuvers, known as Phase 2a, which will stretch the formation orbits to a 1.2×25 RE ellipse. Based on the better-than-expected

performance experienced in Phase 1, hardware-in-the-loop simulations of the Phase 2b orbit were recalibrated and run on an MMS-Navigator Engineering Test Unit to obtain an updated estimate of Phase 2b performance. The results for this simulation are shown in Figure 11. Figure 11a shows that visibility is significantly reduced above around 17 RE, where the sidelobes drop below the sensitivity level of the receiver, but an average of 2-3 mainlobe signals are still predicted visible near apogee without any long outages. Figure 11b shows the RSS position errors reach a maximum 60 m and the formal errors reach a maximum of 150 m. This level of performance is 2-3 times better than preflight simulations and suggest Phase 2b navigation requirements will be met with significant margin. Not shown are the corresponding SMA errors which stay below 20 m maximum when the spacecraft is above 3 RE; this is well below the 100 m requirement for Phase 2b.



(a) MMS Phase 2b signals tracked and radial distance (b) MMS Phase 2b GEONS RSS position errors

Figure 11: The Phase 2b laboratory simulation, recalibrated based on Phase 1 results, provides predictions of the performance we will see in 2017.

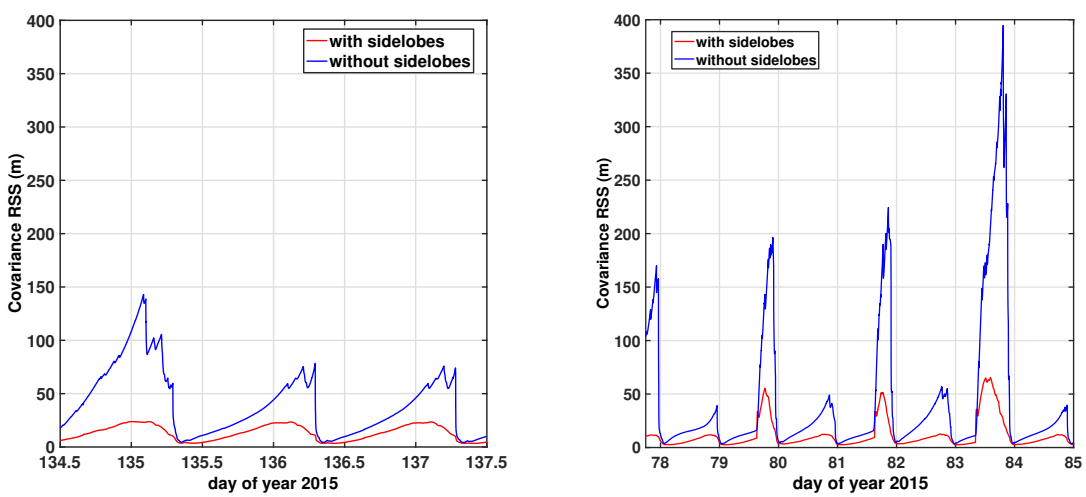
Value of GPS sidelobe signals

A small simulation study was conducted to demonstrate the value of the sidelobe signals for MMS using the Navigator *replayer*, a software tool for reprocessing raw observable telemetry through the receiver flight software on the ground, allowing for modification to the algorithms and/or input data, if desired.

We reprocessed two datasets collected from the on-orbit telemetry and compared the filter formal errors with and without the sidelobe signals. The sidelobes were removed by simply applying an edit threshold to remove input data with C/N_0 below 38 dB-Hz. The first dataset used a four day period

during navigation commissioning week with no maneuvers. The second dataset included four orbits starting around day 79 of 2015 with an early sequence of perigee raise maneuvers (approximately 15 m/s each) to look at the benefit to maneuver recovery time. In a similar fashion to the on-board Navigator, the replayer passed 10 second averaged accelerations to GEONS, which it incorporated into its integration, and the filter's process noise was inflated to account for any mismodeling of the maneuver. The results for the first test are shown in Figure 12a. In this case, the formal errors are reduced by a factor of almost four. Figure 12b shows the results for the sequence of four perigee raising maneuvers. In this case, the formal errors are reduced even more.

The existing GPS SSV requirements specify the availability of four or more GPS transmitter mainlobe signals a mere 1% of the time, for a user at GEO distance. Currently, they leave the sidelobe signals completely unspecified and, thus, at risk for suppression in future GPS constellation blocks. With the ability to track sidelobes, the MMS GPS receivers are seeing four or more signals at twice GEO distance nearly 100% of the time, and see more than eight, on average. This dramatic increase in availability provided by the current GPS constellation's sidelobe transmissions, along with their demonstrated quality for navigation, emphasizes the value of the ongoing effort to develop specifications to protect these signals.[13]



(a) Case with no maneuvers

(b) Case with a sequence perigee raising maneuvers

Figure 12: Filter formal errors in reprocessed on-orbit simulation with/without sidelobes

CONCLUSION

The launch of the four MMS satellites represents, by-far, the highest altitude (and fastest at perigee) operational use of GPS-based navigation. It demonstrates that GPS sidelobe signals dramatically increase signal availability over mainlobe signals alone, are of "navigation quality," and can contribute to the robustness and quality of high-altitude spacecraft navigation to distances well beyond GEO and likely even to the moon.

The implications of these results are significant. For MMS, the excellent GPS navigation performance demonstrated on-orbit has allowed for faster-than-expected maneuver recovery, longer time between formation maintenance maneuvers, and simplified operations. This trend is expected to continue with the transition to Phase 2b coming in winter of 2017. For future high-altitude missions there now exists a precedent and flight-proven receiver and filter technology to support a move to on-board GPS-based navigation to simplify operations, improve navigation performance, reduce mission costs, and perhaps even enable new science.

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