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

Frank H. Bauer, *FBauer Aerospace Consulting Services (FB-ACS)*
Joel J. K. Parker, *NASA Goddard Space Flight Center*
Bryan Welch, *NASA Glenn Research Center*
Werner Enderle, *ESA European Space Operations Center*

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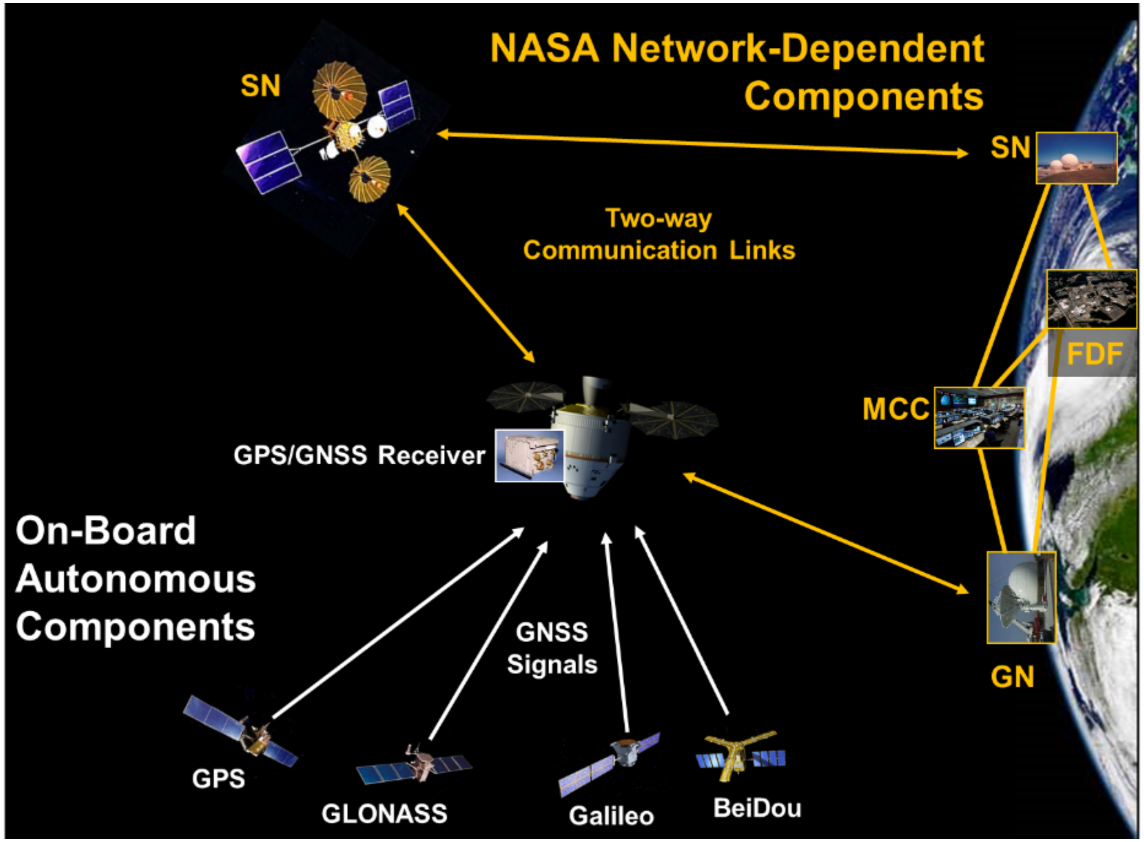
Benefits of GPS/GNSS to NASA

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

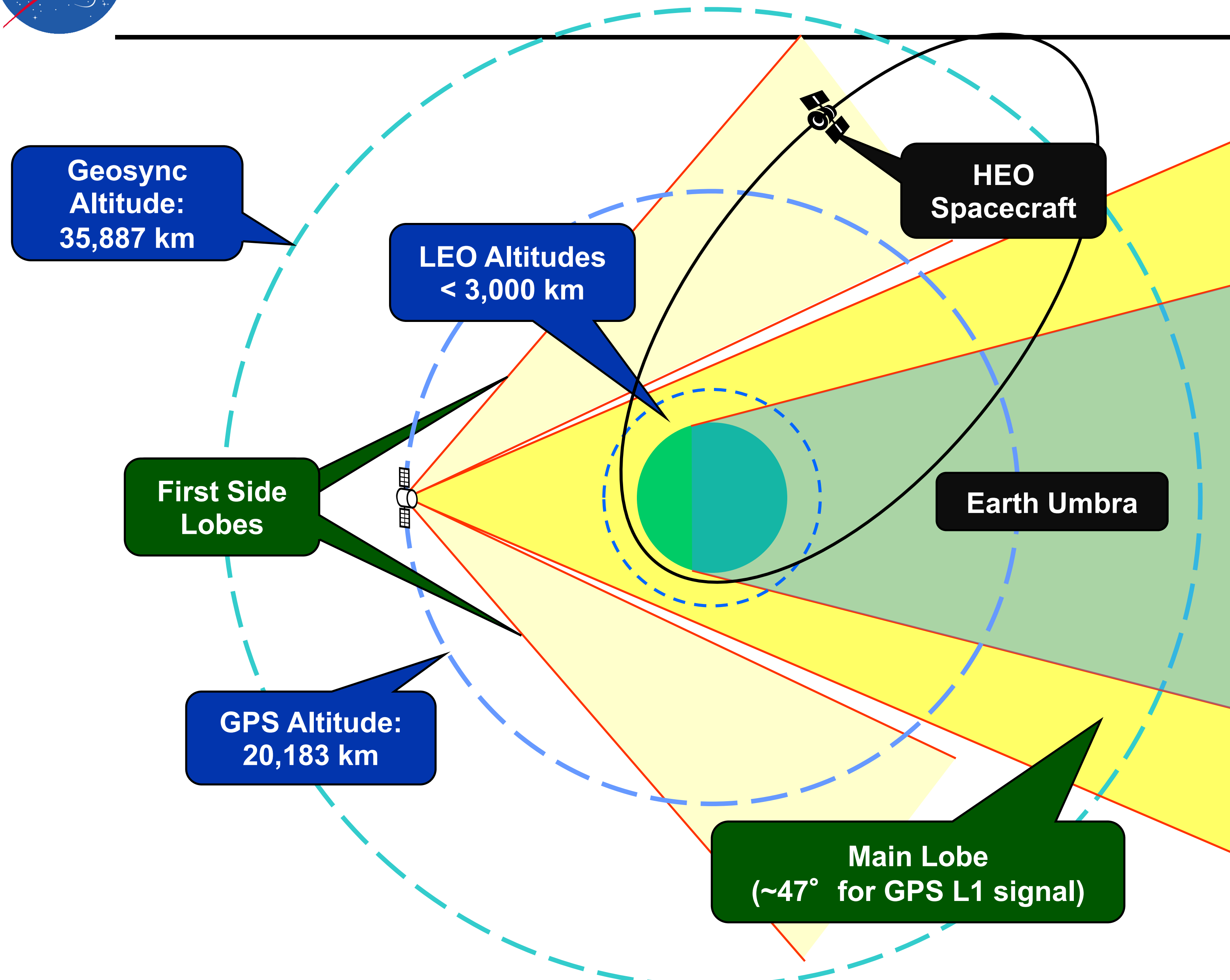
Attitude Determination: Use of GPS/GNSS enables some missions to meet their attitude determination requirements, such as ISS



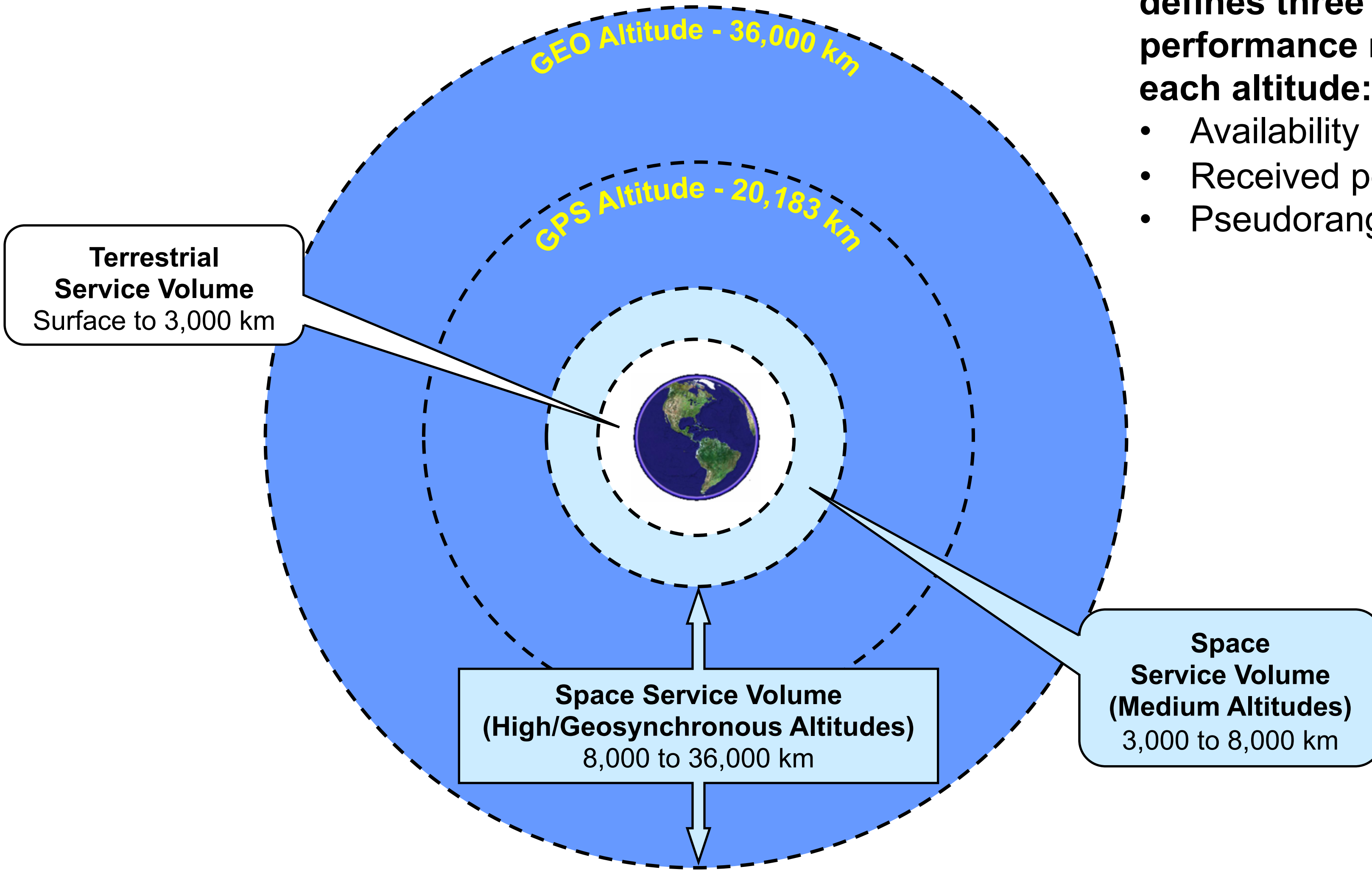
NASA is investing approximately $130M over the next 5 years on GPS R&D and its implementation in support of space operations and science applications

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

Reception Geometry for GPS Signals in Space



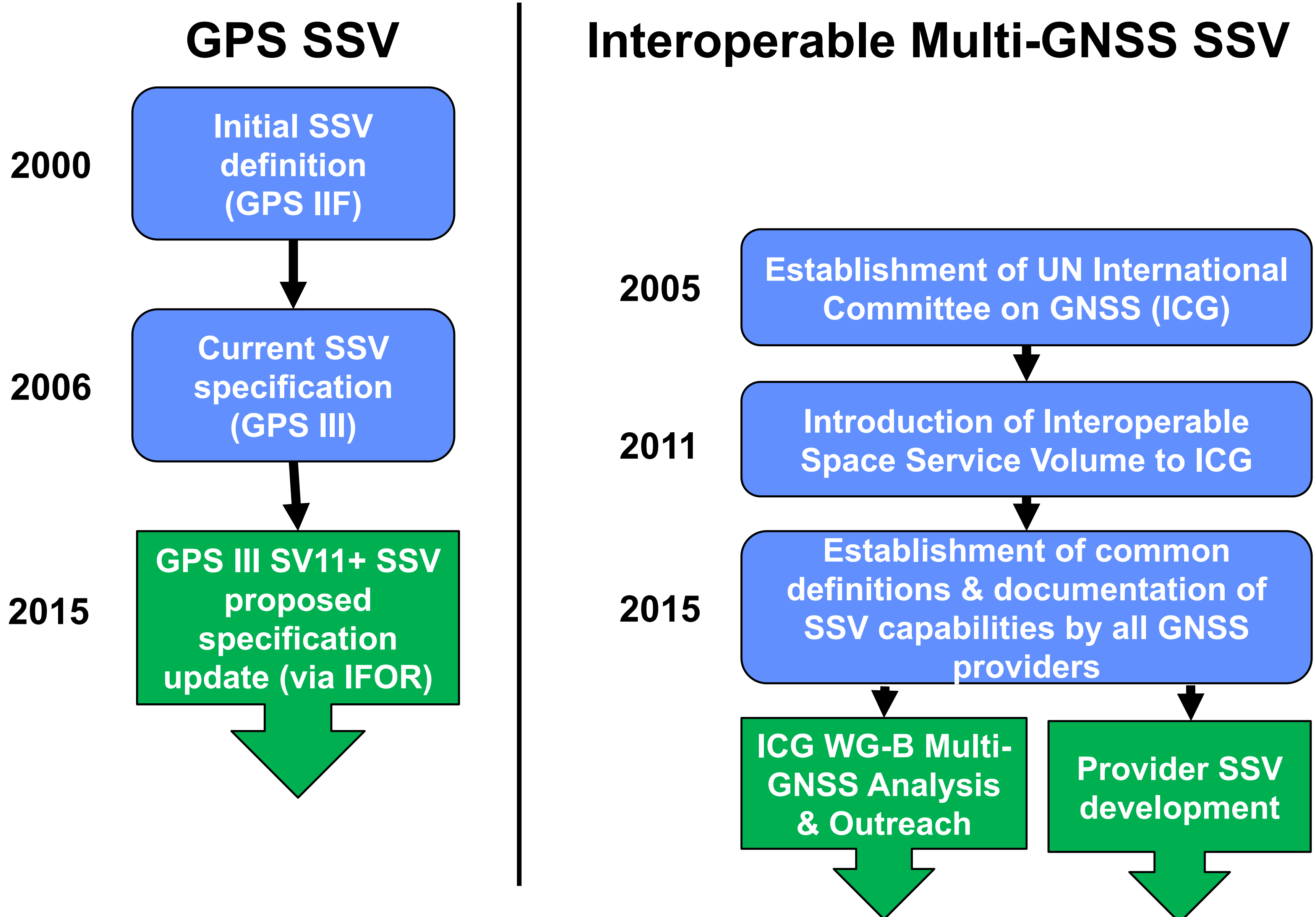
What is a Space Service Volume (SSV)?



The Space Service Volume defines three interrelated performance metrics at each altitude:

- Availability
- Received power
- Pseudorange accuracy

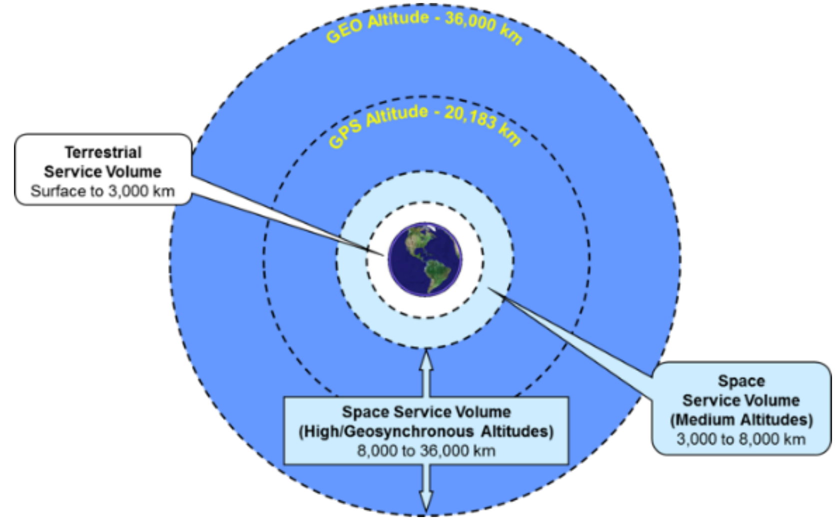
Past and Ongoing Development of the SSV

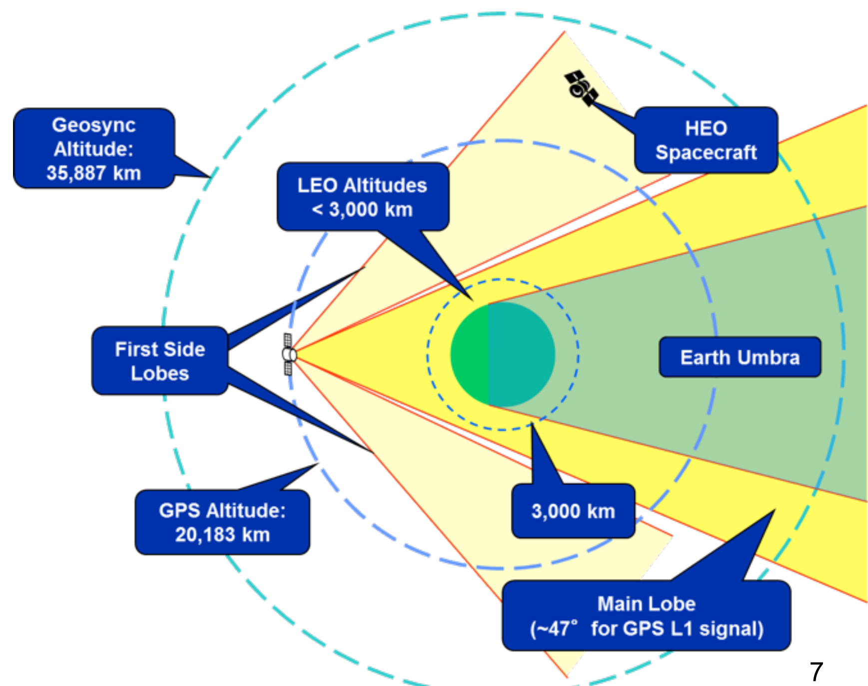


GPS SSV Progress

GPS Space Service Volume: Executive Summary

- 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



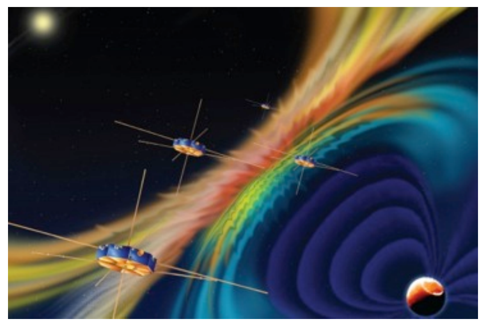


The Promise of using GNSS for Real-Time Navigation in the Space Service Volume

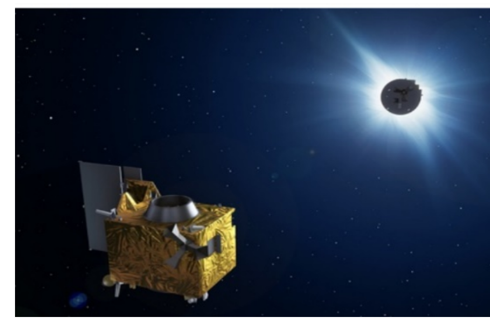
Benefits of GNSS use in SSV:

- 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

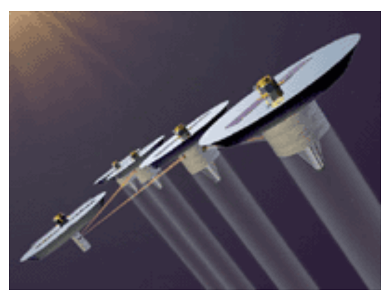


Space Weather Observations

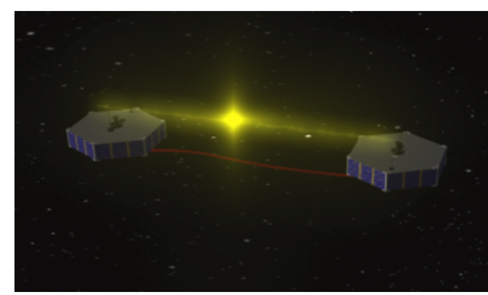


Precise Relative Positioning

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

Parameter	Requirement (m, 1-sigma)
Radial	33
In-track	25
Cross-track	25

- 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.

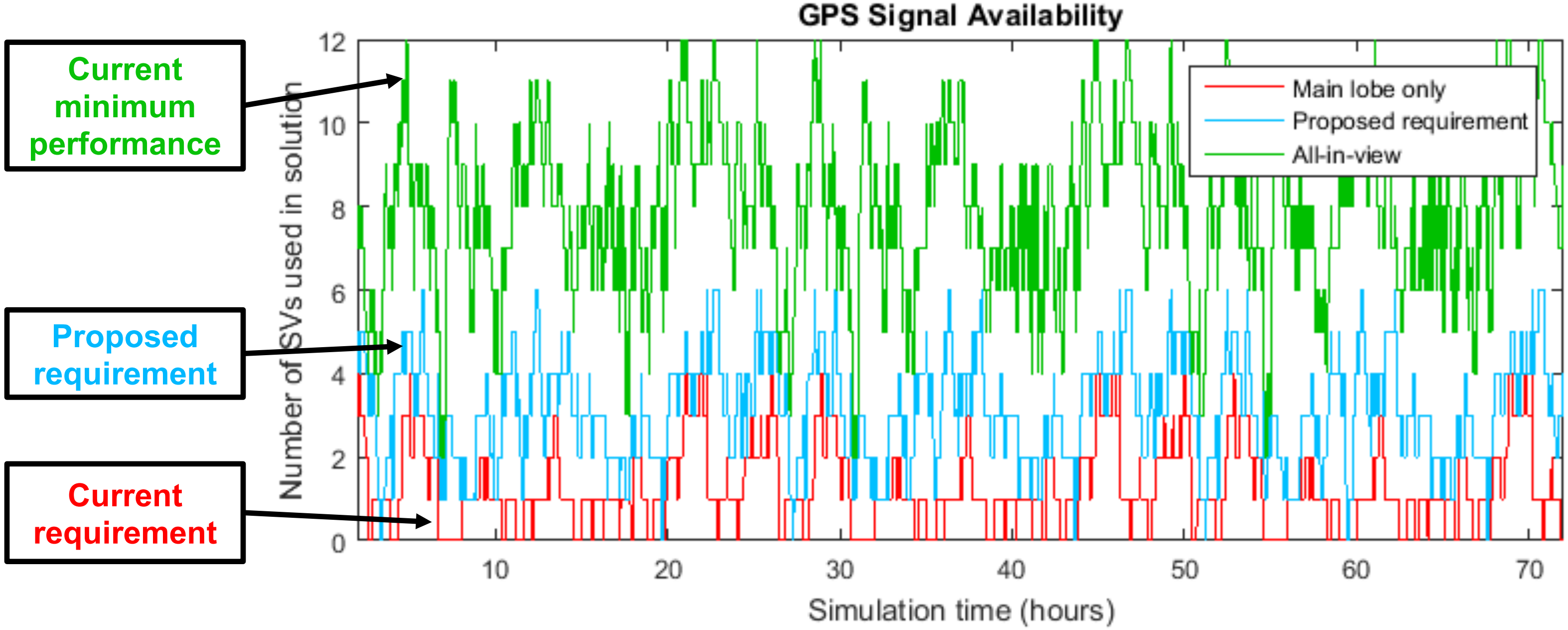
5X FASTER SCANS

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

www.nesdis.noaa.gov

NOAA Satellite and Information Service

Proposed GPSIII SV11+ SSV Requirement



Signal Availability for GOES-R-class GEO Mission

Independent of pseudorange accuracy

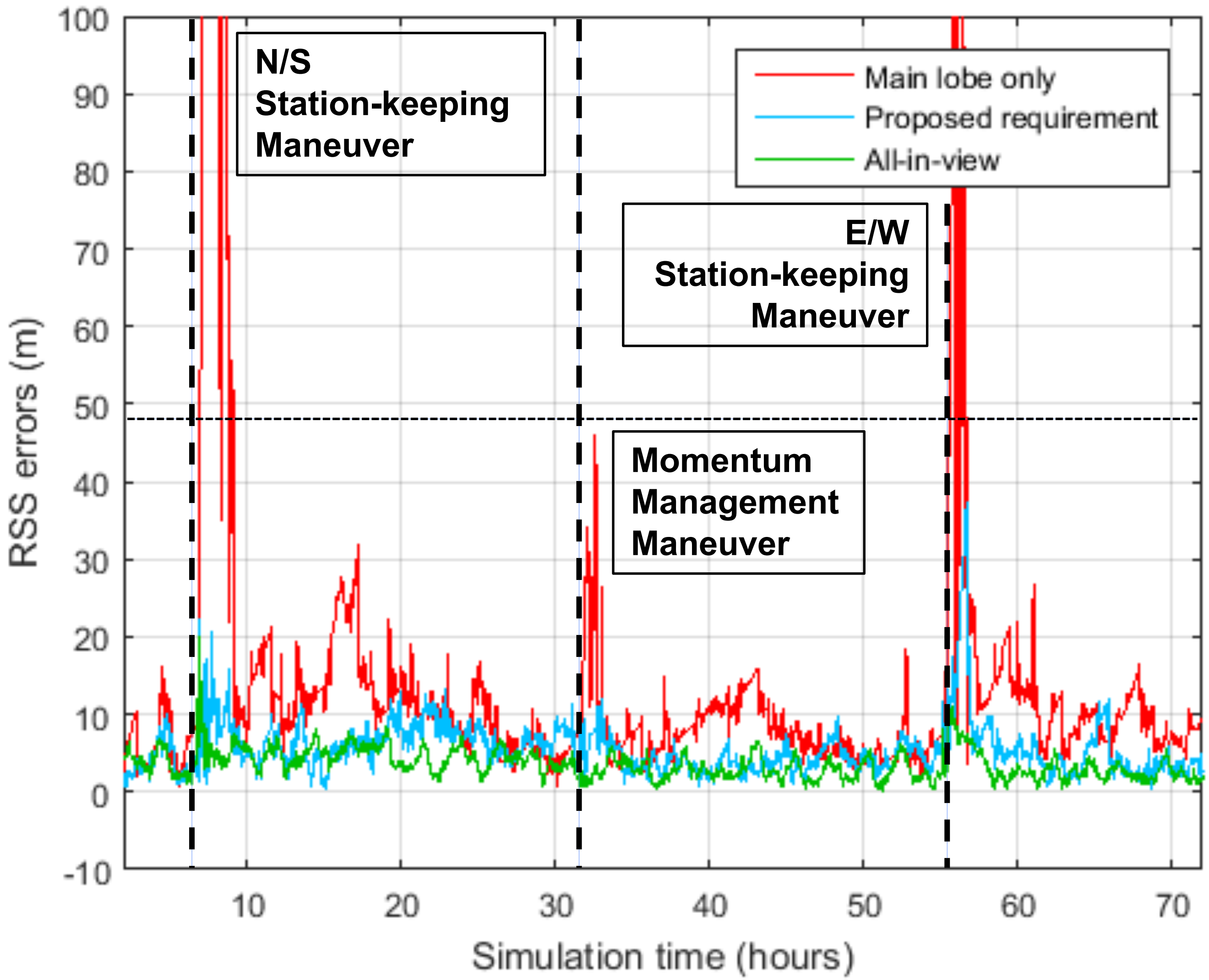
- **Proposed requirement adds second tier of capability specifically for HEO/GEO users**
  - Increased signal availability to nearly continuous for at least 1 signal
  - Relaxed pseudorange accuracy from 0.8m RMS to 4m RMS
  - No change to minimum received signal power
  - Applies to all signals (L1/L2/L5),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

PR acc. (rms)	**0.8 m**	**4m**
1+ signal	≥ 80%	≥ 99%
4+ signals	≥ 1%	≥ 33%
Max outage	108 min	10 min

SSV L1 HEO/GEO availability; 4m spec identical for L2/L5

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

http://www.oosa.unvienna.org/oosa/en/SAP/gnss/icg.html

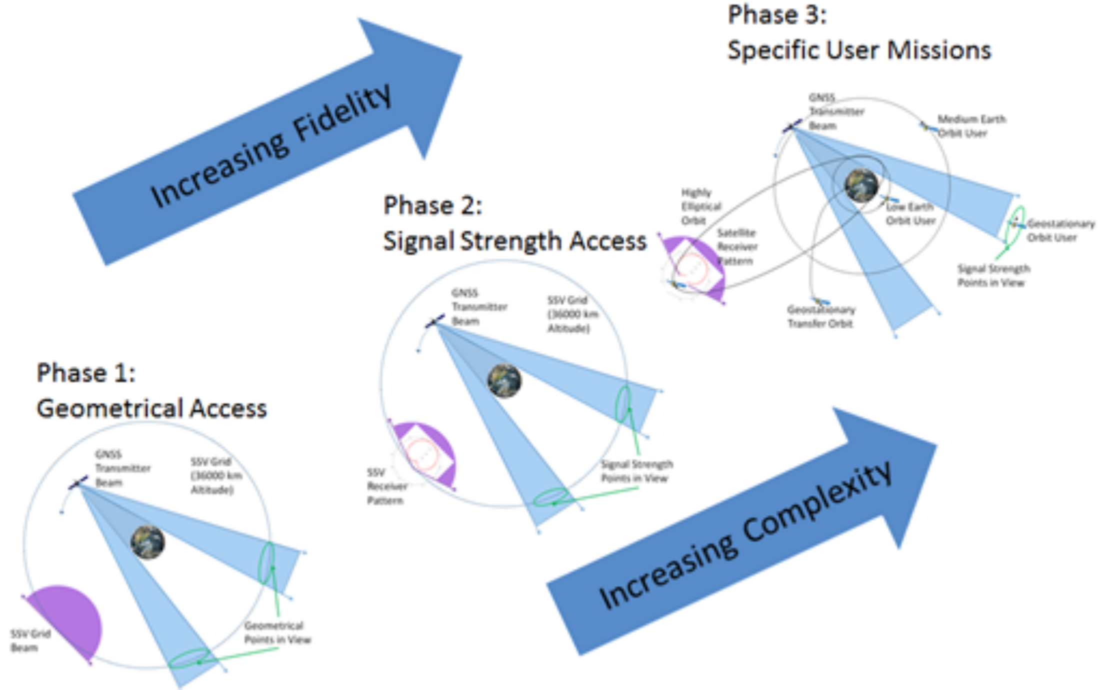
Summary of ICG Multi-GNSS SSV Development Efforts To-Date

- 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

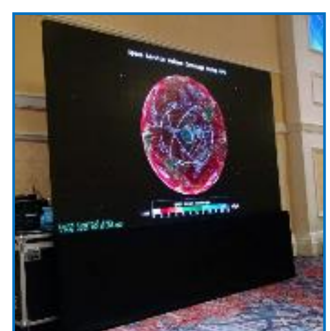
ICG WG-B Joint SSV Analysis Effort

- 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**

Multi-GNSS Simulation Overview

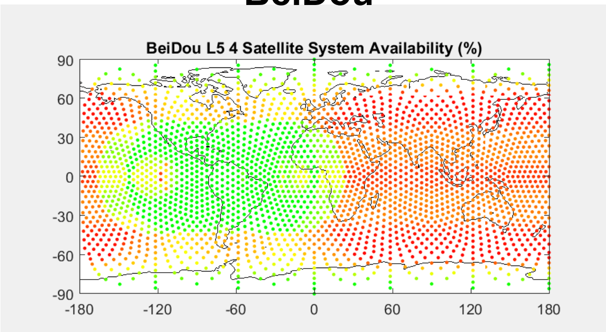


Multi-GNSS Simulation Video



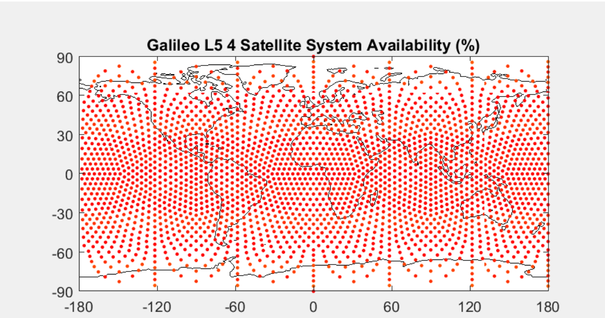
ICG WG-B Phase 1 Results: 4+ Signal Main-Lobe Availability

BeiDou



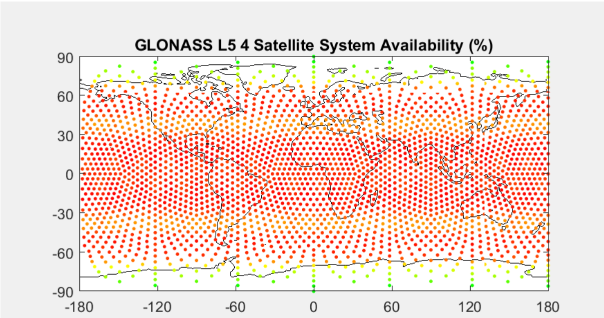
Average 45.4% availability

Galileo



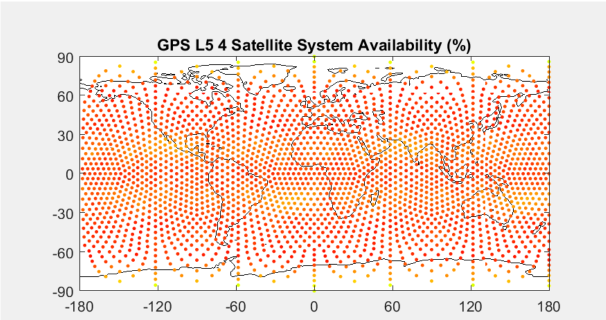
Average 4.2% availability

GLONASS



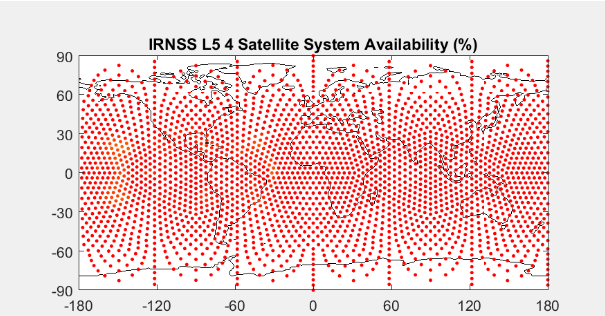
Average 14.5% availability

GPS



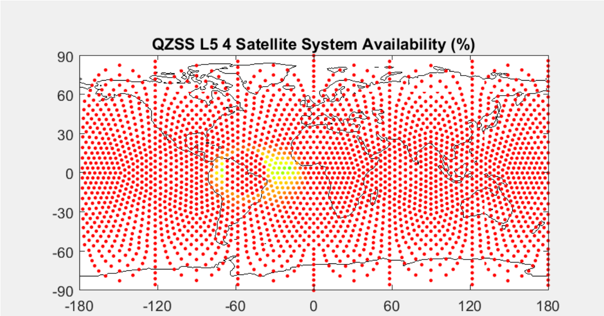
Average 15.6% availability

NAVIC



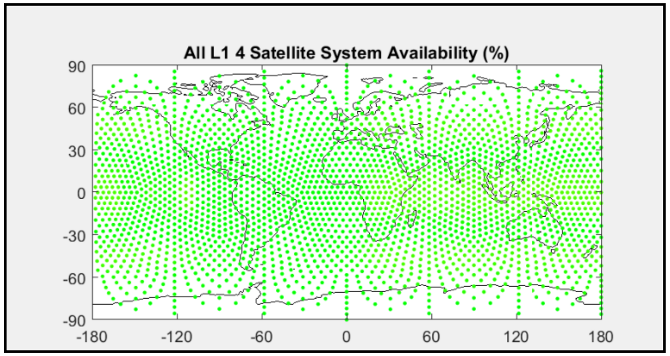
Average 0.6% availability

QZSS



Average 1.5% availability

Interoperable GNSS achieves 100% system availability



ICG-11 SSV Recommendations

ICG/REC/2016

Recommendation 1 for Committee Decision

Prepared by: Working Group B

Date of Submission: 10 November 2016

Issue Title: Support to Space Service Volume (SSV) in Future Generation of Satellites

Background/Brief Description of the Issue:

The importance of establishing an Interoperable GNSS Space Service Volume (SSV) is acknowledged by Space Agencies and Service Providers. Important progress has been made in establishing the interoperable GNSS SSV based on data that was released by the Service Providers.

Discussion/Analyses:

Service providers have been actively contributing to the completion of the SSV templates that include the support of the SSV of the different systems. Many GNSS provided data in the SSV template derived from measurement and characterization efforts conducted based on existing satellite designs.

Recommendation of Committee Action:

Service Providers, supported by Space Agencies and Research Institutions, are encouraged to define the necessary steps and to implement them in order to support SSV in future generation of satellites. Service Providers and Space Agencies are invited to report back to WG-B on their progress on a regular basis.

ICG/REC/2016

Recommendation 2 for Committee Decision

Prepared by: Working Group B

Date of Submission: 10 November 2016

Issue Title: GNSS Space User Database

Background/Brief Description of the Issue:

The understanding of user needs is an essential element for any service implementation or service evolution. This in particular also applies to the case of the Space Service Volume as the user needs are highly depending on the specific space mission and the use case of the on-board GNSS receiver.

Discussion/Analyses:

The understanding of the user base is critical for the development of the Interoperable GNSS Space Service Volume. An exhaustive identification of space missions embarking a GNSS receiver is essential in order to ensure a comprehensive view on the mission needs and the use cases of the GNSS receiver.

Recommendation of Committee Action:

Service providers, supported by Space Agencies and Research Institutions, are encouraged to contribute to the existing IOAG database of GNSS space users. Contributions should be reported to WG-B, which should then contribute to the IOAG via the ICG-IOAG liaison.

The data included in the database should include the following:

Basic details:

- *Mission name & agency*
- *Actual or planned launch date*
- *Development phase (planned, in development, on-orbit, historical)*
- *Orbit regime (LEO, HEO, GEO, cis-lunar, etc.)*

GNSS usage:

- *GNSS constellations used*
- *GNSS signals used*
- *GNSS application (navigation, POD, time, radio occultation, etc.)*
- *Acquisition methods used (traditional, carrier phase)*
- *Solution method (point solution, filtered solution, etc.)*

ICG/REC/2016

Recommendation 3 for Committee Decision

Prepared by: Working Group B

Date of Submission: 10 November 2016

Issue Title: Additional Data for Space Service Volume

Background/Brief Description of the Issue:

In order to exploit the Interoperable GNSS Space Service volume for space missions or to develop GNSS space receivers, information from the service providers regarding the power emissions for wide off-boresight angles are essential. Initial information on this aspect is available from every service provider.

Discussion/Analyses:

Recognizing the success of WG-B in encouraging all providers to provide SSV service details in templates for their constellations, GNSS space users now have the data necessary to determine if the SSV service is applicable to their needs.

Recommendation of Committee Action:

In order to fully support in-depth mission-specific navigation studies, WG-B invites the providers to consider for the future, to provide the following additional data if available:

- *GNSS transmit antenna gain patterns for each frequency, measured by antenna panel elevation angle at multiple azimuth cuts, at least to the extent provided in each constellation's SSV template.*

In the long term, also consider providing the following additional data (see also WG-D Recommendations):

- *GNSS transmit antenna phase center and group delay patterns for each frequency*

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?