Developing a Robust, Interoperable GNSS Space Service Volume (SSV) for the Global Space User Community

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Benefits of GPS/GNSS to NASA

Real-time On-Board Navigation: Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, GEO satellite servicing

Earth Sciences: GPS used as a remote sensing tool supports atmospheric and ionospheric sciences, geodesy, and geodynamics -- from monitoring sea levels & ice melt to measuring the gravity field

Attitude Determination: Use of GPS/GNSS enables some missions to meet their attitude determination requirements, such as ISS

NASA is investing approximately $130M over the next 5 years on GPS R&D and its implementation in support of space operations and science applications

GPS capabilities to support space users may be further improved by pursuing compatibility and interoperability with GNSS (Global Navigation Satellite Systems), such as the Russian GLONASS, European Galileo, and China’s BDS
Geosync Altitude: 35,887 km

GPS Altitude: 20,183 km

First Side Lobes

LEO Altitudes < 3,000 km

Main Lobe (~47° for GPS L1 signal)

HEO Spacecraft

Earth Umbra

Reception Geometry for GPS Signals in Space
What is a Space Service Volume (SSV)?

The Space Service Volume defines three interrelated performance metrics at each altitude:
- Availability
- Received power
- Pseudorange accuracy

Terrestrial Service Volume
Surface to 3,000 km

Space Service Volume
(High/Geosynchronous Altitudes)
8,000 to 36,000 km

Space Service Volume
(Medium Altitudes)
3,000 to 8,000 km

GEO Altitude - 36,000 km

GPS Altitude - 20,183 km
Past and Ongoing Development of the SSV

**GPS SSV**

- **2000**
  - Initial SSV definition (GPS IIF)

- **2006**
  - Current SSV specification (GPS III)

- **2015**
  - GPS III SV11+ SSV proposed specification update (via IFOR)

**Interoperable Multi-GNSS SSV**

- **2005**
  - Establishment of UN International Committee on GNSS (ICG)

- **2011**
  - Introduction of Interoperable Space Service Volume to ICG

- **2015**
  - Establishment of common definitions & documentation of SSV capabilities by all GNSS providers

  - ICG WG-B Multi-GNSS Analysis & Outreach
  - Provider SSV development
GPS SSV Progress
• Current SSV specifications, developed with limited on-orbit knowledge, only capture performance provided by signals transmitted within 23.5° (L1) or 26° (L2/L5) of boresight.

• On-orbit data & lessons learned since spec development show significant PNT performance improvements when the full aggregate signal is used.

• Numerous operational missions in High & Geosynchronous Earth Orbit (HEO/GEO) utilize the full signal to enhance vehicle PNT performance
  – Multiple stakeholders require this enhanced PNT performance to meet mission requirements.

• Failure to protect aggregate signal performance in future GPS designs creates the risk of significant loss of capability, and inability to further utilize performance for space users in HEO/GEO

• Protecting GPS aggregate signal performance ensures GPS preeminence in a developing multi-GNSS SSV environment


Benefits of GNSS use in SSV:

- Significantly improves real-time navigation performance (from: km-class to: meter-class)
- Supports quick trajectory maneuver recovery (from: 5-10 hours to: minutes)
- GNSS 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 HEO and 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
Key Civil Stakeholder: GOES-R

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- Launch: 19 Nov 2016, 15-year life
  - Series operational through 2030s
- Driving requirements:
  - Orbit position knowledge requirement (right)
  - All performance requirements applicable through maneuvers, <120 min/year allowed exceedances
  - Stringent navigation stability requirements
  - Requirements unchanged for GOES-S, -T, -U

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement (m, 1-sigma)</th>
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</thead>
<tbody>
<tr>
<td>Radial</td>
<td>33</td>
</tr>
<tr>
<td>In-track</td>
<td>25</td>
</tr>
<tr>
<td>Cross-track</td>
<td>25</td>
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- GOES-R cannot meet stated mission requirements with SSV coverage as currently documented
- NASA-proposed requirement formulated as minimum-impact solution to meet GOES-R performance needs
GOES-R: The Future of Forecasting

3x More Channels
Improves every product from current GOES Imager and will offer new products for severe weather forecasting, fire and smoke monitoring, volcanic ash advisories, and more.

4x Better Resolution
The GOES-R series of satellites will offer images with greater clarity and 4x better resolution than earlier GOES satellites.

5x Faster Scans
Faster scans every 30 seconds of severe weather events and can scan the entire full disk of the Earth 5x faster than before.

GOES 2005

GOES-R 2016

www.nesdis.noaa.gov

NOAA Satellite and Information Service
Proposed GPSIII SV11+ SSV Requirement

- Proposed requirement adds second tier of capability specifically for HEO/GEO users
  - Increased signal availability to nearly continuous for at least 1 signal
  - Relaxed pseudorange accuracy from 0.8m RMS to 4m RMS
  - No change to minimum received signal power
  - Applies to all signals (L1/L2/L5), all codes

<table>
<thead>
<tr>
<th>PR acc. (rms)</th>
<th>0.8 m</th>
<th>4m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+ signal</td>
<td>≥ 80%</td>
<td>≥ 99%</td>
</tr>
<tr>
<td>4+ signals</td>
<td>≥ 1%</td>
<td>≥ 33%</td>
</tr>
<tr>
<td>Max outage</td>
<td>108 min</td>
<td>10 min</td>
</tr>
</tbody>
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SSV L1 HEO/GEO availability; 4m spec identical for L2/L5

Signal Availability
for GOES-R-class GEO Mission
Independent of pseudorange accuracy
GOES-R Mission Impact

- Modeled each type of GOES-R maneuver at each GPS availability level
- Only 1 signal is necessary to recover nav performance; max outage is key metric
- At current required availability (red), post-maneuver errors exceed requirement in all cases, for up to 3 hours
- Proposed SSV requirement (blue) just bounds errors within GOES-R nav requirement
- RSS requirement is shown for illustration; in actuality, each component meets individually

Errors with respect to simulation truth
Interagency Forum for Operational Requirements (IFOR) Current Status

• **Key participants:**
  – NASA, USAF (user side)
  – SMC/GPV4 (GPS side)
  – AFSPC/A5M (IFOR side)

• **Original proposed recommendation from IFOR (Mar 2015):**
  1. Proceed with NASA requirement as *objective requirement*
  2. SV11+ contractors to provide actual cost to meet objective
  3. Users to confirm & fund, based on actual cost

• **Proposed recommendation after High Power Team (HPT) (Apr 2015):**
  – NASA/USAF to sign MOA for engagement throughout SV11+ acquisition
  – Cost to be revisited at two milestones, based on additional insight from contractors
  – NASA to coordinate civil funding for implementation, based on actual cost

• **Current status:**
  – IFOR process has stalled; no progress since May
  – MOA framework agreement reached, but staffing not initiated
  – **SV11+ Phase 1 is proceeding without stakeholder engagement or insight**
  – Phase 1 represents minimal-impact opportunity to implement proposed requirement for SV11+ series

• **Independent Review Team established by AFSPC to advise on forward path**
GPS SSV
Conclusions & Way Forward

• NASA has proposed an updated GPS SSV requirement to protect high-altitude space users from risk of reduced future GPS capability.
  – Key civil example user is GOES-R
  – Many other emerging users will require these capabilities in the future

• Available data suggests that the updated requirement can easily be met by a minimum-performing constellation of the previous design.
  – If true, cost to implement would be documentation/V&V only, not a hardware change
  – But, in the absence of direct verification data, a risk remains that the requirement would not be met by the current and future designs
  – This has led to a large gap between NASA and USAF impact estimates, with no mechanism to enforce technical transparency, coordination, or mitigations within IFOR.

• NASA seeks USAF engagement to seek and implement minimal-impact requirement based on best available data through SV11+ acquisition cycle
  – Engagement has stalled at IFOR level – no progress on formal recommendation or MOA staffing

• NASA finds the proposed requirement critical to support future users in the SSV across the enterprise and is open to a commitment of funding based on a validated assessment.

• The proposed requirement is an innovative, whole-of-government approach that will protect and encourage next-generation capabilities in space at minimal cost.

• NASA encourages the work of the SSV Independent Review Team to provide independent analysis of proposed requirement and path forward.
Interoperable Multi-GNSS SSV Progress
International Committee on GNSS (ICG)

- Emerged from 3rd UN Conference on the Exploration and Peaceful Uses of Outer Space July 1999
  - Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
  - Encourage compatibility & interoperability among global and regional systems
- Members include:
  - GNSS Providers: (U.S., EU, Russia, China, India, Japan)
  - Other Member States of the United Nations
  - International organizations/associations – Interagency Operations Advisory Group (IOAG) & others
  - 11th annual meeting hosted by Russia in Sochi, November 6-11, 2016

Summary of ICG Multi-GNSS SSV Development Efforts To-Date

- Interoperable, Multi-GNSS SSV coordination is accomplished as part of **ICG Working Group B (WG-B): Enhancement of GNSS Performance, New Services and Capabilities**

- ICG WG-B discussions have encouraged GPS, GLONASS, Galileo, BeiDou, QZSS, & NAVIC to characterize performance for space users to GEO

- **2016 ICG meeting** was held Nov. 6-11, in Sochi, Russia, where:
  - All providers **reaffirmed the criticality** of GNSS for current and emerging space missions
  - Participating members are finalizing a **guidance booklet** on GNSS SSV & are **jointly conducting analyses** to characterize interoperability
  - Stakeholder ICG members will **coordinate a global outreach initiative** to educate & inform policy makers on the importance of a multi-GNSS SSV enabling space users to serve societal needs
ICG WG-B Joint SSV Analysis Effort

The ICG WG-B is performing an international analysis effort to demonstrate the benefits of an interoperable GNSS SSV, consisting of 3 phases of increasing complexity and fidelity:

- **Phase 1** is a geometrical analysis of GNSS signal visibility at MEO & GEO altitudes [completed May 2016]
- **Phase 2** incorporates signal strength constraints to the geometrical analysis at GEO altitude [completed September 2016]
- **Phase 3** extends Phase 2 to realistic user mission scenarios: GEO, HEO, and trans-Lunar

**Phase 1 & 2** Results were presented at the ICG-11 meeting Nov. 6-11 in Sochi, Russia

**Phase 3** mission planning kicked off and was discussed within ICG-11 WG B

Analysis results will be captured in ICG SSV Booklet; joint int’l conference paper, journal articles, etc.

Recently published in InsideGNSS, Nov/Dec 2016
ICG WG-B Phase 1 Results: 4+ Signal Main-Lobe Availability

BeiDou
Average 45.4% availability

Galileo
Average 4.2% availability

GLONASS
Average 14.5% availability

GPS
Average 15.6% availability

NAVIC
Average 0.6% availability

QZSS
Average 1.5% availability

Interoperable GNSS achieves 100% system availability
ICG-11 SSV Recommendations

Service Providers, supported by Space Agencies & Research Institutions encouraged to:

• Support SSV in future generation of satellites
• Contribute to GNSS space users database
• Measure and publish of GNSS antenna gain patterns to support SSV understanding & use of aggregate signal
Conclusions

• The Space Service Volume, first defined for GPS IIF in 2000, continues to evolve to meet high-altitude user needs.

• GPS led the way with a formal specification for GPSIII, requiring that GPS provides a core capability to space users.

• Today, we continue to work in parallel tracks to ensure that the SSV keeps pace with user demands.
  – For GPS, with its well-characterized performance, we are working to update the SSV spec to capture the needs of emerging GPS-only users like GOES-R.
  – In partnership with foreign GNSS providers, we are working jointly to characterize, analyze, document, and publish the capabilities of an interoperable multi-GNSS SSV with ultimate goal of provider specification.

• Both approaches are equally critical: a robust GPS capability will enable and enhance new missions in single-system applications, while an interoperable GNSS SSV ensures that a wider capability is available as needed.
Backup Charts
Before We Begin...

- **Oct 20, 2016**: Guinness World Record awarded to NASA’s Magnetospheric MultiScale (MMS) mission for the highest-altitude GPS fix ever recorded: 70,135 km (2x geostationary altitude)

- **Feb 2017**: MMS apogee raise to 160,000 km
  - New record to follow?