Keeping the universe connected.

GNSS Space Service Volume Update—ICG WG-B

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Expanding the GPS Space Service Volume (SSV) into a multi-GNSS SSV

- At least four GNSS satellites in line-of-sight are needed for on-board real-time autonomous navigation
  - GPS currently provides this up to 3,000 km altitude
  - Enables better than 1-meter position accuracy in real-time

- At Geosynchronous altitude, only one GPS satellite will be available at any given time.
  - GPS-only positioning still possible with on-board filtering, but only up to approx. 100-meter absolute position accuracy.
  - GPS + Galileo combined would enable 2-3 GNSS sats in-view at all times.
  - GPS + Galileo + GLONASS would enable at least 4 GNSS sats in-view at all times.
  - GPS + Galileo + GLONASS + Beidou would enable > 4 GNSS sats in view at all times. This provides best accuracy and, also, on-board integrity.

- However, this requires:
  - Interoperability among these the GNSS constellations; and
  - Common definitions/specifications for use of GNSS signals within the Space Service Volume (3,000 km to Geosynchronous altitude)

≥ 4 GPS satellites in line-of-sight here (surface to 3000 km)

Only 1-2 GPS satellites in line-of-sight at Geosynchronous orbit altitude

≥ 4 GPS satellites in line-of-sight here (space service volume)

... but, if interoperable, then GPS + Galileo + GLONASS + Beidou provide > 4 GNSS sats in line-of-sight at Geosynchronous orbit altitude.
Why is an interoperable Space Service Volume important?

*Global, interoperable Space Service Volume specifications are crucial for real-time GNSS navigation solutions in high Earth orbit*

- Supports increased satellite autonomy for high Earth orbit missions, lowering mission operations costs
- Enables new/enhanced mission capabilities for High Earth orbit and geostationary orbit missions of the future, such as:
  - Improved Weather Prediction using Advanced Weather Satellites
  - Space Weather Observations
  - Astrophysics Observations
  - En-route Lunar Navigation Support
  - Formation Flying & Constellation Missions
  - Closer Spacing of Satellites in Geostationary Arc
Current U.S. Missions using GPS above the GPS Constellation

**GOES-R Weather Satellite Series**
- First operational use of GPS above the constellation
- Improves navigation performance for GOES-R
- Station-keeping operations on current GOES N-Q constellation require relaxation of Image Navigation Registration for several hours
- GPS supports GOES-R breaking large station-keeping maneuvers into smaller, more frequent ones
  - Quicker Recovery
  - Minimal impact on weather science

**Magnetospheric Multi-Scale (MMS) Mission**
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Starts in 1.2 x 12 Re orbit (7600 km x 76,000 km)
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping
**GNSS Space Service Volume Templates**

- GNSS space user performance templates have been distributed to the ICG WG-B and to the Interagency Operational Advisory Group (IOAG), these include:
  - A list of space missions using GNSS for navigation and/or science applications
  - Performance characteristics for the Terrestrial Service Volume (surface to 3000 km altitude)
  - Performance characteristics for the Space Service Volume (3000 km to geosynchronous altitude)

### Terrestrial Service Volume

<table>
<thead>
<tr>
<th>No.</th>
<th>Mission/Program</th>
<th>GNSS/s Used</th>
<th>Orbit</th>
<th>Application/s</th>
<th>Notes</th>
<th>Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>3</td>
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<td>4</td>
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<td>5</td>
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</tbody>
</table>

### Space Service Volume

<table>
<thead>
<tr>
<th>Definitions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Space Service Volume (also known as ‘MEO altitudes’): 3,000 to 8,000 km altitude</td>
<td>Four GPS signals available simultaneously a majority of the time but GNSS signals over the limb of the Earth become increasingly important.</td>
</tr>
<tr>
<td>Upper Space Service Volume (also known as ‘HEO/GEO altitudes’): 8,000 to 36,000 km altitude</td>
<td>Nearly all GPS signals received over the limb of the Earth. Users will experience periods when no GPS satellites are available.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Range Error</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Received Civilian Signal Power</td>
<td>Reference Half Beamwidth</td>
<td></td>
</tr>
<tr>
<td>Signal Availability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower Space Service Volume (MEO)</td>
<td>At least 1 signal</td>
<td>4 or more signals</td>
</tr>
<tr>
<td>Upper Space Service Volume (HEO/GEO)</td>
<td>At least 1 signal</td>
<td>4 or more signals</td>
</tr>
</tbody>
</table>
Realizing the Space Service Volume Vision

The LONG and Winding Road

• Mid-1990s—efforts started to develop a formal Space Service Volume (SSV) with accompanying GPS signal and availability specification

• February 2000—GPS Operational Requirements Document (ORD), released, included first space user requirements and description of SSV

• 1997-Present—Several space flight experiments, particularly the AMSAT-OSCAR-40 experiment, provided data to enhance space user requirements and SSV

• 2000-2010—NASA/DoD team coordinated set of updated Space User requirements to meet existing and future PNT needs
  – Team worked with SMC/GPE, Aerospace support staff and AFSPACE to assess impacts of proposed requirements to GPS-III and to incorporate appropriate language into GPS-III Capabilities Description Document (CDD)
  – Threshold requirements correspond to performance from current constellation (do no harm to space users)
  – Future space user needs included as Objective requirements
  – Continual Joint Program Office “zero impact” push back on CDD levels to GPS-III baseline (Objective requirements)
  – Agreed to perform NASA/DoD study further as constellation design matures with emphasis on moving towards Objective requirements
  – Government System Spec (SS-SYS-800) includes CDD threshold & objective performance
Navigation Improvements Resulting from an Interoperable SSV

• Analysis performed to understand effects of augmenting GPS SSV signals with interoperable GNSS and SBAS

• Configuration analyzed:
  – GPS: 24 + 3 configuration
  – Galileo: 27 satellite configuration
  – GLONASS: 24 satellite configuration
  – Beidou: 27 MEO, 5 GEO, 3 IGSO
  – SBAS: 3 satellites for WAAS, EGNOS, SDCM (planned), QZSS(planned); GAGAN: first satellite launched

• Benefits observed:
  – >4 satellites observed 100% of time w/ all GNSS constellations & augmentations
  – Factor of ~2-5 improvement in geometric dilution of precision (GDOP) when all constellations included

• Global, interoperable Space Service Volume specifications are crucial for real-time GNSS navigation solutions in high Earth orbit
Navigation Coverage, 4+ Satellites in View

GNSS Constellations + SBAS

Graph showing the percentage of coverage over altitude for GNSS and GPS only.
Geometric Dilution of Precision, 36500 km
Acknowledgements

• Sincere thanks to all in the U.S. that have helped realize the Space Service Volume vision:
  – USAF SMC GPS Program Office
  – NASA
  – Frank Bauer
  – Stephan Esterhuizen
  – Dale Force
  – John Rush
  – Jules McNeff
  – James Miller
  – Mike Moreau
  – A.J. Oria
  – Scott Pace
  – Park Temple
  – Larry Young

• Acknowledging, in advance, all outside the U.S. that recognize the in-space advantages of the Space Service Volume specification and provide leadership in developing a Space Service Volume specification for their GNSS constellation
Scientific Applications & Actions from Vienna 2013
Applications: Ocean Altimetry and Terrestrial Reference Frame

How to create: GPS Transmit Antenna Maps (group delay and phase vs. angle)

Variation of antenna patterns between spacecraft and between blocks

Recommendations from the Scientific Community
Uncertainties in GPS transmit antenna phase variations are among the limiting sources of error in global, GPS-based geodesy. Apparent root cause of:

- Bias in Topex GPS antenna position
- Drift in Jason GPS antenna position

Application: Ocean Altimetry

(Bruce Haines et al)
Application: Reference Frame


This Study vs. ITRF2005

Legacy vs. ITRF2005

Legacy vs. ITRF2000

+0.01 ppb/yr

–0.21 ppb/yr

–0.37 ppb/yr

Application: Reference Frame


With GRACE-measured GPS antenna phase maps

With antenna phase-center offset only

(Bruce Haines et al)
GPS Transmit Antenna Maps

- Maps are made from $0^\circ$ to $15^\circ$ off nadir
- Ionosphere-free GPS L1/L2 measurements

**BK IIR-A Group Delay vs Angle**
(Shailen Desai et al)

**BK IIR-M Phase Variations**
(Bar-Sever et al)
Maps created from stacked post-fit POD residuals:
• Iterative approach
• A priori GRACE antenna model from pre-launch anechoic measurements
• Estimates for all PRNs flying Oct. 2006–Nov. 2009
• Includes group delay (Ionosphere-free pseudorange, $PC$)

Off-nadir angle vs. percentage of observations

(Bruce Haines et al)
GPS Block IIA Transmit Antenna

Group Delay

(BLOCK IIA)

Group Delay Variation (mm)

Beam Angle (deg.)

Phase

(BLOCK IIA)

Phase Variation (mm)

Beam Angle (deg.)

(Bruce Haines et al)
GPS Block IIR-A Transmit Antenna

**Group Delay**

**Phase**

(Bruce Haines et al)
GPS Block IIR-B Transmit Antenna

**Group Delay**

![Group Delay Graph](image)

**Phase**

![Phase Graph](image)

(Bruce Haines et al)
GPS Block IIR-M Transmit Antenna

(Bruce Haines et al)
**Recommendations for GNSS Transmit Antennas—Delay and Phase Variation vs. angle**

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Variation</th>
<th>Knowledge of variation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimize group delay (pseudorange)</td>
<td>&lt;1 ns (0.3 m)</td>
<td>0.1 ns (30 mm) (accurate to 0.1ns with 95% probability)</td>
<td>L1: 0° to 23.5° off boresight</td>
</tr>
<tr>
<td>variation with angle</td>
<td></td>
<td></td>
<td>L2: 0° to 26° off boresight</td>
</tr>
<tr>
<td>Minimize phase variation with angle</td>
<td>&lt;0.01 ns (3mm)</td>
<td>0.001 ns (0.3 mm) (accurate to 1ps with 95% probability)</td>
<td>L1: 0° to 23.5° off boresight</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>L2: 0° to 26° off boresight</td>
</tr>
</tbody>
</table>
### Recommendations for GNSS Transmit Antennas – Delay & Phase Centers

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Accuracy</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group delay (pseudorange) center</td>
<td>0.1 ns (30 mm) with 95% probability</td>
<td>95% probability</td>
</tr>
<tr>
<td>Phase center</td>
<td>0.1 ps (0.03 mm)</td>
<td>95% probability. Antenna range measurement precision &lt; 0.03mm</td>
</tr>
</tbody>
</table>

The **best-fit group-and-phase delay center** is defined to be the least-squares solution for the center of a sphere of constant delay, with observations weighted equally by solid angle, from 0 to 14 degrees off boresight.
<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Coherence</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Relative group delay offset</strong> (coherence among codes)</td>
<td>&lt; 10 ns (3 m)</td>
<td>Delay between transitions of signals shall not exceed 10ns (inter-signal, inter-frequency)</td>
</tr>
<tr>
<td><strong>Relative phase offset</strong> (coherence among carriers)</td>
<td>&lt; 10 milliradians (1 ps or 0.3 mm at GPS L1)</td>
<td>Aside from a constant bias, any pair of carriers may not deviate between each other by more than 10 milliradians</td>
</tr>
<tr>
<td><strong>Group delay vs. phase coherence</strong></td>
<td>&lt; 0.030 ns (9 mm) over 6 hour period</td>
<td>Application: Smoothing of pseudorange with carrier phase.</td>
</tr>
</tbody>
</table>
Conclusion

• For the scientific community to realize the full potential of a satellite navigation system, it is crucial to provide a **precise and stable system**.

• **Care must be taken** when designing transmit antennas and spacecraft electronics due to variations between products.

• **Tables of recommendations** were provided, relating to designing of transmit antennas and satellite electronics.
Backups
Specifications (1): Received Signal Power

<table>
<thead>
<tr>
<th>Signal</th>
<th>Terrestrial Minimum Power (dBW)</th>
<th>SSV Minimum Power (dBW)*</th>
<th>Reference Half-beamwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 C/A</td>
<td>-158.5</td>
<td>-184.0</td>
<td>23.5</td>
</tr>
<tr>
<td>L1C</td>
<td>-157.0</td>
<td>-182.5</td>
<td>23.5</td>
</tr>
<tr>
<td>L2C</td>
<td>-158.5</td>
<td>-183.0</td>
<td>26</td>
</tr>
<tr>
<td>L5</td>
<td>-157.0</td>
<td>-182.0</td>
<td>26</td>
</tr>
</tbody>
</table>

(*) SSV Minimum power from a 0 dBiC antenna at GEO

- SSV minimum power levels were specified based on the worst-case (minimum) gain across the Block IIA, IIR, IIR-M, and IIF satellites

- Some signals have several dB margin with respect to these specifications at reference off-nadir point
Specifications (2): Pseudorange Accuracy

• In the Terrestrial Service Volume, a position accuracy is specified. In the Space Service Volume, pseudorange accuracy is specified.

• Position accuracy within the space service volume is dependent on many mission specific factors, which are unique to this class of user, such as user spacecraft orbit, CONOPS, navigation algorithm, and User Equipment.

• Specification: The space service volume pseudorange accuracy shall be ≤ 0.8 m (rms) (Threshold); and ≤ 0.2 m (rms) (Objective).

• In order for GPS to meet the SSV accuracy requirement, additional data must be provided to users:
  
  – The group delay differential parameters for the radiated signal with respect to the Earth Coverage
# Specifications (3): Signal Availability

- Assuming a nominal, optimized GPS constellation and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV should be as follows:

<table>
<thead>
<tr>
<th></th>
<th>MEO SSV</th>
<th>HEO/GEO SSV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at least 1 signal</td>
<td>at least 1 signal</td>
</tr>
<tr>
<td></td>
<td>4 or more signals</td>
<td>4 or more signals</td>
</tr>
<tr>
<td>L1</td>
<td>100%</td>
<td>≥ 97%</td>
</tr>
<tr>
<td></td>
<td>≥ 97%</td>
<td>≥ 80%</td>
</tr>
<tr>
<td>L2, L5</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>≥ 92%</td>
<td>≥ 6.5%</td>
</tr>
</tbody>
</table>

1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

- Objective:
  - MEO SSV: 4 GPS satellites always in view
  - HEO/GEO SSV: at least 1 GPS satellite always in view
Signals Present for 25 dB-Hz Sensitivity
GPS Receiver at Moon

Receiver at Moon: 25 dB-Hz Sensitivity and 10 dB Receiving Antenna

Longest Outages ~90 minutes

Typical Pass Durations 50 min

Typical Pass Durations 10-15 minutes

Elapsed Days
GPS Use in Cislunar Space

- Weak GPS signal tracking technology enables tracking signals up to approximately $\frac{1}{2}$ the distance to the Moon.
- For example, a spacecraft returning from the Moon could start using GPS data 16 hours before Earth Insertion (EI) for trajectory determination.