

NAVIGATION OPERATIONS FOR THE MAGNETOSPHERIC MULTISCALE MISSION

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Abstract: *The Magnetospheric Multiscale (MMS) mission employs four identical spinning spacecraft flying in highly elliptical Earth orbits. These spacecraft will fly in a series of tetrahedral formations with separations of less than 10 km. MMS navigation operations use onboard navigation to satisfy the mission definitive orbit and time determination requirements and in addition to minimize operations cost and complexity. The onboard navigation subsystem consists of the Navigator GPS receiver with Goddard Enhanced Onboard Navigation System (GEONS) software, and an Ultra-Stable Oscillator. The four MMS spacecraft are operated from a single Mission Operations Center, which includes a Flight Dynamics Operations Area (FDOA) that supports MMS navigation operations, as well as maneuver planning, conjunction assessment and attitude ground operations. The System Manager component of the FDOA automates routine operations processes. The GEONS Ground Support System component of the FDOA provides the tools needed to support MMS navigation operations. This paper provides an overview of the MMS mission and associated navigation requirements and constraints and discusses MMS navigation operations and the associated MMS ground system components built to support navigation-related operations.*

Keywords: *Onboard Navigation, MMS, GPS*

1. Introduction

The primary science objective of the Magnetospheric Multiscale (MMS) mission is to study the phenomenon known as magnetic reconnection, which converts magnetic energy into heat and kinetic energy of charged particles [1]. The Earth's magnetosphere is the only location in which this process can be practically studied in situ at this time. The regions of prime science interest are the electron diffusion regions of the Earth's dayside magnetopause and night-side neutral sheet in the magneto-tail. Consequently, the MMS mission design incorporates a two-phase apogee approach, where the apogee region of the orbit provides long durations in the Earth's dayside magnetopause and night-side neutral sheet. The MMS mission employs four identical spinning spacecraft flying in highly-elliptical Earth orbits, each hosting 25 science instruments. These spacecraft will fly in a series of tetrahedral formations with separations of less than 10 km to provide 3-dimensional simultaneous observations in the regions of prime science interest. The science data provided by this mission are expected to dramatically advance understanding of events driven by magnetic reconnection such as solar flares and auroras on Earth and other planets in the solar system.

The MMS science objectives present several challenges for spacecraft navigation. Development of the MMS navigation concepts was initiated more than a decade ago as part of the overall

mission concept development process. The navigation operations concepts were successively refined as the overall mission concepts were refined, mission requirements and operations constraints were derived, and MMS ground system development progressed. The resulting MMS navigation concepts employ onboard navigation using Global Positioning System (GPS) L1 signals to satisfy the mission orbit and time determination requirements and to minimize operations cost and complexity. The GPS receiver, Navigator, and the onboard navigation software, Goddard Enhanced Onboard Navigation System (GEONS), are both products of in-house NASA Goddard Space Flight Center (GSFC) development tailored to MMS needs.

The four MMS spacecraft are operated from a single Mission Operations Center (MOC) located at GSFC. The MMS MOC includes the Flight Dynamics Operations Area (FDOA). The FDOA supports MMS navigation operations, as well as maneuver planning, conjunction assessment and, attitude ground operations. The GEONS Ground Support System (GGSS) component of the FDOA provides the tools needed to support MMS navigation operations. This paper provides an overview of the MMS mission and associated navigation requirements and constraints and discusses MMS navigation operations and the GGSS ground system component built to support navigation-related operations during both the commissioning and routine mission phases.

2. MMS Mission Overview

On March 13, 2015, the four MMS spacecraft were launched directly into highly eccentric Earth orbits. Figure 1 provides an overview of the various phases of the MMS mission. Starting 5 days after launch, five perigee-raising maneuvers per spacecraft were performed to place all four spacecraft into orbits characterized by a 1.2 Earth Radii (Re) perigee and 12 Re apogee radius. Following these maneuvers, the commissioning phase commenced to check out all spacecraft subsystems prior to science operations. The commissioning phase is also known as Phase 0.

Science operations for the MMS mission are being conducted in two distinct Phases, known as Phase 1 and Phase 2. Phase 1 consists of Phase 1a, 1x, and 1b. Phase 1a begins when the orbit apogee crosses from the Earth night-side (i.e., in opposition to the Sun), to the day-side (i.e., in inferior conjunction with the Sun). In Phase 1a, the distances between the spacecraft in the region of prime science interest, i.e. the formation scale sizes, will be adjusted in three stages from 160 kilometers to 10 kilometers. Following the resizing campaign, the formation scale size will be adjusted to an “optimum” separation selected by mission scientists after monitoring science data during Phase 1a. This variation in the formation size permits the formation to be used in the study of reconnection on the day-side boundary between the solar system magnetic field generated primarily by the Sun and the Earth’s magnetosphere. This region is known as the “bow shock” region. Phase 1a lasts approximately 6 months as the Earth travels around the Sun. Phase 1x occurs during the following 6 months when the apogee is located on the night side of the Earth. Phase 1b occurs during the 6 months after the conclusion of Phase 1x as the apogee once again is located on the dayside region.

Phase 2 consists of Phase 2a and Phase 2b. During Phase 2a, a series of maneuvers will be executed to incrementally increase the orbital apogee of each spacecraft from 12 Re to 25 Re. Phase 2b begins after the apogee raising of all four spacecraft is complete. During Phase 2b the formation separations will vary from 400km to 30km, followed by an “optimum” separation

selected by the scientists as they study the night-side reconnection events that occur within the Earth's magneto-tail. After Phase 2b, the spacecraft will be decommissioned. A more detailed description of the MMS mission appears in [1] and [2].

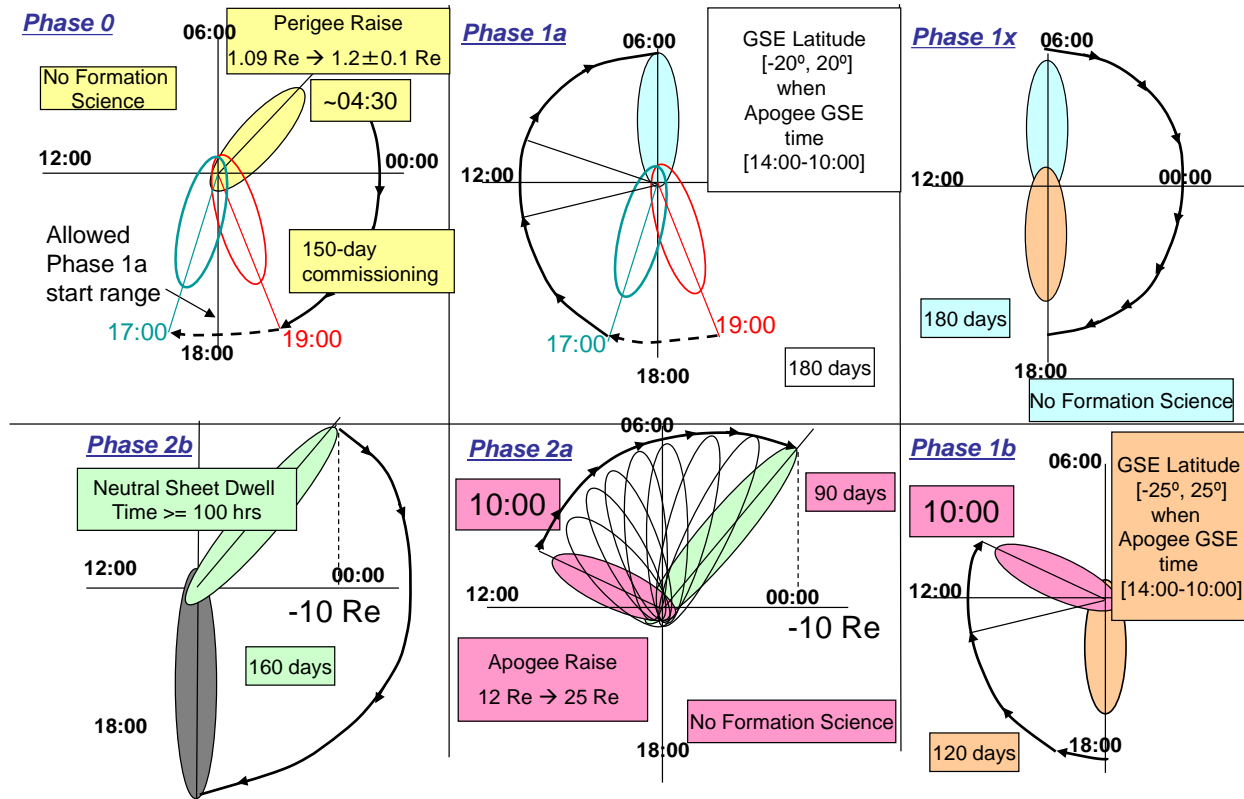


Figure 1. MMS Mission Overview (Times shown are with respect to the Earth-Sun Vector at 12:00)

3. Navigation Operations Drivers

The primary mission characteristics that influence the MMS navigation operations are:

- Highly elliptical orbits with apogees of 12 to 25 Re and a perigee of 1.2 Re and an initial inclination of 28.5 degrees
- Four spacecraft flying so that a regular tetrahedron is formed during the region of prime science interest, centered at apogee. The side length of the tetrahedron varies from less than 10 km to about 400 km with pairs of formation resize or formation maintenance maneuvers nominally executed every 2 weeks
- Fuel budget limitations and close approach considerations require that the large number of maneuvers be planned based on high accuracy velocity predictions
- Short turnaround time to replan the second maneuver in a pair following the completion of the first maneuver

Critical orbit and time determination requirements include

- A maximum definitive mean semi-major axis error above 3 Re of 50 meters and 100 meters for Phase 1 and Phase 2b, respectively, to satisfy close approach prediction requirements.
- A maximum error in the definitive interspacecraft range of one percent of the separation or 100 meters, whichever is larger, to meet science requirements in the science region of interest.
- A maximum predicted velocity error at the maneuver times of one percent of the maneuver impulsive delta-V or 10 millimeters per second, whichever is greater, to meet formation maintenance maneuver planning requirements for the first maneuver in a pair.
- A maximum predicted velocity error at the maneuver times of one percent of the maneuver impulsive delta-V or 2 millimeters per second for Phase 1 and 3 millimeters per second for Phase 2b, respectively, whichever is greater, to meet formation maintenance maneuver planning requirements for the second maneuver in a pair.
- A maximum USO clock bias error of 325 microseconds is to meet a science requirement for time synchronization among observatories to within 1 millisecond.

The science requirement for definitive relative orbit knowledge of 1% of the separation of the spacecraft in the regions of prime science interest is the primary driver for the design of the MMS navigation system and the associated ground system operations. Additional drivers for the design of the associated ground system components are the need to automate navigation support for the four spacecraft and to provide accurate spacecraft state and covariance solutions in near real-time to support maneuver planning and conjunction assessment among the spacecraft.

4. Navigation Operations

The MMS navigation operations concepts are based on the use of onboard navigation to satisfy the mission definitive orbit and time determination requirements and in addition to minimize operations cost and complexity. Development of the MMS navigation concepts was initiated more than a decade ago as part of the overall mission concept development process. Extensive trade studies were performed that included realistic simulations of the navigation options to assess the expected navigation accuracy vs the navigation requirements. The navigation options that were studied include (1) ground processing of range and Doppler measurements from NASA's space and ground networks, (2) onboard processing of one-way forward Doppler measurements from NASA's space and ground networks, (3) onboard processing of GPS L1 pseudorange (PR) measurements from a GPS receiver designed for weak signal tracking, and (4) onboard processing of interspacecraft range in addition to GPS L1 PR measurements. These studies indicated that only options (3) and (4) would satisfy the requirement for definitive relative orbit knowledge of the separation of the spacecraft for the smaller formation sizes.

The ground orbit determination scenario that was studied to evaluate option (1), involved three 20-minute contacts per day per spacecraft with range and Doppler from United Space Network (USN) stations at Wallops, Hawaii, and Madrid. This study assumed that each MMS was tracked sequentially from the same ground station, with only a 10-minute gap between, which allowed for some minimal level of common error cancellation in the relative solutions. Simulated tracking measurement errors were about the best case for USN, assuming that the effect of the spacecraft spin on the Doppler would be accurately modeled. These

simulations produced worst case absolute errors of about 1 km. Maximum relative errors were also about 1 km, but would be worse by about 40-50% if the tracking did not allow any common error cancellation. If the worst case relative errors were 2 km, the 1% of separation science requirement could be met only for formation scale sizes of 200 km and larger, which is larger than the largest formation scale size planned for Phase 1 and therefore not acceptable. Because navigation option (2) processes one-way forward Doppler measurements but not range measurements, it would provide less accuracy than navigation option 1.

MMS navigation operations concepts were successively refined as the overall mission concepts were refined, mission requirements and operations constraints were derived, and MMS ground system development progressed. Option (4) was subsequently eliminated due to the additional cost of developing the interspacecraft ranging system and the assessment that all requirements could be met by processing GPS L1 PR from a GPS receiver with weak-signal acquisition down to 28 dB-Hertz and tracking down to 25 dB-Hertz. References [3] and [4] present the results from specific studies performed to assess the expected performance of the onboard navigation system based on Option (3) versus the MMS navigation requirements. The decision was made to embed the navigation processing software in the GPS receiver to simplify ground operations as well as to meet the requirement for spacecraft time synchronization.

4.1. Onboard Orbit and Time Determination Operations

Each MMS spacecraft hosts an onboard navigation subsystem to provide onboard orbit and time determination for all mission phases. The onboard navigation subsystem consists of a 12-channel GPS receiver with weak signal acquisition capability and capability to handover between GPS antennas spinning at about 3 revolutions per minute, onboard navigation software, a USO, and two sets of four 120-degree field of view GPS antennas (one set of prime, one set of redundant) distributed around the spacecraft deck apexes. The GPS receiver, Navigator, and the onboard navigation software, GEONS, are both products of in-house GSFC development tailored to MMS needs. Figure 2 illustrates the MMS navigation concept of operations.

The weak signal acquisition capability allows Navigator to acquire and track GPS signals well above the GPS constellation. During Phase 0, Navigator has acquired an average of six or more GPS Space Vehicles (SVs) throughout the entire orbit for spin rates of ≤ 4 rpm. Using the USO as a frequency reference and the estimated time bias with respect to GPS time, Navigator maintains highly accurate time knowledge on each observatory. The spacecraft's Command and Data Handling (C&DH) subsystem uses the time provided by Navigator to maintain time synchronization among the observatories to within one millisecond.

Navigator performs high accuracy orbit and time bias determination via the GEONS flight software. GEONS estimates each spacecraft's position, velocity, onboard clock bias, onboard clock bias drift (rate), and onboard clock bias drift rate (acceleration) using a factorized Extended Kalman Filter (EKF) coupled with a high-fidelity dynamics model to process GPS PR measurements referenced to the USO. High-resolution thrust acceleration measurements from the onboard accelerometer within the Attitude Control System are included in the EKF to model the frequent formation resize and formation maintenance maneuvers. In addition, Navigator performs single point orbit and time solutions whenever PR and Doppler measurements from

four or more GPS SVs are available. These solutions are used to initialize GEONS and provide a sanity check on the quality of the GEONS solutions.

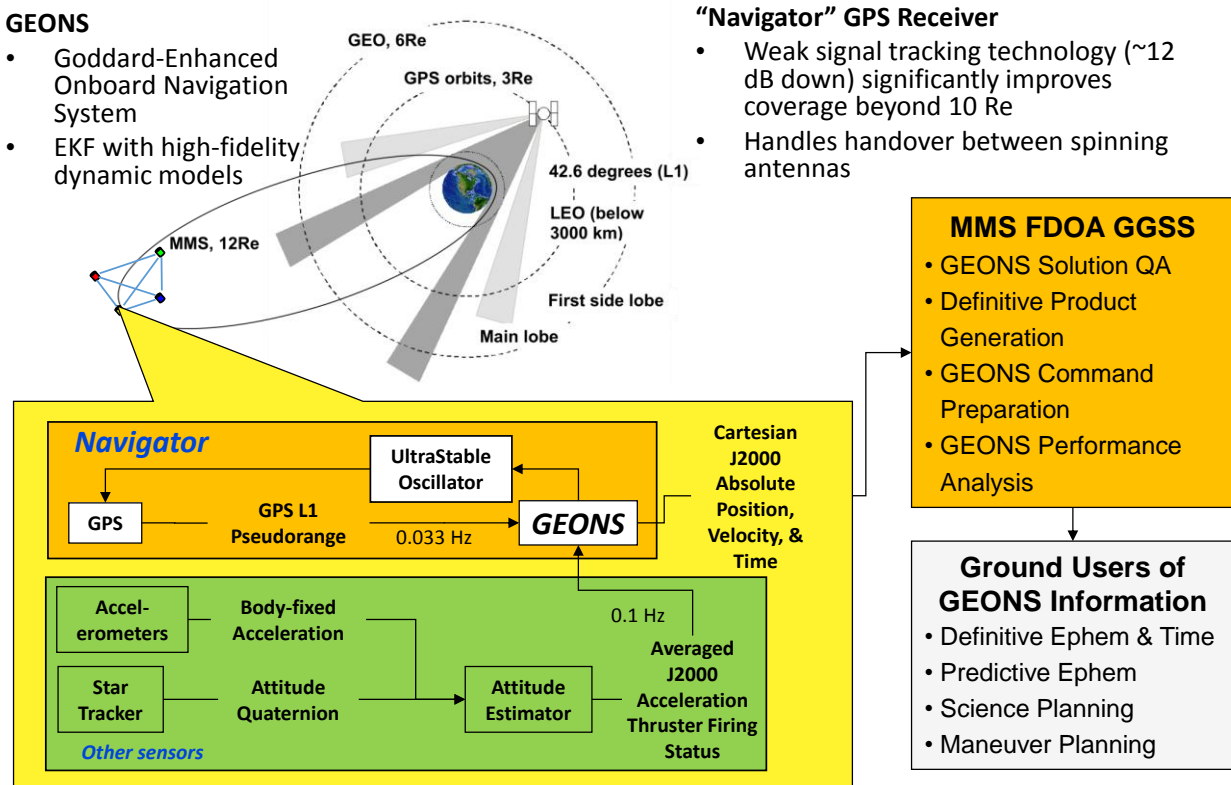


Figure 2. Overview of MMS Navigation Concept of Operations

4.2. Navigation Ground Operations

Onboard orbit and time determination eliminates the need to perform these functions as part of nominal ground operations. The states and covariance estimated by GEONS are periodically downlinked and used in the MMS FDOA to support quality assurance (QA) of the onboard solutions and to generate definitive products needed for science data analysis. Predicted products, including acquisition data for tracking services and predicted ephemerides for close approach screening and mission and science planning, are generated by propagating the definitive state and full covariance downlinked near the end of the spacecraft contact that occurs 1h to 3h following perigee.

The daily ground operations schedule is dictated by the Deep Space Network (DSN) and Space Network (SN)/Near-Earth Network (NEN) contact schedule and scheduled formation resize and formation maintenance maneuvers. Figure 3 illustrates the planned DSN and SN/NEN contacts during Phase 1 of the MMS mission on orbits with potential formation maintenance maneuvers. Navigator/GEONS real-time telemetry is available during all contacts. Navigator/GEONS playback telemetry is downloaded at least once per day during a DSN contact.

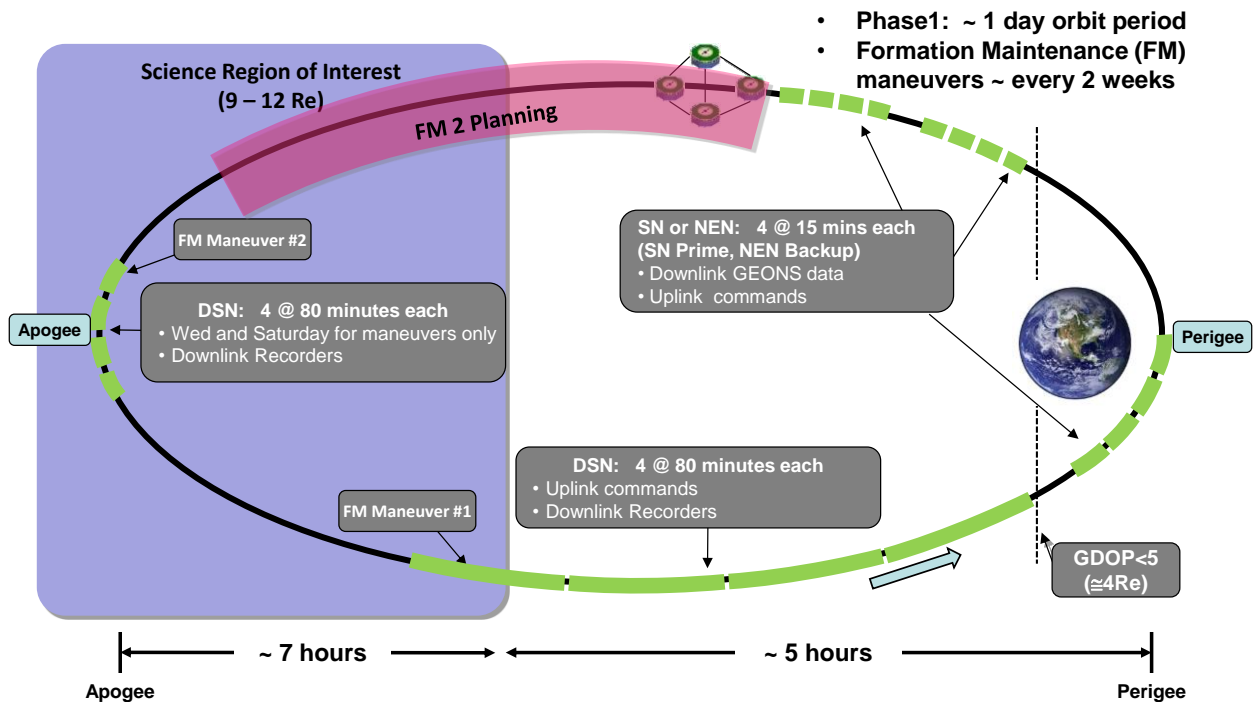


Figure 3. MMS Phase-1 Orbit in the Life with FM Maneuvers (Wednesdays and Saturdays)

When formation resizing/maintenance or apogee-raising maneuvers are scheduled, the operations team transitions to a more intense level of activity. The team subjects the onboard states to a more rigorous screening and then begins an iterative maneuver planning process. During each maneuver, the operations team monitors real-time telemetry from the onboard navigation system, including the GEONS filter output and onboard accelerometers.

Following the nominal launch of the MMS observatories on March 13, 2015, GEONS was initialized when the first Navigator Single Point Solution with a geometric dilution of precision (GDOP) ≤ 5 was available. During the initial 2 months of the mission, prior to the completion of Navigator/GEONS commissioning support, the GSFC Flight Dynamics Facility (FDF) provided definitive orbit solutions by processing range-rate measurements from DSN contacts and range and Doppler measurements from SN contacts. During this time period, the following operations were performed to commission Navigator/GEONS for mission operations:

- GEONS maneuver command generation for perigee-raise and initial orbit-stabilization maneuvers
- GEONS coordinate system command generation (weekly to provide current values for Earth Orientation Predictions (EOPs))
- Navigator/GEONS commissioning analysis that included detailed comparisons with definitive solutions computed by FDF. This analysis confirmed that Navigator/GEONS performance should satisfy the associated mission navigation requirements. Reference [5] presents a detailed discussion of these results

Following successful commissioning of Navigator/GEONS for mission operations, GEONS-related operations are now as follows:

- Navigator/GEONS real-time telemetry processing (Every contact)
- Navigator/GEONS playback telemetry processing (Daily)
- GEONS maneuver command and coordinate system command generation (weekly)

The following subsections discuss routine Navigator/GEONS real-time and play-back telemetry processing operations.

4.2.1. Navigator/GEONS Real-Time Telemetry Processing Operations

During every spacecraft contact, Navigator/GEONS telemetry is downlinked for the time span of the contact, typically a minimum of 1 hour for DSN and 15 minutes for SN and NEN contacts. This real-time telemetry downlink provides the opportunity to perform a quick check on the current GEONS solutions and, in the case of the post-perigee SN contacts, to extract the GEONS state vector and full covariance matrix to be used for maneuver planning, conjunction assessment, and GEONS warm restart if needed. Figure 4 illustrates this operation.

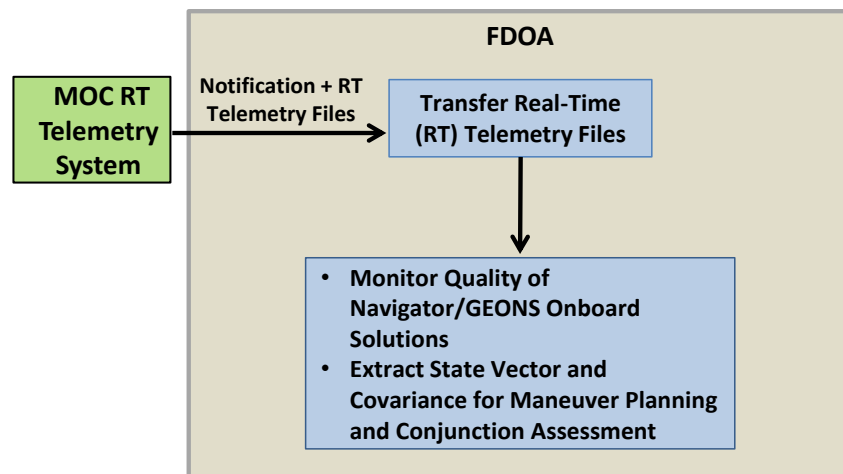


Figure 4. Navigator/GEONS Real-Time Processing Operations

The MOC real-time telemetry display system extracts telemetry data from the real-time telemetry packets, copies these data to a server accessible to the FDOA for retrieval, and publishes a data notification message. Initiation of the Navigator/GEONS Real-Time Telemetry Processing is triggered by the availability of these new files. GEONS Real-time Telemetry processing consists of telemetry checks against expected values for nominal performance. The GEONS telemetry processing tools generate text summaries of the values for a number of key telemetry values and associated plot files and identify non-nominal performance. In addition, this process produces files containing the state vector and full covariance matrix.

4.2.2. Navigator/GEONS Playback Telemetry Processing Operations

The Navigator/GEONS playback telemetry process is associated with DSN contacts that include the downlink of playback telemetry. During these contacts, all Navigator/GEONS telemetry is downlinked that has been stored onboard since the previous playback telemetry contact (typically about 1 day). This operation provides the opportunity to trend the quality of the GEONS solutions over one or more days/orbits and to extract the definitive GEONS state vectors and root-variances that are used to generate the definitive products provided to the MMS science community.

The MOC front-end system extracts telemetry data from the play-back telemetry packets and stores it in the telemetry archive where it is available for retrieval. Following the end of each scheduled playback contact, the FDOA requests playback telemetry for the time span of each definitive product, i.e. from perigee – 5min to perigee + 5 min in Phase 1. When the requested telemetry data files are available, the MOC sends a message to the FDOA indicating that the products are available. Figure 5 illustrates this operation as well as the associated QA and Definitive Product Generation operations:

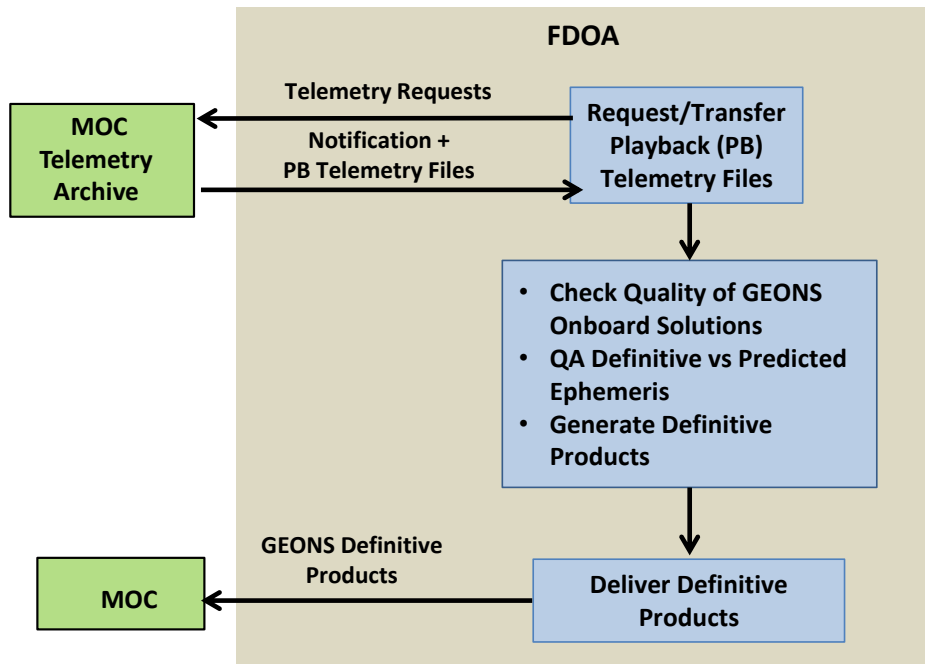


Figure 5. Navigator/GEONS Play-Back Processing Operations

Initiation of the Navigator/GEONS Playback (PB) Telemetry Processing is triggered by the availability of these files. The GEONS PB telemetry processing consists of telemetry checks against expected values for nominal performance. The PB telemetry processing tools generate text summaries of the values for a number of key telemetry values and associated plot files used to identify and analyze non-nominal performance.

5. MMS GEONS Ground Support System

The MMS FDOA includes the systems and tools that support definitive and predictive orbit and time product generation, spacecraft maneuver support, conjunction assessment, and attitude ground operations. Figure 6 provides an overview of the MOC/FDOA Ground System architecture and associated interfaces. The FDOA consists of the Flight Dynamics Ground Support System (FDGSS) and the Attitude Ground System (AGS). In addition, the FDOA hosts the Constellation High-Fidelity (CHiFi) system, which provides a high-fidelity simulation of the onboard attitude control system.

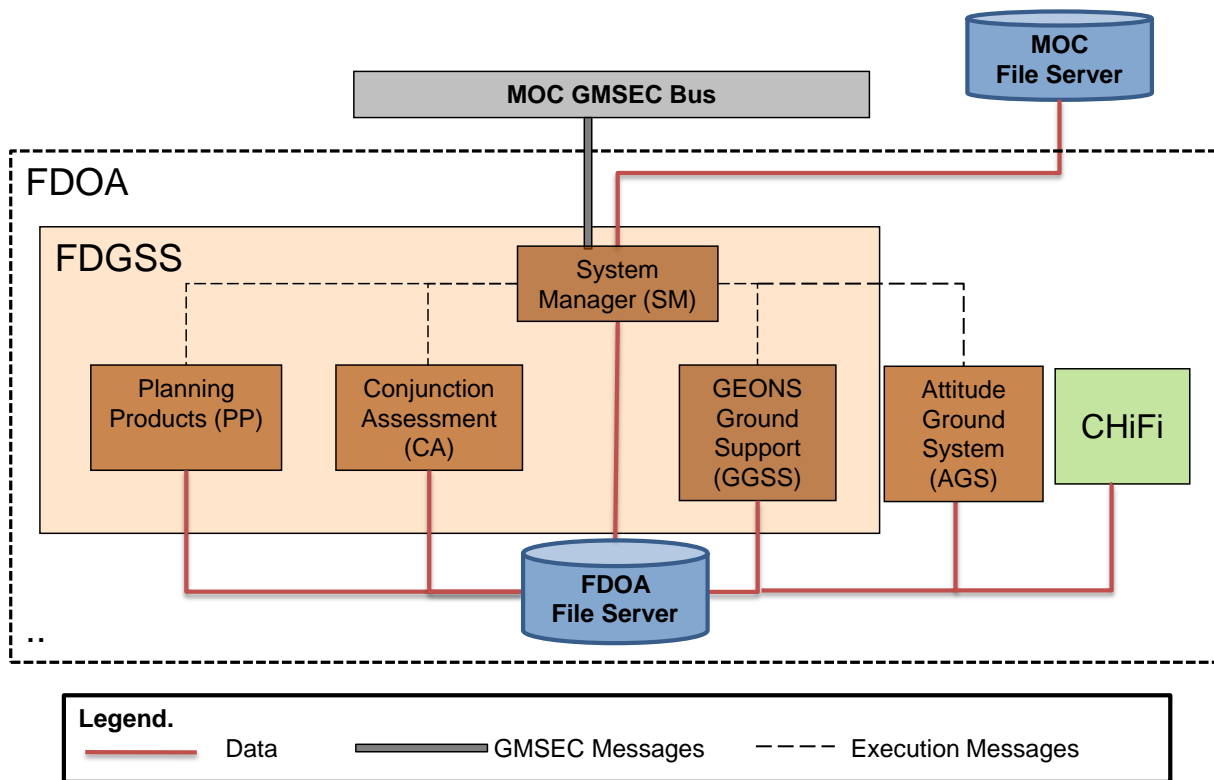


Figure 6. MMS FDOA High-Level Architecture

The following are the primary activities supported by the FDGSS:

- Definitive orbit and time product generation
- Navigator/GEONS command generation and performance checkout, calibration, and analysis
- Predicted orbit-related product generation
- Station contact prediction and acquisition data generation
- Perigee- and apogee-raising maneuver planning, reconstruction, and calibration

- Tetrahedron formation initialization, resizing, and maintenance maneuver planning, reconstruction, and calibration
- Conjunction assessment analysis and collision avoidance maneuver planning

To significantly reduce the likelihood of operator error and the need for operator involvement in routine operations tasks, the FDOA System Manager component is used to automate scheduling and execution of routine operations tasks for all four spacecraft. System Manager automates schedule-driven and event-driven operational processes running on multiple processors. System Manager supports unattended automated operations for 72 hrs and can initiate execution of all AGS and FDGSS tools including FreeFlyer, Matlab, and Python scripts and Java executables. System Manager makes direct calls to the GGSS tools that support the automated real-time and play-back telemetry operations discussed in Section 4.

GGSS is an extensible ground system software tool developed to support space missions that use GEONS as the onboard navigation system. GGSS was designed to be portable so that it can be installed in other locations without requiring any significant rework. GGSS uses the NetBeans Platform module system as a base, which permits developers to leverage an existing collection of NetBeans plugins. The NetBeans Platform plugin model allows for clean encapsulation of disparate features including both new and existing software tools. GGSS performs a significant amount of data analysis and product generation using a custom Matlab toolbox developed for the MMS mission and also supports tools written in Java, Python and C. GGSS also provides an assortment of wizards developed to reduce manual input and simplify workflows. The platform's support for custom projects and file types simplifies the organization of data.

In addition to the tools that support real-time and play-back telemetry operations, GGSS includes GEONS command generation tools and an extensive set of tools used to checkout and calibrate the onboard navigation system during the commissioning phase and later for performance trending and anomaly investigation. GGSS performance analysis tools are available to perform the following functions:

- Ephemeris Comparison: Calculation of the ephemeris differences and covariance of the differences as a function of time and period-folded plot of the differences as a function of true anomaly, including the mean values and 99% confidence intervals from any of the following sources
 - Predicted ephemeris
 - GEONS onboard estimated solution
 - GEONS ground estimated solution
 - Navigator Single Point Solution
 - FDF ground estimated solution
- Measurement Statistics Analysis:
 - Measurement residual statistics as a function of GPS SV, Navigator channel and GPS antenna
 - Plot of measurement residuals as a function of signal-to-noise ratio
 - Plot of measurement signal-to-noise ratio vs True Anomaly

- Number of GPS SVs acquired versus time and period-folded plot of the number of GPS SVs acquired as a function of mean anomaly, including the mean values and 99% confidence intervals
- USO Stability Analysis: Calculation of Allan and Hadamard overlapping variances for the time bias estimated onboard by GEONS

Because the MMS orbits are highly elliptical, the performance measures vary significantly over each orbit. As a result, simple time series trending is not particularly useful. Therefore, GGSS performs period-folded trending for many of the performance measures and computes the average value and 99% confidence limits for each bin. Initially, the period-folded plots were generated using true anomaly bins but later the trending plots were changed to use mean anomaly bins. In the case of MMS, the true anomaly bins contain many fewer points near perigee than at apogee such that the empirical confidence intervals are not consistently computed across the bins; mean anomaly bins provide more consistent confidence intervals. Figure 6 is an example of the time series and period-folded trending plots for the number of GPS PRs processed by GEONS. Figure 7 is an example of the time series and period-folded trending plots for the component differences in the Velocity (V)/Normal (N)/Binormal (B) frame between the predicted MMS position and the position estimated using Navigator\GEONS.

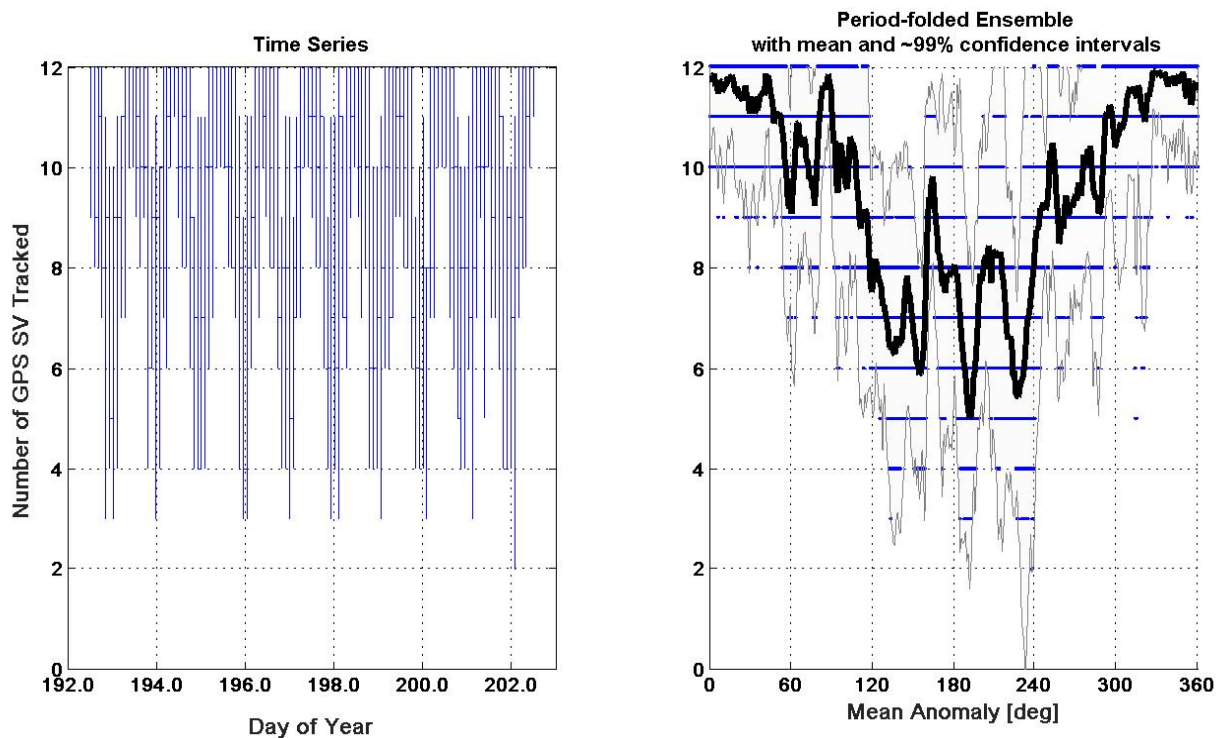


Figure 6. Trending Plots for the Number of GPS PRs Processed in GEONS

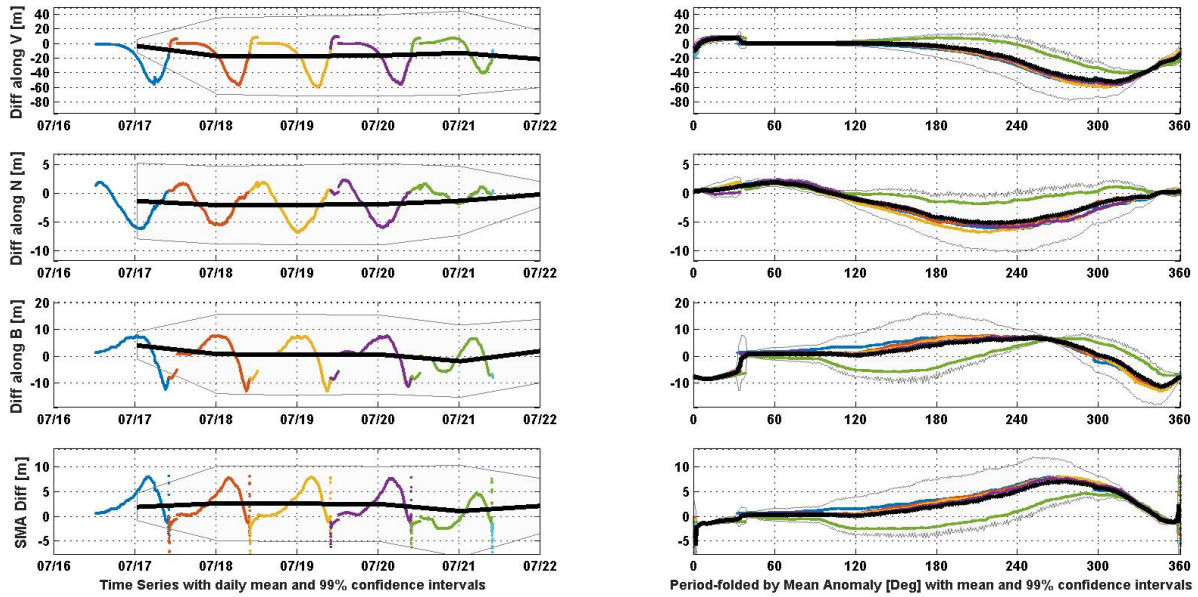


Figure 7. Trending Plots for the Predicted vs Estimated Position Components

6. Conclusions

MMS navigation operations were highly successful during the Phase 0 commissioning phase. Onboard navigation operations proceeded very smoothly from launch, requiring only one reinitialization of the GEONS filter following a series of thruster calibrations that produced higher than anticipated changes to the velocity. The Navigator/GEONS checkout activities confirmed that Navigator/GEONS performance satisfies the associated mission navigation requirements [5].

During the commissioning phase, the ground navigation operations procedures were successively refined, particularly the procedures for automation and performance trending. Automation of the routine navigation operations was increased to the point where manual operation is needed only in the case of data anomalies. The use of period-folding proved to be very useful for analysis of the navigation performance. The GGSS tool set was extended to include period-folding analysis of additional performance indicators, e.g. number of PR measurements processed in GEONS.

The GGSS has proven to be very reliable, easy to use, and to extend to add new capabilities. The GGSS has been installed in the GSFC FDF for evaluation in support of future missions that use GEONS as an onboard navigation system.

7. References

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