Development of an Interoperable GNSS Space Service Volume

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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

**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) -182.5 (C)(^2)</td>
<td>23.5</td>
</tr>
<tr>
<td></td>
<td>GLONASS</td>
<td>-179</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Galileo</td>
<td>-182.5</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>BDS</td>
<td>-184.2 (MEO)(^3) -185.9 (I/G)(^4)</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>QZSS</td>
<td>-185.5</td>
<td>22</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) -182.5 (E5a)</td>
<td>22.5</td>
</tr>
<tr>
<td></td>
<td>BDS</td>
<td>-182.8 (MEO) -184.4 (I/G)</td>
<td>28</td>
</tr>
<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>

\(^1\)average across all grid locations
\(^2\)at worst-case grid location
\(^3\)no 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
• 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% 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 cislunar 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.