GPS Navigation above 76,000km for the MMS mission

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Outline

- Background on high altitude GPS
- GSFC Navigator GPS receiver
- GPS Navigation for the MMS mission
  - MMS mission
  - MMS navigation system
  - Performance results from MMS Phase 1
  - Value of sidelobes
  - Predicted performance in MMS Phase 2
- Summary
HEO GPS navigation offers performance and cost improvements, but poses challenges
- Sparse mainlobe availability, sidelobes weak, unspecified/uncharacterized, harsher radiation environment.

Ongoing research in HEO GPS R&D since 1990’s, GSFC among leaders
- Numerous simulations studies, indicate excellent performance at GEO, HEO, lunar distances
- GSFC led effort to define/expand GPS Space Service Volume definition and characterize in-situ patterns (GPS-ACE 2015)
- Developing Navigator HEO GPS receiver

Early on-orbit experiments in late 1990’s-early 2000’s
- AFRL Falcon Gold, TEAMSAT, EQUATOR-S
- NASA GSFC / AMSAT OSCAR-40, 2000

Recent growth in available receivers/applications, e.g.,
- GD Monarch flying on USG SBIRS (GEO) (~2011-2012)
- Surrey Satellite SGR-GEO experiment on GIOVE-A (2013)
- Airbus/Astrium MosiacGNSS and LION GNSS Rx for HEO
- Moog-Broad Reach Navigator (AFRL ANGELS 2015, EAGLE 2017)
- General Dynamics’ Viceroy-4 to fly on GOES-R (2016)
- RUAG Podrix to fly on ESA Proba-3 (2018)
- NASA GSFC Navigator GPS flying on HEO MMS 2015
**Navigator GPS Receiver**

- **Legacy Navigator**
  - C/A code receiver
  - ~10m level onboard accuracy for LEO/GEO/HEO
- **Performance for high altitude applications enabled by**
  - *Fast, unaided* weak signal acq. and tracking (<25 dB-Hz)
  - Integrated on-board navigation filter (GEONS)
  - Radiation hardened
- **Early demonstration on Hubble Space Telescope Servicing Mission 4 STS-125 (May 2009)**
  - Captured unique reflected GPS dataset
- **Global Precipitation Measurement Mission (Feb 2014)**
  - First operational use of Navigator
- **Orion EFT-1 (Dec 2014)**
  - Navigator technology integrated in Honeywell GPS receiver
  - *Fast acquisition of GPS signals* benefits navigation recovery after re-entry radio blackout without relying on IMU, stored states.
- **Magnetospheric Multiscale Mission (March 2015)**
  - *Currently represents the highest (and fastest) GPS receiver operations*
Magnetospheric MultiScale Mission (MMS)

- Discover the fundamental plasma physics process of reconnection in the Earth’s magnetosphere.
- Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 10km
- Flying in two highly elliptic orbits in two mission phases
  - Phase 1 1.2x12 $R_E$ (magnetopause)
  - Phase 2B 1.2x25 $R_E$ (magnetotail)
MMS Navigation

- MMS baselined GSFC Navigator + GEONS Orbit Determination (OD) filter software as sole means of navigation (mid 2000’s)
  - Original design included crosslink, later descoped
- Trade vs. Ground OD (2005)
  - Estimated >$2.4M lifecycle savings over ground-based OD.
  - Enhanced flexibility wrt maneuver support
  - Quicker return to science after maneuvers
- Main challenge #1: Sparse, weak, poorly characterized signal signal environment
  - MMS Navigator acquires and tracks below 25dB-Hz (around -178dBW)
  - GEONS navigation filter runs embedded on the Navigator processor
  - Ultra stable crystal oscillator (Freq. Electronics, Inc.) supports filter propagation
- Main challenge #2: Spacecraft are spin stabilized at 3RPM with obstructions on top and bottom of spacecraft
  - Four GPS antennas with independent front end electronics placed around perimeter achieve full sky coverage with low noise
  - Receiver designed to hand off from one antenna to next every 5s
GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends
Goddard’s Enhanced Onboard Navigation System (GEONS)

- **UD-factorized Extended Kalman Filter, 4th/8th order RK integrator, realistic process noise models**
- **Estimation state:** Absolute and/or relative position and velocity vectors for multiple satellites, clock states, drag and SRP coeff corrections, measurement biases
- **Dynamic models:** High fidelity geopotential, solar system bodies, Harris-Priester atmospheric density, SRP with spherical or multi-plate area models, measured accelerations, impulsive delta-V maneuver model
- **Measurement types:** GPS differenced/undifferenced, WAAS, differential corrections, TDRSS, Ground station, Crosslink, Celestial object line of sight, XNAV
- **Development history**
  - Ground-based experiments on Landsats 4 & 5, COBE (1980s) onboard exp. EUVE (1990s)
  - TDRSS Onboard Navigation System (TONS): operational onboard OD for Terra 1999-current
  - Enhanced Onboard Navigation System (EONS) = TONS + GS meas on GD Command Receiver
  - Celnav tested on the ground with POLAR and SOHO data
  - TONS -> GPS for GPS Enhanced Orbit Determination Experiment (GEODE) on Lewis (1996), follow on EO-1 and licensed to industry flown on Microstars, Orbvies, SORCE, CALIPSO ++
  - XNAV measurement model added for NICER/SEXTANT demonstration (2016 launch)
  - GEONS = GEODE + EONS + Celnav + XNAV
- **MMS GEONS**
  - Estimate absolute pos/vel, clock bias, rate & accel, integrator step 10s
  - 13x13 geopotential, sun, moon point mass, SRP, drag
  - Process L1 C/A GPS undifferenced pseudorange at 30s rate
  - Accelerometer data at 10s during maneuver
Phase 1 Performance: signal tracking

- Once powered, receiver began acquiring weak signals and forming point solutions
- Long term trend shows average of >8 signals tracked above 8R_E
- Above GPS constellation, vast majority of these are sidelobe signals
- Visibility exceeded preflight expectations

Signals tracked during first few orbits

Signal to noise vs. time

Average Number of Satellites Tracked With Radius > 8 Re

Number of Tracked Satellites
Phase 1 results: measurement and navigation performance

- GEONS filter RSS 1-sigma formal errors reach maximum of 12m and 3mm/s (typically <1mm/s)
- Although geometry becomes seriously degraded at apogee, point solutions almost continuously available
- Measurement residuals are zero mean, of expected variation. Suggests sidelobe measurements are of high quality.

![Diagram of measurement results]

**day of year 2015**
• Certification campaign from day of year 133 to 137: no maneuvers, increased TDRSS and DSN measurement schedule
• GSFC Flight Dynamics Facility performed independent OD using TDRSS/DSN radiometrics
• Plot shows MMS1 orbit difference and 3-sigma total variance along with component variance fractions.
  - FDF is, by far, largest contributor to total variance.

MMS requirements: 100km absolute position accuracy (needed for science)
• 50m (99%) SMA knowledge above 3Re and outside maneuver recovery (for formation maintenance)

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<thead>
<tr>
<th>FDF V02</th>
<th>MMS1</th>
<th>MMS2</th>
<th>MMS3</th>
<th>MMS4</th>
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<tr>
<td>Maximum Difference in RSS Position</td>
<td>65 m</td>
<td>50 m</td>
<td>50 m</td>
<td>25 m</td>
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<tr>
<td>SMA Difference (Max of 99% CI Above 3 RE)</td>
<td>&lt; 4 m</td>
<td>&lt; 5 m</td>
<td>&lt; 6 m</td>
<td>&lt; 4 m</td>
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Simulation study looked at reprocessing flight measurements from MMS Phase 1 through Navigator FSW (w/GEONS) on ground, compared:
- Processing all data (matching on-orbit results) in blue
- Removed signals below 38dB-Hz simulating removal of side-lobes in red

Dataset includes early sequence of four perigee raising maneuvers
- Process noise inflated during maneuver window, accelerometer data passed to GEONS

Sidelobes significantly improve initial convergence, peak errors at apogee and maneuver recovery
It has become apparent that the MMS preflight simulations had significant conservatism built in.

Recalibrated MMS Phase 2B hardware-in-the-loop simulations conducted in GPS test lab (FFTB) with MMS EM show improved performance.
Summary, Future Work

- High altitude GPS is now a proven technology that can reduce operations costs and even enable missions like MMS.
  - Applications and receiver availability expanding rapidly
- MMS currently in Phase 1 orbit at 12Re (almost twice GEO distance) navigating onboard with GPS using GSFC-Navigator receiver with GEONS filter software
  - Highest (and fastest) operational use of GPS
  - Onboard navigation significantly exceeding requirements
  - Signal visibility throughout Phase 1 orbit is excellent
  - Sidelobe signals are of “navigation quality”
  - Promising for MMS Phase 2B with 25Re apogee, and future mission

- GSFC continues to conduct high-altitude GPS R&D
  - Next Generation Navigator in development
    - Modernized, Multi-frequency, multi-GNSS, reduced SWaP
    - Real-time navigation at GEO in “bent-pipe” mode for GPS-ACE project (2014)
    - First on-orbit use for TASS (TDRSS beacon) demonstration on STP-H6 (2018)
  - Leading efforts to protect and characterize GPS signals for high-altitude users
  - Maintains world-class test facility and expertise