The Expanding Civil Space User Segment: Reaching for New Frontiers

Joel J.K. Parker
U.S. National Aeronautics and Space Administration
CGSIC
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ICG Collaboration on GNSS Beyond the SSV, including the Deep Space Gateway
Space Uses of Global Navigation Satellite Systems (GNSS)

- **Real-time On-Board Navigation**: Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences**: Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements
- **Launch Vehicle Range Ops**: Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use
- **Attitude Determination**: Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements
- **Time Synchronization**: Support precise time-tagging of science observations and synchronization of on-board clocks

The capabilities of individual GNSS constellations to support space users will be further improved by pursuing multi-GNSS compatibility and interoperability
Use of GNSS for navigation in space is now routine

The latest data from the Interagency Operations Advisory Group shows 102 current or upcoming civil missions utilizing GNSS, representing 7 international space agencies.

This data does not include:
• Commercial users (e.g. communication satellites)
• Many other government space agencies
• Non-civil users
• Educational applications, etc.

Therefore, it is likely that hundreds of satellites have used GNSS in space since the initial experiments in the 1980s, and that number is only increasing.

Of these, a small fraction are considered high-altitude users, orbiting at altitudes above approximately 3,000 km.

Civil Space's New Frontier: Expanding GNSS use from 3,000 km to lunar orbit
High-altitude GNSS reception comes with many challenges

Low altitudes (below approx. 3,000 km):
• Signal reception largely similar to terrestrial
• Major factor is higher user velocities
• Signal reception is via central main lobe signals

GNSS usage is widespread.
High-altitude GNSS reception comes with many challenges

Medium altitudes (3,000 to 8,000 km):
- Decreased reception of primary main-lobe signals via zenith antenna
- Spillover signals can increase overall signal reception with omni-directional or additional nadir-pointing antenna.
- Signal reception is via direct and spillover main lobe signals.

GNSS usage is operational.
High-altitude GNSS reception comes with many challenges

**High altitudes** (8,000 to 36,000 km):
- Signal reception is primarily via spillover signals and side lobe signals.
- Signals are much weaker due to additional distance traveled
- Signal availability is reduced due to signal power and narrower beamwidths in spillover signal
- Receivers typically employ navigation filter algorithms to allow processing of individual measurements.

GNSS usage is operational but emerging.
High-altitude GNSS reception comes with many challenges

Beyond-GEO altitudes (36,000+ km):
• Very weak signals and low availability
• Very poor geometric diversity leads to increased navigation uncertainty
• Use of specialized receivers, high-gain antennas, navigation filters critical.

GNSS usage is operational to 150,000 km, and experimental beyond.
Transition from experimentation to operational use:

- **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 and recently 150,000 km
- **2016–2017**: **GOES-16/17** employed GPS operationally at GEO
The United Nations International Committee on GNSS (ICG) brings together all six GNSS providers and other voluntary participants to:

- Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
- Encourage compatibility and interoperability among global and regional systems

The ICG consists of four working groups. Of these two have primary roles related to high-altitude users:

**WG-S: Systems, Signals and Services**—Ensures underlying compatibility and interoperability of signals

**WG-B: Enhancement of GNSS Performance, New Services and Capabilities**—Leads development of the Multi-GNSS Space Service Volume concept and related activities
What is the Multi-GNSS Space Service Volume (SSV)?

The internationally-adopted definition of the Multi-GNSS Space Service Volume.

Two altitude regions:
- Lower SSV
- Upper SSV

Three performance metrics:
- Pseudorange accuracy
- Received signal power
- Signal availability
  Specified as:
  - Percent availability
  - Maximum outage duration
Every GNSS Constellation Provider has Published SSV Performance Characteristics

Expected performance data (extracted sample shown here) was requested via a “template” for each:
- GNSS constellation
- Civil signal
- SSV characteristic

Data was requested for nominal constellations, and for primary main lobe signals only.

Supplied data represents minimum performance expectations for each signal; specification and requirement status varies by provider.

Data is intended to provide a conservative baseline performance level for mission planning activities. See the SSV Booklet for details constellation-specific information.

<table>
<thead>
<tr>
<th>Band</th>
<th>Constellation</th>
<th>Minimum Received Civilian Signal Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0dBi RCP antenna at GEO (dBW)</td>
</tr>
<tr>
<td>L1/E1/B1</td>
<td>GPS</td>
<td>-184 (C/A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-182.5 (C)</td>
</tr>
<tr>
<td></td>
<td>GLONASS</td>
<td>-179</td>
</tr>
<tr>
<td></td>
<td>Galileo</td>
<td>-182.5</td>
</tr>
<tr>
<td></td>
<td>BDS</td>
<td>-184.2 (MEO)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-185.9 (I/G)</td>
</tr>
<tr>
<td></td>
<td>QZSS</td>
<td>-185.5</td>
</tr>
<tr>
<td>L5/L3/E5/B2</td>
<td>GPS</td>
<td>-182</td>
</tr>
<tr>
<td></td>
<td>GLONASS</td>
<td>-178</td>
</tr>
<tr>
<td></td>
<td>Galileo</td>
<td>-182.5 (E5b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-182.5 (E5a)</td>
</tr>
<tr>
<td></td>
<td>BDS</td>
<td>-182.8 (MEO)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-184.4 (I/G)</td>
</tr>
<tr>
<td></td>
<td>QZSS</td>
<td>-180.7</td>
</tr>
<tr>
<td></td>
<td>NavIC</td>
<td>-184.54</td>
</tr>
</tbody>
</table>
Multi-GNSS activities in the ICG WG-B

As amended in 2015, the ICG WG-B work plan directs it to:

“continue the implementation of an interoperable GNSS Space Service Volume and provide recommendations to Service Providers regarding possible evolution needs arising from users/application developers."

This is being accomplished via several initiatives:

- **SSV Definition/Assumption Maturation**: Adopting the formal definition of the Multi-GNSS SSV
  - **Status**: Completed 2017
- **Constellation-Specific SSV Performance Data**: Publishing high-altitude performance characteristics for each GNSS constellation
  - **Status**: Completed 2015
- **Multilateral SSV Analysis**: Conducting an internationally-coordinated analysis of simulated multi-GNSS SSV performance
  - **Status**: Completed 2017
- **Multi-GNSS SSV Booklet**: Development of a formal UN publication defining the Multi-GNSS SSV, its characteristics, benefits, and applications.
  - **Status**: Completed 2018
- **Beyond SSV studies**: Lunar vicinity GNSS performance and augmentation architecture studies
  - **Status**: Ongoing
- **SSV Capabilities Outreach**: Coordinating a joint international outreach activity to raise awareness of the final policy.
  - **Status**: Ongoing
Development And Utilization of High Altitude GNSS Offers Numerous Benefits To Users

- **Improve navigation performance:**
  - Increase number of usable signals over individual constellations alone
  - Improve geometric diversity by using multiple constellations in different regimes
  - Reduce or eliminate periods of outage, reducing the need for highly stable on-board clocks

- **Enable new mission types and operations concepts:**
  - Improved availability of navigation signals enables increased satellite autonomy, reducing the need for ground interactions and enabling reduced operations costs.
  - Increase operational robustness via diversity of independent constellations, signals, geometries, etc.
  - Reduce the navigation burden on ground-based communications assets, simplifying mission architectures.

- **Encourage development of the high-altitude GNSS user community**
  - Adoption of the Multi-GNSS SSV indicates GNSS provider support for the high-altitude user community, encouraging development of specialized receivers and new mission applications.
  - Established UN ICG process provides a forum for further development.

Image: Southeastern USA at night, from ISS (NASA)
The Promise of using GNSS for Real-Time Navigation at High Altitudes & Beyond the Space Service Volume

**Benefits of High Altitude GNSS use:**

- **Supports real-time navigation/timing performance** (from: *no real time* to: real-time 1 km – 100 m position, µsec timing)
  - Improved performance with (pseudo-) satellite and clock augmentations
- **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 mission scenarios**, including:

  - Earth Observations
  - Space Weather Observations
  - Precise Relative Positioning
  - Launch Vehicle Upper Stages & Cislunar applications
  - Formation Flying, Space Situational Awareness, Proximity Ops
  - Lunar Orbiting Platform-Gateway Human & Robotic Space Applications
User Application: Earth Weather Observations

Needs:
• Near-continuous availability of GNSS signals at GEO to maintain platform stability without service outages

Examples:
• US: Geostationary Operational Environmental Satellite (GOES) R-series
• Russia: Elektra-L
User Application: Precision Formation Flying

Needs:
• Availability of GNSS navigation signals at very high altitude to maintain precise relative positioning between spacecraft

Examples:
• ESA: Proba-3

Image: Proba-3 (ESA)
User Application: Cislunar Trajectories

Needs:
• GNSS signal availability at extremely high altitude, such as to lunar distance, to perform on-board navigation of exploration vehicles
• Few signal outages around critical return events, to ensure precise navigation solution for Earth reentry

Examples:
• Lunar exploration vehicles
• Launch vehicle upper stages

Image: Earthrise from Apollo 8 (NASA)
User Application: Satellite Servicing

Needs:
- Continuously-available GNSS signals at GEO, to support precise relative positioning, spacecraft agility, and on-board autonomy

Examples:
- Proposed GEO automated servicing vehicles
User Application: GEO Colocation

Needs:
• GNSS signal availability, improved geometric diversity, and few outages, enabling reduced spacing between satellites, responsive maneuvering, and autonomous operations.

Examples:
• GEO communications satellites

Image: TDRS-H, I, J illustration (NASA)
Operational U.S. Missions using GNSS in the High Altitude New Frontier

**GOES-R Weather Satellite Series:**
- Next-generation U.S. operational GEO weather satellite series
- Series is first to use GPS for primary navigation
- GPS provides quicker maneuver recovery, enabling continual science operations with <2 hour outage per year
- Introduction of GPS and new imaging instrument are **game-changers to humanity**, delivering data products to substantially improve public and property safety

**Magnetospheric Multi-Scale (MMS):**
- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- Highest-ever use of GPS; Phase I: 12 Earth Radii (RE) apogee (76,000 km); Phase 2B: 25 RE apogee (~150,000 km) (**40% of way to the moon**)
- Additional apogee raising to 29.34 RE (50% of way to moon) completed in February 2019
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping

**GOES GPS Visibility**:
- Minimum SVs visible: 7
- DOP: 5–15

**GOES Nav. Performance** (3σ):
- Radial: 14.1 m
- In-track: 7.4 m
- Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m


**MMS Nav. Performance** (1σ)

<table>
<thead>
<tr>
<th>Description</th>
<th>Phase 1</th>
<th>Phase 2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major axis est. under 3 RE (99%)</td>
<td>2 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Orbit position estimation (99%)</td>
<td>12 m</td>
<td>55 m</td>
</tr>
</tbody>
</table>
U.S. Initiatives & Contributions to Develop & Grow an Interoperable High Altitude GNSS Capability for Space Users

Operational Users

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

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

Space Flight Experiments

- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)

Breakthroughs in Understanding; Supports Policy Changes; Enables Operational Missions

SSV Policy & Specifications

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

Operational Guarantees Through Definition & Specification

From 1990’s to Today, U.S. Provides Leadership & Guidance Enabling Breakthrough, Game-changing Missions through use of High Altitude GNSS
Renewed Interest in Lunar Exploration

- There is significant global interest in sustained lunar exploration; dozens of missions in planning
- US human lunar exploration will start with EM-1 and EM-2 in the early 2020s
- NASA and international partners plan to establish a Gateway, a permanent way-station in the vicinity of the moon
- GNSS on lunar missions would:
  - enable *autonomous* navigation
  - reduce tracking and operations costs
  - provide a backup/redundant navigation for human safety
  - provide timing source for hosted payloads
  - reduce risk for commercial development

Lunar Missions Represent a Ripe New Frontier for High Altitude GNSS

Global Exploration Roadmap
Lunar Exploration Mission Types
Enabled via GNSS Navigation & Timing

- Lunar Surface Operations
  Robotic Prospecting & Human Exploration
- Human-tended Lunar Vicinity
  Lunar Orbiting Platform-Gateway
- Robotic Lunar Orbiters
  Resource & Science Sentinels
- Earth & Astrophysics Observations
- Satellite Servicing
- Solar & Space Weather Observations
Conclusions

• Use of GNSS for navigation & timing in space is now routine at altitudes below 3,000 km

• **High-altitude space use of GNSS**, (i.e. expansion of GNSS use from 3,000 km to lunar orbit), represents Civil Space’s **Newest Frontier**

• Despite significant technical challenges, high-altitude GNSS offers numerous benefits to space users including:
  – Promising new mission types and operations concepts
  – Precise real-time navigation and time sensing
  – Enhanced on-board autonomous operations and reduced ground support

• The international GNSS community have overcome high-altitude GNSS technology & political hurdles through:
  – On-orbit flight experiments and demonstrations
  – High-altitude GNSS receiver developments
  – UN ICG initiatives where all **GNSS constellation providers** have adopted common interoperable definitions, including the Multi-GNSS Space Service Volume, have published performance characteristics, and have performed joint analyses documenting the benefits of utilizing multi-GNSS in this regime
  – Sharing operational mission results, including the GOES and MMS spacecraft, to show high-altitude GNSS is realizable

• Numerous planned geostationary and lunar exploration missions are poised to reap great benefits from this new technological capability
Backup
# Operational Challenges, Mitigations and Use of GPS/GNSS in Space

<table>
<thead>
<tr>
<th>Ops Scenario</th>
<th>Altitude Range (km)</th>
<th>Challenges &amp; Observations (Compared to previous scenario)</th>
<th>Mitigations</th>
<th>Operational Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial Service Volume</td>
<td>100- 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>
</tr>
<tr>
<td>SSV Medium Altitudes</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>
</tr>
<tr>
<td>SSV High-GEO Altitudes</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>Nav-Orbit Filter/Fusion algorithms (e.g. GEONS) enables ops w/ &lt;4 signals and flywheel through 0 signal ops; 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>Beyond the SSV</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>
</tr>
</tbody>
</table>
## Example: Global Performance Summary

<table>
<thead>
<tr>
<th>Band</th>
<th>Constellation</th>
<th>At least 1 signal</th>
<th>4 or more signals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Avail. (%)&lt;sup&gt;1&lt;/sup&gt;</td>
<td>MOD (min)&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>L1/E1/B1</td>
<td>Global systems</td>
<td>78.5–94</td>
<td>48–111</td>
</tr>
<tr>
<td></td>
<td>QZSS</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>99.9</td>
<td>33</td>
</tr>
</tbody>
</table>

<sup>1</sup>average across all grid locations  
<sup>2</sup>at worst-case grid location  
*no signal observed for the worst-case grid location for full simulation duration

### Observations:
- Using all constellations provides nearly continuous single-signal coverage (99.9% on average) at GEO.  
- Combined, average four-signal availability grows by an order of magnitude over the best-performing individual constellation.  
- Performance estimates are conservative, based on constellation baseline main lobe performance estimates shown previously.

Summary data condenses individual constellation results for:  
- L1 band  
- Upper SSV  
- 20 dB-Hz receiver threshold
• The Terrestrial Service Volume (TSV) is defined as the volume of space including the surface of the Earth and LEO, i.e., up to 3,000 km.

• The Space Service Volume (SSV) is defined as the volume of space surrounding the Earth from the edge of LEO to GEO, i.e., 3,000 km to 36,000 km altitude.

• The SSV overlaps and extends beyond the GNSS constellations, so use of signals in this region often requires signal reception from satellites on the opposite side of the Earth – main lobes and sidelobes.

• Use of GPS in the SSV increasing despite geometry, Earth occultation, and weak signal strength challenges.

• Spacecraft use of GPS in TSV & SSV enables:
  • reduced post-maneuver recovery time
  • improved operations cadence
  • increased satellite autonomy
  • more precise real-time navigation and timing performance.