GPS Navigation for the Magnetospheric Multi-Scale Mission

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BIOGRAPHY

William Bamford, Jason Mitchell, Michael Southward and Philip Baldwin have ~~managed~~ staffed the GSFC Formation Flying Test Bed for 5 years and have advanced NASA's capabilities for closed-loop, hardware-in-the-loop simulations for missions such as the Magnetospheric Multiscale Mission (MMS)~~MMS~~, the Global Precipitation Measuring Mission (GPM)~~GPM~~, The Geostationary Operational Environment Satellite (GOES)~~-R~~ and Orion.

Luke Winternitz, Gregory Heckler, and Rishi Kurichh have spent more than eight years exploring weak signal GPS culminating in the Navigator GPS receiver. They have also successfully combined their receiver with a crosslink transceiver yielding the IRAS instrument and developed a crosslink channel simulator for testing the IRAS in a lab environment~~GSE~~.

Steve Sirotzky is the primary FPGA designer for the Navigator project, and is currently the hardware lead for the MMS flight GPS receivers.

ABSTRACT

In 2014, NASA is scheduled to launch the Magnetospheric Multiscale Mission (MMS), a four-satellite formation designed to monitor fluctuations in the Earth's magnetosphere. This mission has two planned phases with different orbits (1.2 x 12Re and 1.2 x 25Re) to allow for varying science regions of interest. To minimize ground resources and to mitigate the probability of collisions between formation members, an on-board orbit determination system consisting of a Global Positioning System (GPS) receiver and crosslink transceiver was desired. Candidate sensors would be required to acquire GPS signals both below and above the constellation while spinning at three revolutions-per-minute (RPM) and exchanging state and science information among the constellation. The Intersatellite Ranging and Alarm System (IRAS), developed by Goddard Space Flight Center (GSFC) was selected to meet this challenge. IRAS leverages the eight years of development GSFC has invested in the Navigator GPS receiver and its spacecraft communication expertise, culminating in a sensor capable of absolute and relative navigation as well as intersatellite communication.

The Navigator is a state-of-the-art receiver designed to acquire and track weak GPS signals down to -147dBm. This innovation allows the receiver to track both the main lobe and the much weaker side lobe signals. The Navigator's four antenna inputs and 24 tracking channels, together with customized hardware and software, allow it to seamlessly maintain visibility while rotating. Additionally, an integrated extended Kalman filter provides autonomous, near real-time, absolute state and time estimates. The Navigator made its maiden voyage on the Space Shuttle during the Hubble Servicing Mission, and is scheduled to fly on MMS as well as the Global Precipitation Measurement Mission (GPM). Additionally, Navigator's acquisition engine will be featured in the receiver being developed for the Orion vehicle.

The crosslink transceiver is a ¼ Watt transmitter utilizing a TDMA schedule to distribute a science quality message to all constellation members every ten seconds. Additionally the system generates one-way range measurements between formation members which is used as input to the Kalman filter.

In preparation for the MMS Preliminary Design Review (PDR), the Navigator was required to pass a series of Technology Readiness Level (TRL) tests to earn the necessary TRL-6 classification. The TRL-6 level is achieved by demonstrating a prototype unit in a relevant end-to-end environment. The IRAS unit was able to meet all requirements during the testing phase, and has thus been TRL-6 qualified. ~~This paper describes the series of tests and the receiver's performance.~~

INTRODUCTION

MMS is a Solar Terrestrial Probe (STP) mission designed to study the phenomenon of collisionless magnetic

reconnection and particle acceleration in the electron diffusion regions of the Earth's dayside magnetopause and nightside neutral sheet in the magentotail.[1] To capture these phenomenoan, four identical spinning spacecraft will be inserted into a loose formation which varies from a string-of-pearls at perigee to a tetrahedron at apogee. The two-year mission will include two distinct science collection orbits. The Phase 1 is a 1.2x12Re ellipse with a science Region of Interest (ROI) greater than 9Re, and the Phase 2 orbit, a 1.2x25Re orbit with ROI greater than 15Re. These orbits are depicted in Figure 1.
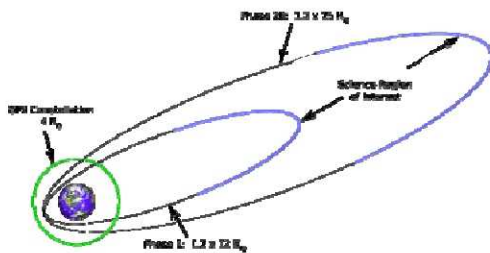

Figure 1: MMS Mission Orbits

IRAS

To reduce the scheduling burden and cost of ground operations, an autonomous, on-board, orbit determination (OD) platform was proposed. This sensor, known as the Intersatellite Ranging and Alarm System (IRAS), consisted of a GPS receiver, the GSFC Navigator, combined with an integrated crosslink transceiver. GPS pseudorange measurements were to be combined, using an onboard Kalman filter, with range and Doppler measurements from the crosslink communication system

The resulting state estimates were to be passed down to the ground for maneuver planning and conjunction analysis. Additionally, the intersatellite communication system provided a science quality message, which was a convenient way of synchronizing data collection modes between the spacecraft.

Navigator

The Navigator, a space-borne GPS receiver, developed and built at NASA's Goddard Space Flight Center (GSFC), is optimized for fast signal acquisition and weak signal tracking.[2,3] The fast acquisition capabilities provide exceptional Time To First Fix (TTFF) performance with no a-priori receiver state, time, or GPS almanac information. Additionally, it allows the receiver to rapidly acquire/reacquire GPS satellites after signal outages or blockages. This highly parallelized acquisition engine reduces Navigator's acquisition threshold from -137dBm, standard for traditional space-borne receivers, to -147dBm. The increased sensitivity results in significantly better GPS observability at High Earth Orbits (HEO) than would be possible using a conventional GPS receiver. The four coherent Radio Frequency (RF) front ends coupled with the 24 available tracking channels allow for continuous acquisition and tracking, even of weak signals, at the three revolutions per minute (RPM) satellite spin rate. For MMS, Navigator also utilizes the Goddard Enhanced Onboard Navigation System (GEONS)[4] extended Kalman filter to process the GPS pseudorange and crosslink range measurements.
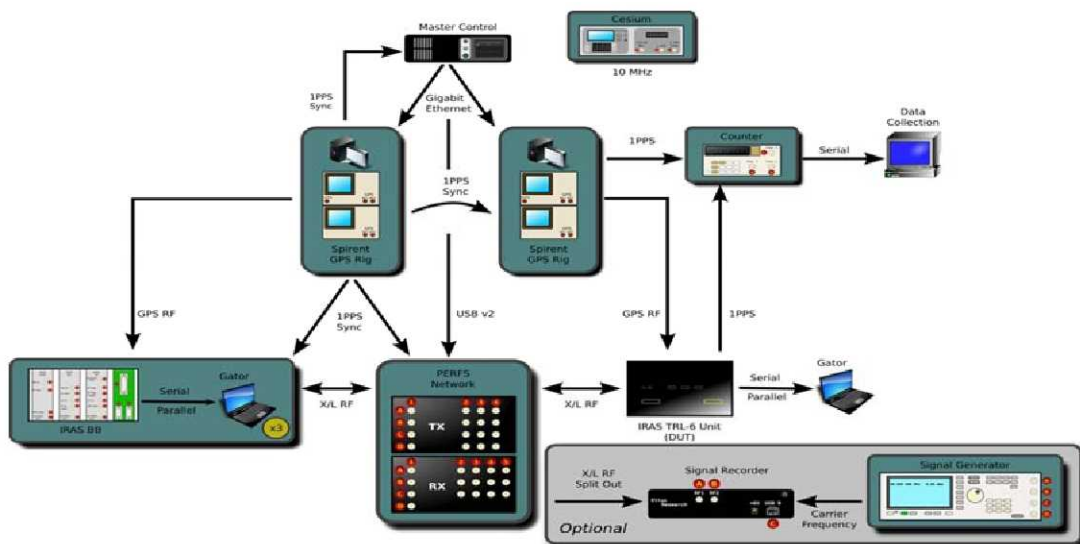

Figure 2: FFTB Laboratory Setup

The filter will provide near-real time estimates of the absolute state of the local vehicle and the relative states of ~~the remainder of the constellation.~~the other MMS satellites

Transceiver

To enable intersatellite communication the Navigator GPS receiver was augmented with an S-band communication transceiver, with two transmit and four receive antennas. The communications were based upon a TDMA schedule that guaranteed the complete circulation of the science quality message every ten seconds. Additionally, the range measurements generated via the transceiver and local clock estimates were circulated to the other members of the formation. This remote data was to be used in conjunction with local ranges to develop a pseudo two-way range estimate for filtering. This range was generated by combining two one-way ranges that were taken at slightly different times. To ensure message validity, the communication link utilized rate ½ convolutional encoding for forward error control (FEC).

This paper details the TRL-6 testing of the Navigator receiver including the laboratory setup, target requirements, and the final results of the TRL-6 tests.

MMS MISSION REQUIREMENTS

An extensive series of off-line Monte Carlo analyses were performed to determine the necessary characteristics of a navigation sensor to meet the MMS mission requirements. The performance requirements analyzed during the TRL-6 testing are summarized below:

- The definitive RSS absolute position error must not exceed 100km with 99% probability.
- While in the ROI, the definitive RSS relative position between any two MMS spacecraft shall not exceed the maximum of 1% of their scalar separations or 100m, with 99% probability
- The root sum squared (RSS) relative position error growth rate of the 7 day predictive orbit shall not exceed 200m/day with 99% probability.
- Pseudorange measurement precision shall not exceed 6m and 30m (3σ) for strong (greater than -129dBm) and weak signals (less than -129dBm) respectively.
- The receiver must acquire all in-view weak signals within 120 seconds when orbit knowledge is available.
- The receiver must acquire all in-view strong signals within 600 seconds when orbit knowledge is not available.
- The receiver must acquire and track all visible GPS signals with an incident signal power of -141dBm or higher.
- The receiver must maintain knowledge of GPS time to within 100 microseconds.

- Crosslink measurement precision shall not exceed 30m or 0.1% (3σ) of the intersatellite range when this range is less than 640km.
- Crosslink measurement precision shall not exceed 0.5% (3σ) of the intersatellite range when this range is between 640 and 1800km.
- Crosslink measurement precision shall not exceed 1% (3σ) of the intersatellite range when this range is greater than 1800km.

LABORATORY SETUP

As part of the risk-reduction strategy, the IRAS design was required to achieve a TRL level of 6 prior to the mission's Preliminary Design Review (PDR). TRL-6 classification is earned by demonstrating a prototype unit in a relevant end-to-end environment. The testing was carried out in NASA's Formation Flying Testbed (FFTB)[5] which serves as the requisite end-to-end relevant environment defined by the TRL-6 guidelines. The FFTB is a Guidance, Navigation, and Control (GN&C) laboratory with the capability of performing high fidelity, open and closed loop, hardware-in-the-loop simulations. The general lab setup, as depicted in Figure 2 consists of four main components: GPS simulators, Master Control Program (MCP), the crosslink RF simulators, and the IRAS units.

IRAS Hardware

To fully simulate the MMS constellation, four IRAS units were provided to the FFTB. Three of the boards were breadboard level designs using Xilinx reprogrammable Field Programmable Gate Arrays (FPGA) in place of the fuse-based Actels used on the Engineering Test Unit (ETU) and flight designs. The breadboard RF front-ends were limited to one each for the GPS receiver and the transceiver transmit and receive chains, each constructed from discrete connectorized components. These boards, initially utilized to earn the TRL-5 rating for the IRAS system, were a quicker, less expensive alternative to building four ETUs. The fourth unit was a form, fit, and function box much closer to the flight design and utilizing mainly flight components. All of the TRL-6 requirements had to be met with the data from this box, and thus it was designated the Device Under Test (DUT). Unlike the TRL-5 boxes, the DUT featured four GPS receive RF chains which allowed for the verification of the antenna switching algorithms during vehicle spinning, two crosslink transmit chains and four crosslink receive chains. The DUT is shown in Figure 3.

GPS Signal Generators

The MMS TRL-6 testing utilized four Spirent 4760 GPS Signal Generators to provide sufficient RF pathways to the units under test. This included four RF inputs to the DUT to simulate spinning and one each to the three TRL-5 boards. The Spirent simulator scenario characterization parameters were selected as follows:

Figure 3: IRAS DUT

- The GPS transmit gain pattern was based on an averaged Block II/IIA L1 reference gain pattern.[6]
- The GPS receive pattern was based on a 4dB peak gain hemispherical reference pattern with a 3dB roll off at 60 degrees from the boresight. These models are functionally identical to the antennas being manufactured for the mission.
- The Spirent "global gain" setting was set to 8dB to compensate for a 4dB peak gain antenna model, +3dB for a *typical* minimum GPS signal strength of -157dBW at the surface of the Earth (Spirent is referenced to -160dBW), +0.5dB for assumed atmospheric losses not applicable to space users, and +0.5dB to account for losses in connectors between the Spirent output port and the Low Noise Amplifier (LNA).
- Since the Spirent ionospheric delay model is not able to realistically simulate ionospheric effects when the receiver is above the constellation, this model was disabled during testing.
- No intentional GPS clock or ephemeris errors were introduced in this testing.
- The effects of multipath and partial blockage of the GPS receive antennas by the MMS spacecraft were not modeled in this study.

PERFS Crosslink Simulator System

The Path Emulator for RF Systems (PERFS)[7] was created by GSFC for hardware-in-the-loop testing of RF communication and ranging systems. PERFS simulates the effects of relative range, velocity, and attenuation by accurately emulating the dynamic environment through which the RF signals travel. Dynamic environments include effects of the medium, moving platforms, and radiated power. PERFS consists of a software client and one or more hardware units. Each hardware unit emulates a symmetrical bi-directional path based on the real-time delay, relative motion, and attenuation inputs provided by the software client. PERFS can simulate interspacecraft ranges between .2 and 4,000km, Dopplers which span ± 50MHz, and has 63 dB of dynamic range adjustable in 0.5dB steps [8,9,10]. A total of six PERFS units were required for simulating the pairwise RF crosslink paths between the four IRAS boxes under test.

Master Control Program

The initial challenge to the FFTB was to set up a laboratory environment that could sustain real-time hardware-in-the-loop simulations for at least 16 days. This included time synchronization and data distribution to four Spirent simulators and the six PERFS units. The requisite data had to be distributed at 10Hz to each simulation box to prevent discontinuities amongst the hardware. The Master Control Program (MCP) was created to handle the synchronization of the simulation environment, the distribution of the required state information (over USB and UDP), and the monitoring/logging of critical simulation data. Additionally, the MCP was tasked to emulate sensors found on the spacecraft, providing acceleration and attitude information to all IRAS units under testing.

TRL-6 TESTING

~~The TRL-6 test suite consisted of six tests designed to demonstrate the requirements detailed above.[11] Four tests verified the correct operation of the IRAS DUT at a fundamental level, while the last two tests demonstrated its performance in representative MMS orbits.~~

The TRL-6 test suite originally consisted of five tests designed to demonstrate the requirements detailed above.[11] The tests were ordered in such a way as to verify low level performance before exercising the entire system. Specifically the sequence of tests originally planned were

1. GPS pseudorange measurement precision.
2. GPS acquisition and tracking threshold verification
3. PPS accuracy
4. Crosslink measurement precision
5. Full system test in a Phase I orbit

Beyond testing the technology, the IRAS TRL6 test suite was intended to serve as a means to verify the baseline requirements and, if necessary, provide guidance on how to adjust to those requirements. Upon completion of Test 4, the crosslink measurement precision test, it was determined that the favorable performance of the Navigator receiver, coupled with an improvement to the

science data storage design, meant that the critical science objectives could all be met without the crosslink capability. Accordingly the crosslink was removed from the IRAS system design and the TRL6 test plan was adapted to deal with this change. Specifically one additional test (Test 6) was added to test the entire system (now consisting of the four spacecraft with GPS-only IRAS systems) in a Phase II orbit. This phase of the mission includes long GPS outages that make meeting relative navigation requirements without the crosslink somewhat more challenging. This~~e~~ modification to the IRAS sensor ~~also removed the capability of each satellite to perform relative navigation among the other three formation satellites~~eliminated the ability to autonomously share state information between the spacecraft, thus the relative navigation problem became purely a ~~. This task then became a~~ ground station function: absolute state estimates from each spacecraft are sent down to the ground where relative states are then estimated. ~~via telemetered measurement data, and the individual satellites became responsible for absolute state estimation.~~

Measurement Precision Test

The measurement precision test was performed to verify that the IRAS DUT was able to perform comparably to previous versions of the Navigator receiver, and thus satisfy the requirements levied on the measurement noise. To perform this analysis, a procedure developed by Holt[12] was utilized for isolating the noise on the pseudorange measurements. This method, which is depicted in Figure 4, initially differences two pseudorange measurements against their true ranges to determine the range errors. These errors are then differenced to remove all common errors such as clock and geometrical biases. This process is similar to the traditional *double differencing* of GPS measurements. The resulting signal, after rescaling, is the raw pseudorange error generated by the receiver.

In order to generate a relationship between the received signal power and the pseudorange measurement noise, a minor modification was made to the simulation. For the given orbit, all of the in-view satellites were held at a constant received signal power, ensuring that the signal power between any two double-differences would be identical. This process can be continued, varying the power levels for each simulation, until a characterization plot can be constructed. Figure 5 details the measurement noise for the DUT using three different satellite pairs, each with different relative dynamics.

It can be inferred from Figure 5 that the 5m 3σ noise for signals with received power greater than -129dBm and the 28m 3σ noise for signals with received power less than -12dBm are well within the measurement noise requirements. Additionally, the different relative

dynamics between the receiver and the GPS satellites had no appreciable differences on the overall measurement noise.
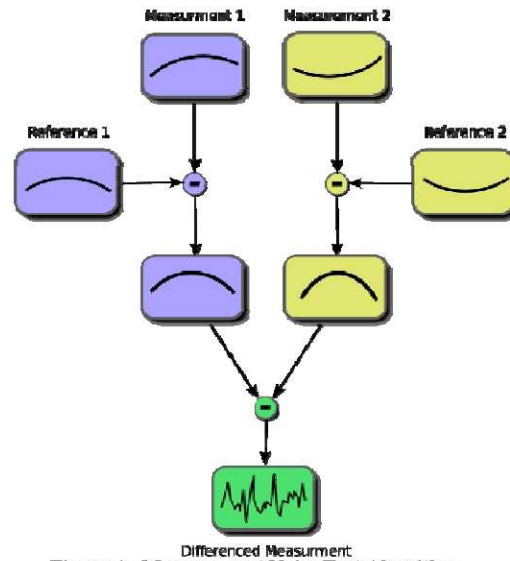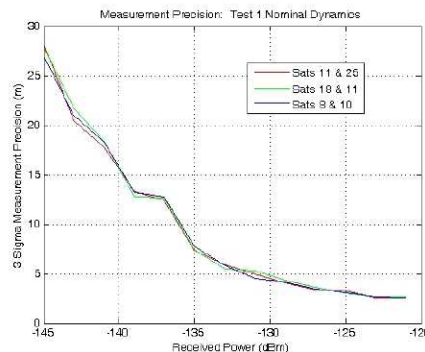

Figure 4: Measurement Noise Test Algorithm

Acquisition and Tracking Threshold

The Navigator receiver has demonstrated the ability to acquire and track satellites with Carrier-to-Noise Ratios (C/N_o) down to -147dB-Hz.[13] The receiver's massively parallel search engine allows it to nominally acquire all visible signals, within five seconds for strong signals and five minutes for weak signals. It was known a-priori that the addition of the antenna swapping algorithm to accommodate the nominal 3 RPM spacecraft spin rate could have a negative effect on the acquisition time, and thus a basic test was implemented to determine if the receiver could meet the required time limits.

Figure 5: Measurement Noise Test Results

Two separate ten minute scenarios were generated to verify both parts of the acquisition requirements. The first test was centered about perigee of a Phase 2 orbit, where the receiver had no a-priori information of its state or time. The time to acquire each of the satellites is documented in Table 1. The second test focused on acquisition with knowledge of the receiver's state, time, and the current GPS almanac. This test also utilized a Phase 2 orbit, but at roughly 6 Re where there is a mix of weak and strong signals. The data for this test is tabulated in Table 2.

The acquisition times detailed in Table 1 show that the receiver was able to acquire all but one of the in-view satellites within the 10 minute window allotted by the requirements. It is worth noting that the majority of the signals were acquired within 2 minutes. For the single missed acquisition, depicted by the red cell, SV 10 was only present for the first 60 seconds of the simulation. Thus after the first failed initial acquisition attempt, there was insufficient time to reacquire before it dropped from view.

In the case where the receiver was provided a-priori information, successful acquisition was only achieved 20% of the time within the required two minute window, and in 23% of the time, the receiver was unable to acquire an in-view SV within 10 minutes. This failure can be explained by examining the amount of time it takes for the receiver to scan the constellation: post test calculations determined that, for weak signals, the time required to search for a given signal on all four antennas is roughly 10 seconds for each 9kHz Doppler bin. So, for example, if the acquisition algorithm is only required to search over two 9kHz bins, it would take roughly 10 minutes to scan the entire constellation once. To meet the requirements, the acquisition algorithm would therefore need to be 100% efficient. In post-test analysis, it was determined that the IRAS, while spinning, had a probability of acquiring a satellite that could be as low as 75%. The net result of this test was to redefine the requirements to reflect the actual performance of the receiver.

The receiver's tracking threshold was determined by slowly reducing the power level of a tracked satellite until the DUT could no longer produce a valid pseudorange measurement. To meet requirements, this level had to be less than -141dBm, as indicated by the red horizontal line in Figure 6. The results, plotted in Figure 6, show demonstrate that 98% of the time the DUT is able to track satellites down to its published spec of -147dBm, which is represented by the horizontal line. This performance demonstrates a 4 6 dB margin over the requirements.

Table 1: Acquisition Times for Run with no A-Priori Knowledge (red squares indicate no acquisition made)

SV	Run 1	Run 2	Run 3	Run 4	Run 5
1	27	181	455	52	19
2	15	20	25	28	19
3	27	20	25	28	19
8	27	20	25	28	19
10	27	45	44	28	
11	27	25	25	28	19
17	27	19	25	28	60
22	27	140	30	38	40
23	27	140	157	28	40
27	27	20	25	38	68
28	143	263	44	149	68
29	143	230	173	38	20

Table 2:   Acquisition Times for Run with A-Priori Knowledge (red squares indicate no acquisition made)

SV	Run 1	Run 2	Run 3	Run 4	Run 5
1		396		365	360
5	33	499			420
7	44	44	25	47	49
9	69	65	46	68	70
13	110	103	81	105	75
14	120	118	96		117
15	130	127	107	140	127
18		156	139	160	
24		236	233	225	
27		184	268	268	290
29		317		198	

The three premature signal drops were caused by large discontinuities in the way the Spirent simulator models the RF signal. The transmit antenna model input file is discretized into 1 degree increments for azimuth and elevation. This, in turn, introduces discontinuities in the broadcast power as the signal crosses these boundaries. For the mean Block IIA antenna, this could yield an instantaneous 3 to 4 dB variation in signal power, as shown in Figure 7. This plot depicts the reported Spirent signal power for a satellite in geostationary orbit. The discontinuous signal power levels can cause loss of tracking, especially if IRAS is performing an antenna handoff under rotational dynamics.
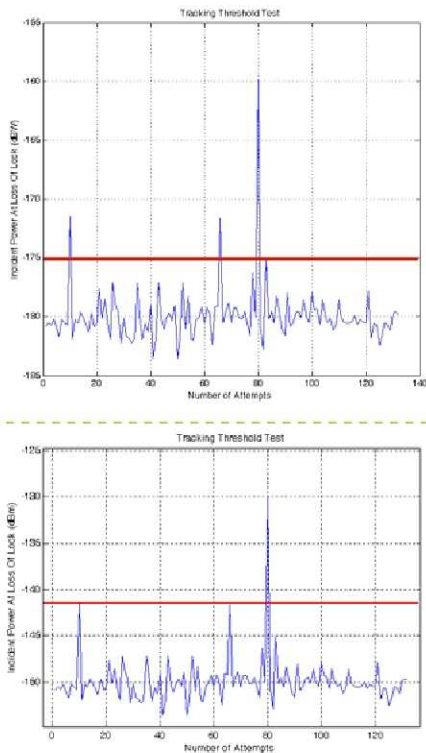
**Figure 6: DUT Tracking Threshold Results**
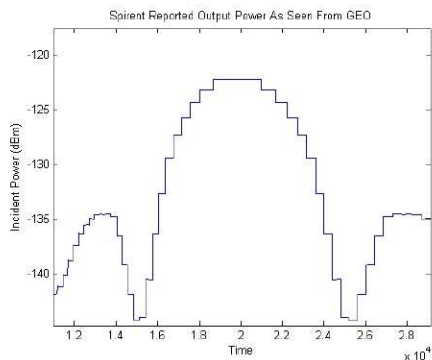
Figure 7: Jumps in the Simulator Reported Output

<u>Pulse-Per-Second Test</u>
The IRAS unit is responsible for providing time synchronization for each of the MMS spacecraft via a pulse-per-second (PPS) signal preceded by a packet defining the time at the pulse. To ensure time coordination amongst all four satellites, this timing structure is required to be accurate to within 100 microseconds at all times. For Phase 2 orbits, therefore, the clock must be modeled sufficiently accurate so that, over the 2.4 days where there are no GPS measurements, absolute time is maintained to within 100 microseconds. Each flight MMS box will have an ultra-stable crystal oscillator (USO) to help maintain stability. Though similar, the USO used in the TRL-6 testing is not the same oscillator that will be used in the flight design. The PPS test utilized a universal counter to difference the time pulses between the 1 PPS signal from the Spirent GPS simulator and the signal from the DUT.

Initial tests using the position, velocity, and time (PVT) deterministic solution generated by the DUT to drive the PPS were inconclusive. It was determined that the noise on the PVT solution was insufficiently accurate to provide a robust and repeatable signal for timing purposes. This is due to the poor geometry and low signal strengths available to the receiver as it is exiting the region of GPS coverage. In a second approach, the time estimate from the GEONS filter was used at the input for the 1 PPS control loop. In this way, the external PPS is kept to within 10ns of the GEONS time estimate. The 1PPS errors during a Phase 2 orbit can be seen in Figure 8. The large spikes are believed to be caused by temperature fluctuations in the lab. These errors are well below the 100 microsecond requirement, and are typically less than 30 microseconds.
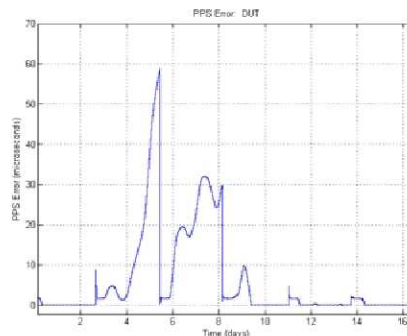
Figure 8: PPS Testing Errors

<u>Crosslink Measurement Precision Test</u>
As an analog to the GPS measurement precision test, the crosslink range measurement precision was also tested. The test was broken into two subtests: step tests and harmonic tests. The step tests, performed in Near Mode (satellite ranges less than 640km), Intermediate Mode (satellite ranges between 640 and 1800km) and Far Mode (satellite ranges greater than 1800km), held the satellite ranges fixed for several minutes before stepping to the next range. The harmonic tests, which stressed the

IRAS's ability to automatically transition between each of the modes and track at high signal dynamics, had ranges which oscillated back and forth over the near-intermediate mode boundaries and the intermediate-far boundaries. The measurement errors were generated by differencing the measured range from the true range simulated by the PERFS unit at each time epoch. The near mode step test and the intermediate-far mode harmonic test results are plotted in Figures 9 and 10. The results of the test are listed in Table 3.
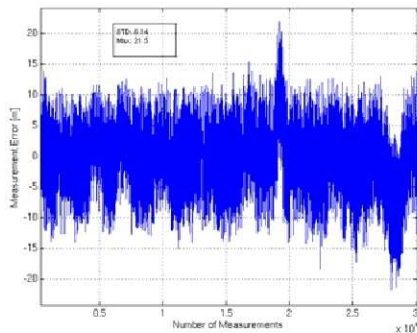

Figure 9: Crosslink Step Test Through Near Mode
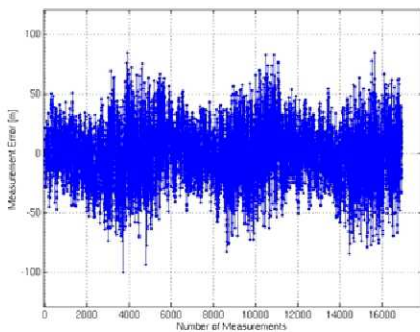
Figure 10: Harmonic Test Between Near and Far Mode

Table 3: Crosslink Measurement Precision Results

Test	3σ Noise (m)	Requirement
Step: Near	18.4	30
Step: Mid	44.4	3201
Step: Far	67.2	12240
Harmonic Near-Mid	53.4	5761
Harmonic Mid-Far	61.2	23760

The crosslink ranging system performed well and ~~easily~~ meet all the requirements. Thanks to a robust design, the measurement precision did not have a large variation with range. This is particularly evident in the far cases, where the range topped out at 3,500km, but the noise remained well below 70m.

~~Due to budgetary issues, the MMS projected was forced to descope the crosslink transceiver at this point in the testing. The remainder of the testing focused on the IRAS performance with only the GPS receiver. The TRL 6 testing of the transceiver is currently scheduled to be completed later in the year.~~

As discussed in the *TRL-6 Testing* section above, it was at this point that the crosslink transceiver was removed from the IRAS system, leaving ~~the~~ just the GPS functionality. Test 5, the full system test in Phase I orbit was conducted without the crosslink, and Test 6, the full system test in a Phase II orbit was added to the test plan.

Full System Test: Phase 1
With the satisfactory completion of the fundamental receiver tests, the first of the full-system tests were implemented. These tests utilized all three TRL-5 boards using one GPS antenna each. This antenna was created by mathematically fusing the four individual antennas used for the DUT. The test plan called for a six day test which would capture a sufficient number of perigee passages to verify filter convergence and performance. For this test the filter is initialized from the receiver's PVT solution shortly after the acquisition of the first four GPS Satellite Vehicles (SV)s. The truth and filter parameters associated with the full system tests are listed in Table 4.

Table 4: Parameters for the Full System Tests

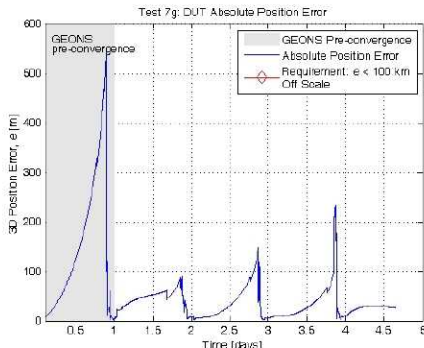| Parameter	Truth	Filter
Gravity Field	50 X 50 JGM2	8 X 8 JGM2
External Gravity	Sun, Moon, Mars, Jupiter	Sun, Moon
Mass	1006 Kg	1006 Kg
SRP Area	2m^2	2m^2
SRP Coefficient	1.4	1.37
Drag Area	2m^2	2m^2
Drag Coefficient	2.2	2.0

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Figure 11: Absolute Position Error for Phase 1

After nearly five days of testing, the simulation was stopped and the data post processed. The results for this test are summarized in Figures 11-13.

The absolute position error of the DUT, plotted in Figure 11, is well below the 100km requirements. The initial spike in the region labeled *GEONS pre-convergence* is well understood from the initial software analysis, and thus ignored. The gradual increase in the absolute error, which could be caused by a dynamical model mismatch between the truth and the filter models, is currently under investigation. In Figure 12, the relative definitive position errors between the DUT and one TRL-5 board are plotted along with the requirements. In Figure 13, the relative predictive error results are plotted with the associated required error. In both cases, the results were well below the MMS requirements.
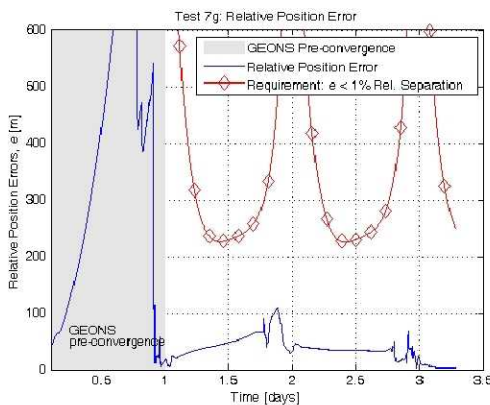

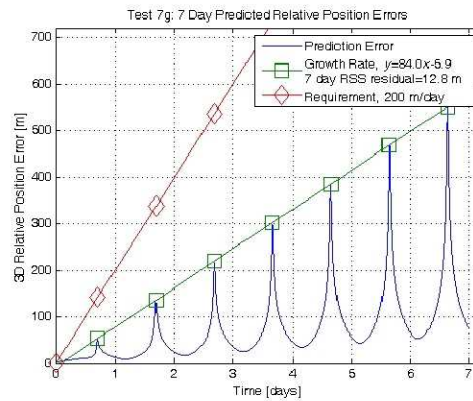**Figure 12: Relative Definitive Position Error for Phase 1**

Figure 13: Relative Predictive Position Errors for Phase 1

Full System Test: Phase 2

The Phase 2 simulation ran for 10 days, ensuring there was enough data for filter convergence. The absolute position errors are plotted in Figure 14, which illustrates that the 100km 3σ was easily met. Figures 15 and 16 show the relative definitive solution between the DUT and two of the TRL-5 boxes. In both cases, the errors are well within the requirement envelopes. Figures 17 and 18 show the relative predictive error growth over a seven day period. One combination of DUT and TRL-5 boxes exhibits a roughly 40m/day error growth, while another approximately 100m/day growth. Both of these results are well within the 200m/day requirement.
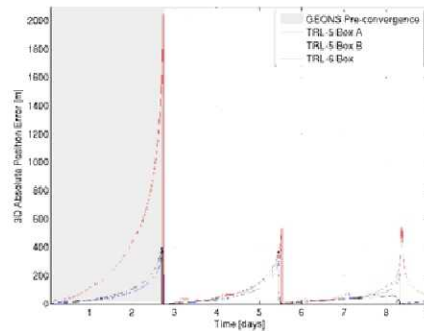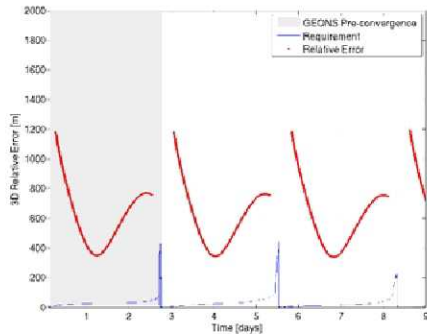

Figure 14: Absolute Position Errors Phase 2
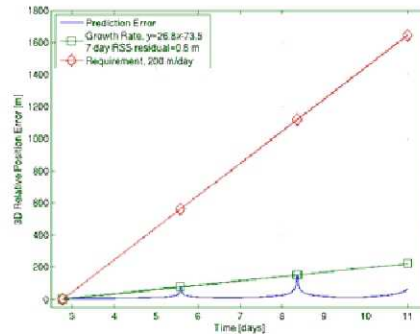
Figure 15: Relative Definitive Errors DUT-TRL-5 Box A Phase 2

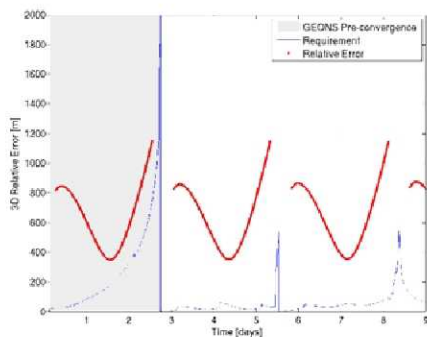**Figure 16: Relative Definitive Errors DUT-TRL-5 Box B for Phase 2**

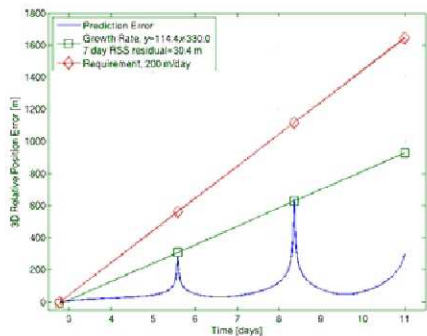**Figure 17: Relative Definitive Errors DUT-TRL-5 Box A Phase 2**

Figure 18: Relative Definitive Errors DUT-TRL-5 Box B Phase 2

FUTURE WORK

With the completion of the TRL-6 testing, the Navigator team is forging forward with the MMS ETU and flight designs. Additionally, the Navigator GPS receiver has been selected as the primary absolute navigation sensor for the upcoming Global Precipitation Mission (GPM) being built at NASA GSFC. As laboratory time becomes available, the full system test for Phase 1 will be re-run with the crosslink transceiver enabled. This final test will earn a TRL-6 rating for the entire system, and provide insight on the OD accuracy gained with the addition of crosslink measurements.

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REFERENCES

1. Gramling, C. "Overview of the Magnetospheric MultiScale Formation Flying Mission", AAS Astrodynamics Specialist Conference, Pittsburgh, PA, August 10-13, 2009

2. Winternitz, L., Moreau, M., Boegner, G., and Sirotzky, S., "Navigator GPS Receiver for Fast Acquisition and Weak Signal Space Applications", Proceedings of the Institute of Navigation GNSS 2004 Conference, September 2004.

3. Winternitz, L, Bamford W., Heckler, G., "A GPS Receiver for High Altitude Navigation", *IEEE Journal of Selected Topics in Signal Processing, Special Issue on Advanced Signal Processing for GNSS and Robust Navigation*, August 2009.

4. Honeywell Technical Solutions, Inc., Mission Operations and Mission Services, MOMS-FD-UG-0208,

Global Positioning System (GPS) Enhanced Onboard Navigation System (GEONS) System Description and Users Guide, Version 2, Release 2.4, prepared by Anne Long, and Dominic Leung, August 31, 2005

5. Mitchell, J., Luquette, R., "Recent Developments in Hardware-in-the-Loop Formation Navigation and Control," 2005 Flight Mechanics Symposium, NASA Goddard Space Flight Center, Greenbelt, MD, October 18-20, 2005.

6. Czopek, F., "Description and Performance of the GPS Block I and II L-Band Antenna and Link Budget," Proceedings of the Institute of Navigation GPS 93 Conference, September 1993.

7. Heckler, G., Kurichh, R., and Boegner, G., "Path Emulator for RF Systems", Proceedings of the Institute of Navigation National Technical Meeting, January 2008.

8. G. Holt, E.G Lightsey, and O. Montenbruck, "Benchmark Testing for Spaceborne Global Positioning Receivers," in AIAA Guidance, Navigation and Control Conference, Austin, TX, 2003

9. Bamford, W., Naasz, B., Moreau, M., "Navigation Performance in High Earth Orbits Using Navigator GPS Receiver", AAS Guidance and Control Conference, February 2006.

10 Mitchell, J., Baldwin, P., Barbee, B., Kurichh, R., Luquette, R., "Characterization of a Radio Frequency Space Environment Path Emulator for Evaluating Spacecraft Ranging Hardware", AIAA Guidance, Navigation, & Control Conference, August, 2008.

11 Heckler, G., Winternitz, L., Bamford, W., "MMS-IRAS TRL-6 Testing", International Technical Meeting of the Satellite Division of the Institute of Navigation, September 2008.

12 Mitchell, J., Barbee, B., Baldwin, P., Luquette, R., "Expanding Hardware-in-the-Loop Formation Navigation and Control with Radio Frequency Crosslink Ranging,", International Symposium on Space Flight Dynamics, September, 2007.

13 Mitchell, J., Baldwin, P., Kurichh, R., Naasz, B., Luquette, R., "Characterization of a Prototype Radio Frequency Space Environment Path Emulator for Evaluating Spacecraft Ranging Hardware," AIAA Guidance, Navigation, & Control Conference, August, 2007.