Development of an Interoperable GNSS Space Service Volume

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GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS
High-Altitude GPS

- **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**: GOES-16 employed GPS operationally at GEO
International Committee on GNSS (ICG)

- The UN International Committee on GNSS (ICG) brings together all six GNSS providers (China, Europe, India, Japan, Russia, & USA) 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

- Most recent meeting: ICG-12, Kyoto, Japan
- Next Meeting: ICG-13, X’ian, China

**WG-S: Systems, Signals and Services**
Major topics include:
- Spectrum compatibility
- Interference detection & mitigation
- Service interoperability
- Performance standards & monitoring

**WG-B: Enhancement of GNSS Performance, New Services and Capabilities**
Major topics include:
- Development of interoperable multi-GNSS SSV
- GNSS-hosted search-and-rescue payloads
- Space weather and ionosphere modeling

**WG-D: Reference Frames, Timing and Applications**
Major topics include:
- ITRF, geodetic reference frame interoperability
- Time standards & multi-constellation offsets
- Constellation orbit modeling & technical data

* Also: WG-C: Information Dissemination and Capacity Building*
The Multi-GNSS Space Service Volume

- Two components:
  - Lower SSV (3,000 km–8,000 km)
  - Upper SSV (8,000 km–36,000 km)

- Three performance metrics:
  - Pseudorange Accuracy
  - Signal Availability
  - Received Signal Power
# Constellation-Specific Support to SSV

<table>
<thead>
<tr>
<th>Band</th>
<th>Constellation</th>
<th>Minimum Received Civilian Signal Power</th>
<th>Upper SSV Signal Availability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0dBi RCP antenna at GEO (dBW)</td>
<td>Reference off-boresight angle (°)</td>
</tr>
<tr>
<td>L1/E1/B1</td>
<td>GPS</td>
<td>-184 (C/A)(^1)</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-182.5 (C)(^2)</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>GLONASS</td>
<td>-179</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>Galileo</td>
<td>-182.5</td>
<td>97.40</td>
</tr>
<tr>
<td></td>
<td>BDS</td>
<td>-184.2 (MEO)(^3)</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-185.9 (I/G)(^4)</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>QZSS</td>
<td>-185.5</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>GLONASS</td>
<td>-178</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Galileo</td>
<td>-182.5 (E5b)</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-182.5 (E5a)</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>BDS</td>
<td>-182.8 (MEO)</td>
<td>28</td>
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<tr>
<td></td>
<td></td>
<td>-184.4 (I/G)</td>
<td>22</td>
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<tr>
<td></td>
<td>QZSS</td>
<td>-180.7</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>NavIC</td>
<td>-184.54</td>
<td>16</td>
</tr>
</tbody>
</table>

\(^1\)L1 C/A signal  
\(^2\)L1C signal  
\(^3\)Medium Earth Orbit satellites  
\(^4\)Inclined geostationary (I) and geostationary (G) satellites
Performance Estimates

• Two types of analysis were performed over three phases:
  1. Global performance analysis
  2. Mission-specific performance analysis, consisting of:
     • GEO case
     • HEO case
     • Lunar case
• Phase 1 & 2 were focused on global analysis
• Phase 3 was mission-specific analysis
Global Performance

- Analysis performed to estimate signal availability on global grid of points (see right)
- Each grid point assumed to be stationary receiver with 0dBi antenna
- Results show improvement in Upper SSV:
  - 1+ signals: 94% -> 99.9%
  - 4+ signals: 7% -> 89.8%

<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. (%)¹</td>
<td>MOD (min)²</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>*³</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>99.9</td>
<td>33</td>
</tr>
<tr>
<td>L5/L3/E5a/B2</td>
<td>Global systems</td>
<td>93.4–99.9</td>
<td>7–*</td>
</tr>
<tr>
<td></td>
<td>Regional systems</td>
<td>1–30.5</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Combined</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

¹average across all grid locations
²at worst-case grid location
³no signal observed for the worst-case grid location for full simulation duration
GEO Performance

- Mission-specific analysis at six GEO locations (see right)
- Each satellite simulated with realistic high-gain nadir-pointed antenna
- Results (below) show drastic improvement from any individual constellation to all combined
- Visibility variable with location around GEO belt
HEO Performance

- Mission-specific analysis of example highly-elliptical science mission
- User satellite modeled with both nadir-pointed and zenith-pointed antennas (see figure above)
- Results (left) show improvement when all constellations are used together
- 100% coverage with multiple-satellite visibility is possible even at apogee with all constellations
Lunar Performance Simulations

- Mission-specific analysis of example lunar outbound trajectory
- User satellite modeled with both nadir-pointed and zenith-pointed antennas
- Results (below) show two key features:
  - Overall visibility is split into low-altitude regime with 100% 1+ visibility under approx. 30 RE, and zero-visibility high-altitude region
  - With moderate user equipment improvements, visibility can be achieved all the way to lunar distance
Benefits of Real-Time GPS Navigation in the SSV

**Benefits of GPS use in SSV:**
- Supports **fast trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- GPS timing **reduces need for expensive on-board clocks** (from: $100sK-$1M to: $15K–$50K)
- 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 Earth Orbit (GEO) missions**, such as:

Earth Weather Prediction using Advanced Weather Satellites

Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications

Formation Flying, Space Situational Awareness, Proximity Operations

Precise Position Knowledge and Control at GEO
SSV: Future Civil Applications

- **Earth Weather Missions**
  - Objectives: Improve weather forecasting from 3-5 days to 5-7 days; protecting people and property through early warning of tornados, flash floods, and wildfires
  - Role of the SSV: Accurate orbit prediction (position and velocity), fast recovery from trajectory maneuvers, navigation stability to prevent internal image and image to image pixel, and timing

- **Space Weather and Heliospheric Science Missions**
  - Objectives: Enable High Earth Orbit and Cislunar observations of the magnetosphere to improve understanding of space weather and to potentially start space weather prediction.
  - Role of the SSV: Improved navigation performance (e.g. 10-meter to 1-meter class) and fast recovery from trajectory maneuvers (minute class) for accurate placement of space weather phenomenon; improved operations cadence and increased satellite autonomy to support constellation or formation flying missions; Precise timing enabling lower cost clock alternatives
SSV: Future Civil Applications (cont.)

- **Satellite Servicing**
  - Objectives: Extend the lives of satellites through upgrade, repair, refueling, and orbit adjustment; debris removal; in-orbit construction or installation
  - Role of the SSV:
    - Fast recovery from trajectory maneuvers required—on the order of minutes during critical rendezvous, proximity operations, and docking
    - Near-continuous GPS signal availability needed to support satellite responsiveness and autonomy
    - Highly accurate absolute orbit state (position and velocity) are necessary to support far-field rendezvous—as a general rule of thumb, position must be known to an accuracy of 10% the inter-vehicle range

- **Formation Flying Missions**
  - Objectives: Enable new classes of missions and new scientific viewpoints through formation flying; spans full spectrum of vehicle sizes (CubeSats to ISS class) and mission orbits (MEO, HEO, GEO, Cislunar)
  - Role of the SSV: Precise navigation and timing, fast recovery from trajectory maneuvers, enhanced operations cadence, and increased satellite autonomy. Requirements as low as meter-class navigation in real time, cm-level relative navigation and micro- to nanosecond timing synchronization
SSV: Future Civil Applications (cont.)

- **Commercial GEO Missions**
  - Objectives: Increase density of the most coveted real estate in space, benefiting commercial and civil space users
  - Role of the SSV: Accurate position and velocity measurements and near-continuous GPS signal availability needed to enable accurate, autonomous vehicle station keeping during near-continuous low thrust maneuvering

- **Launch Vehicle Upper Stages & Deep Space Missions, En Route, and Return**
  - Objectives: Improve real-time vehicle insertion and trajectory accuracy reducing fuel requirements and improving payload mass capacities
  - Role of the SSV: High accuracy, high cadence position, velocity, and time knowledge to minimize the trajectory propagation errors of the vehicle during flight
SSV: Future Civil Applications (cont.)

• Lunar Missions
  – Objectives: There is a renewed interest in the moon as a target for rovers, landers, and human exploration. The US plans to return to human exploration of the moon and cis-lunar space in the next few years with Exploration Missions (EM) 1 and 2. EM-3 may begin construction of a “gateway”—a permanent way-station in the vicinity of the moon for staging deep space activity.
  – Role of the SSV:
    • GPS can provide measurements for mid-course correction burns during outbound and return cruise.
    • Simulations have shown that GPS signal availability can be extended to lunar distances by augmenting existing high-altitude GPS navigation systems (such as MMS) with a high-gain antenna (Winternitz et al. 2017, Ashman et al., 2018).
    • Navigation backup for the crew capsule, Orion, if communications link is lost.
    • Lunar platform like the gateway could use GPS for position, velocity, and attitude, as well as a stable and accurate timing source for hosted science and technology payloads.
Conclusions

• Use of high-altitude GNSS has expanded significantly, and is now an enabling technology for future missions.

• Through the UN International Committee on GNSS (ICG), all GNSS and RNSS providers have agreed to the Multi-GNSS Space Service Volume, which documents performance expectations above 3,000 km altitude.

• Performance estimates (global and mission-specific) show significantly enhanced signal availability at all altitudes when multiple constellations are used.

• Full results are available in UN SSV Booklet.