An Introduction to High-Altitude Space Use of GNSS (For Timing People)

Mr. Joel J. K. Parker
PNT Policy Lead, NASA Goddard Spaceflight Center
joel.j.k.parker@nasa.gov

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Space Uses of Global Navigation Satellite Systems (GNSS)

- **Real-time On-Board Navigation**: Precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing

- **Earth Sciences**: GNSS as a measurement for atmospheric and ionospheric sciences, geodesy, and geodynamics

- **Launch Vehicle Range Operations**: Automated launch vehicle flight termination; providing safety net during launch failures & enabling higher cadence launch facility use

- **Attitude Determination**: Some missions, such as the International Space Station (ISS) are equipped to use GPS/GNSS to meet their attitude determination requirements

- **Time Synchronization**: Support precise time-tagging of science observations and synchronization of on-board clocks
Reception of High-Altitude GNSS Signals

- **Terrestrial Service Volume (TSV):**
  - altitude ≤3,000 km
  - Covers terrestrial and low Earth orbit (LEO) users

- **Space Service Volume (SSV):**
  - **Lower SSV:** altitude 3,000–8,000 km
  - **Upper SSV:** altitude 8,000–36,000 km
  - Covers users near to and above GNSS constellations

- Signal coverage in the Upper SSV is achieved primarily via:
  - GNSS main lobe “spillover” signals
  - GNSS side lobe signals (not shown)
# Operational Challenges

<table>
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<tr>
<th>Regime</th>
<th>Altitude Range (km)</th>
<th>Challenges &amp; Observations (Compared to previous scenario)</th>
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<tr>
<td><strong>Terrestrial Service Volume</strong></td>
<td>≤3,000</td>
<td>Acquisition &amp; Tracking: Higher Doppler, faster signal rise/set; accurate ephemeris upload required; signal strength &amp; availability comparable to Earth use</td>
<td>Development of space receivers; fast acquisition algorithm eliminates ephemeris upload</td>
<td>Extensive Operational use</td>
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<tr>
<td><strong>Lower SSV</strong></td>
<td>3,000–8,000</td>
<td>More GPS/GNSS signals available; highest observed Doppler (HEO spacecraft)</td>
<td>Max signals require omni antennas; receiver algorithms must track higher Doppler</td>
<td>Operational (US &amp; foreign)</td>
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<tr>
<td><strong>Upper SSV</strong></td>
<td>8,000–36,000</td>
<td>Earth obscuration significantly reduces main lobe signal availability; frequent ops w/ &lt;4 signals; periods of no signals; weak signal strength due to long signal paths</td>
<td>Navigation filter/fusion algorithms (e.g. GEONS) enable nav w/ &lt;4 signals and flywheeling through outages; use of signal side lobes and/or other GNSS constellations; higher gained antennas, weak signal receivers</td>
<td>Operational (US &amp; foreign)</td>
</tr>
<tr>
<td><strong>Beyond the SSV</strong></td>
<td>36,000–360,000+</td>
<td>Even weaker signals &amp; worse signal geometry</td>
<td>Use higher gain, small footprint antenna; accept geometric performance degradation or augment with signals of opportunity to improve</td>
<td>Operational to 150,000 km (MMS), Orion Lunar perf. experiment</td>
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A History of High-Altitude GPS Users

- **1990s**: Early flight experiments demonstrated basic feasibility – *Equator-S, Falcon Gold*
- **2000**: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- **2001**: *AMSAT OSCAR-40* mapped GPS main and sidelobe signals (Davis et al. 2001)
- **2015**: *MMS* employed GPS operationally at 76,000 km (since raised to 150,000 km)
- **2016**: *GOES-16* employed GPS operationally at GEO
The Promise of using GNSS in the Space Service Volume

• GPS timing reduces need for expensive on-board clocks (from: $100sK-1M to: $15K–50K)
• Significantly improves real-time navigation performance (from: km-class to: meter-class)
• Supports quick trajectory maneuver recovery (from: 5-10 hours to: minutes)
• Supports increased satellite autonomy, lowering mission operations costs (savings up to $500-750K/year)
• Enables new/enhanced capabilities and better performance for High Earth Orbit (HEO) and Geosynchronous Orbit (GEO) missions, including:

- Earth Weather Prediction using Advanced Weather Satellites
- Space Weather Observations
- Launch Vehicle Upper Stages & Beyond-GEO applications
- Formation Flying, Space Situational Awareness (SSA), Proximity Operations
- Precise Relative Positioning
- Precise Position Knowledge & Control at GEO
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

Magnetospheric Multi-Scale (MMS)
- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - **Phase 1**: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - **Phase 2**: Extends apogee to 25 Re (~150,000 km) (40% of way to Moon!)

MMS Navigator GPS System
- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set Guinness world record for the highest-ever reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h
MMS Navigation & Clock

- MMS baselined Goddard’s high-altitude Navigator GPS receiver + GEONS Orbit Determination (OD) filter software as sole means of navigation (mid 2000’s)
  - Original design included crosslink, later descoped
  - In order to meet requirements without crosslink, a USO would be needed.
- **Main challenge:** 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.) is a key component that supports filter propagation
  - **USO was specified to meet 100µs holdover over 65 hours under all environmental conditions**
    - Eventually the timing requirement was relaxed to 325us due to spare margin.
- Specific requirements were developed based on a simulation of the ability of the GEONS filter to estimate the USO behavior, and resulted in around a **5e-11 stability requirement (at 65hrs)** over all enveloping environmental conditions.
MMS Navigator GPS hardware

GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends
On-orbit Phase 1 results: Clock Performance

- Filter is able to estimate clock bias to within 15m (or about 50ns)
- Rapid clock reconvergence after maneuvers

- Filter is able to estimate clock rate to within 4mm/s or about $1 \times 10^{-11}$ fractional frequency
- Precise estimation across all oscillators
On-orbit Phase 2B results: signal tracking

- Consider 8-day period early in Phase 2B (150k km apogee)
- Above GPS constellation, majority of signals are sidelobes
- Long term trend shows average of ~3 signals tracked near apogee, with up to 8 observed.
  - Cumulative outage over sample orbit: 0.5% (22 min over 67-hour orbit); average duration: 2.8 min
- Visibility exceeds preflight expectations significantly
On-orbit Phase 2B results: measurement/nav performance

- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- As apogee increases, range and clock errors become highly correlated; seen in pos/clock covariances below
  - 50m corresponds to 167ns clock bias

Measurement residuals (above) are zero mean, of expected variation <10m 1-sigma. Suggests sidelobe measurements are of high quality.
MMS study: Concept Lunar mission

- Study: How will MMS receiver perform if used on a conceptual Lunar mission with 14dBi high-gain antenna?
- Concept lunar trajectory similar to EM-1: LEO -> translunar -> Lunar (libration) orbit -> return
- GPS measurements simulated & processed using GEONS filter.
- Visibility similar to MMS2B, as high-gain makes up for additional path loss
  - Avg visibility: ~3 SVs; C/N0 peaks > 40dB-Hz (main lobes) or > 30 dB-Hz (side lobes)
- Range/clock-bias errors dominate – order of 1-2 km (3–7 µs); lateral errors 100-200 m
  - With atomic clock, or, e.g., periodic 2-way range/Doppler, could decorrelate and reduce range errors to meas. noise level
  - Additional (independent) measurement source breaks range/clock bias ambiguity

*Top: Signals tracked and radial dist to Earth (red) and Moon (cyan); Bottom: C/N₀*
Next Steps: Multi-GNSS

- Multi-GNSS usage at high altitude promises to widely expand the availability of GNSS signals for navigation and timing.
- Efforts through the UN International Committee on GNSS (ICG) seek to establish and develop the combined Multi-GNSS SSV.
- Efforts underway include:
  - **SSV Booklet Development**
    - Documents and publishes SSV performance metrics for each individual constellation
    - Includes internationally coordinated SSV analyses and simulations
    - Communicates assumptions & analysis results
    - Supports international space user characterization of PNT performance in SSV
    - Booklet final draft distributed to ICG and providers for final approval; planned publication: Nov 2018
  - **Companion SSV Outreach Video** being produced by NASA on behalf of ICG
  - **Coordinated Outreach Initiative** to communicate capabilities of SSV to future SSV users
  - **ICG-approved Recommendation** to examine use of GNSS SSV for exploration activities in cis-Lunar space
Conclusions

• High-altitude space use of GNSS is an emerging operational capability
  • Latest operational examples include: GOES-16, MMS
  • Applications extend both to navigation and timing

• Signal availability is key to both timing and navigation; nearly-continuous availability of signals enables benefits for time synchronization, clock bias estimation, maneuver recovery, etc.

• MMS on-orbit performance exceeds requirements and expectations; predictions show that good performance may be extendable to lunar distance.
  • Breaking the range & clock bias ambiguity will be key to increased performance at increasingly high altitudes
  • High-quality clock OR periodic independent range measurement are potential solutions

• Future performance increases will be achieved via advanced receivers and the move to multi-GNSS. This is enabled by work via the UN International Committee on GNSS (ICG).

• For more:
  • Attend “The Navigation of Satellites” session, Thursday PM at ION GNSS+
  • See References, next chart
References

- **MMS**

- **GOES-16**

- **General**
U.S. Initiatives & Contributions to Develop & Grow a High-Altitude GNSS Capability for Space Users

### Operational Users
- MMS
- GOES-R, S, T, U
- EM-1 (Lunar enroute)
- Satellite Servicing

### Space Flight Experiments
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)

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**Operational Use Demonstrates Future Need**

**SSV Receivers, Software & Algorithms**
- GEONS (SW)
- GSFC Navigator
- General Dynamics
- Navigator commercial variants (Moog, Honeywell)

**Develop & Nurture Robust GNSS Pipeline**

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**SSV Policy & Specifications**
- SSV definition (GPS IIF)
- SSV specification (GPS III)
- ICG Multi-GNSS SSV common definitions & analyses

**Operational Guarantees Through Definition & Specification**

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**Breakthroughs in Understanding; Supports Policy Changes; Enables Operational Missions**
The Promise of using GNSS beyond the Space Service Volume

- **GPS timing reduces need for expensive on-board clocks** (from: $100sK-1M to: $15K–50K)
- **Supports real-time navigation performance** (from: no real time to: km or ten meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- **Near-continuous navigation signals reduces DSN navigation support**
- **Increased satellite autonomy & robotic operations**, lowering ops costs (savings up to $500-750K/year)
- Supports vehicle autonomy, new/enhanced capabilities and better performance for Cis-Lunar & Gateway mission scenarios, including:

![Earth Observations beyond GEO](image1.png)

![Space Weather Observations](image2.png)

![Precise Relative Positioning](image3.png)

![Launch Vehicle Upper Stages & Cislunar applications](image4.png)

![Formation Flying, Space Situational Awareness, Proximity Ops](image5.png)

![Lunar Orbiting Platform-Gateway Human & Robotic Space Applications](image6.png)
Some key USO derived requirements

- Hadamard deviation
  
  1 second ........ 1E-11
  30 seconds ...... 2E-12
  6 hours .......... 7.07E-12
  24 hours ......... 1.41E-11
  65 hours .......... 2.32E-11

- The USO frequency stability vs. incremental temperature change shall be within 3.0E-11 per degree C, across the proto-flight temperature range.

- The USO frequency stability vs. magnetic field intensity shall be within ±1E-11 for magnetic field intensities of ±0.5 Oersted.

- USO frequency aging after 30 days within ±5E-11/day.

- Other requirements covered stability over comprehensive environmental effects: acceleration, pressure, aging, supply voltage, impedance, etc.
**Total USO Hadamard deviation**

- Measured through filter clock rate estimate.
- Requirement line shown is lab Hadamard deviation requirement with 3C temp change and 0.5T magnetics stability req. RSS’d in for intervals >6hrs
  
  Covers rough expected environment change over those periods
GOES-R Series Weather Satellites

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- GOES-R/GOES-16 Launch: 19 Nov 2016; GOES-S/GOES-17 Launch: March 1 2018
- 15 year life, series operational through mid-2030s
- Employs GPS at GEO to meet stringent navigation requirements
- Relies on beyond-spec GPS sidelobe signals to increase SSV performance
- Collaboration with the USAF (GPS) and ICG (GNSS) expected to ensure similar or better SSV performance in the future
- NOAA also identifies EUMETSAT (EU) and Himawari (Japan) weather satellites as reliant on increased GNSS signal availability in the SSV
GOES-R/GOES-16
In-Flight Performance

GPS Visibility
• Minimum SVs visible: 7
• DOP: 5–15
• Major improvement over guaranteed performance spec
  (4+ SVs visible 1% of time)

Navigation Performance
• 3σ position difference from smoothed ground solution (~3m variance):
  • Radial: 14.1 m
  • In-track: 7.4 m
  • Cross-track: 5.1 m
• Compare to requirement: (100, 75, 75) m

Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D.,
Krimchansky, A., and Concha, M., “GPS Receiver On-Orbit Performance for the
GOES-R Spacecraft,” ESA GNC 2017,
29 May–2 Jun 2017, Salzburg, Austria.