GPS/GNSS Space Service Volume (SSV) Update Initiatives

U.S. and International Benefits – GOES-R in Action!

Mr. Joel J. K. Parker
Aerospace Engineer
Navigation and Mission Design Branch (Code 595)
NASA Goddard Space Flight Center

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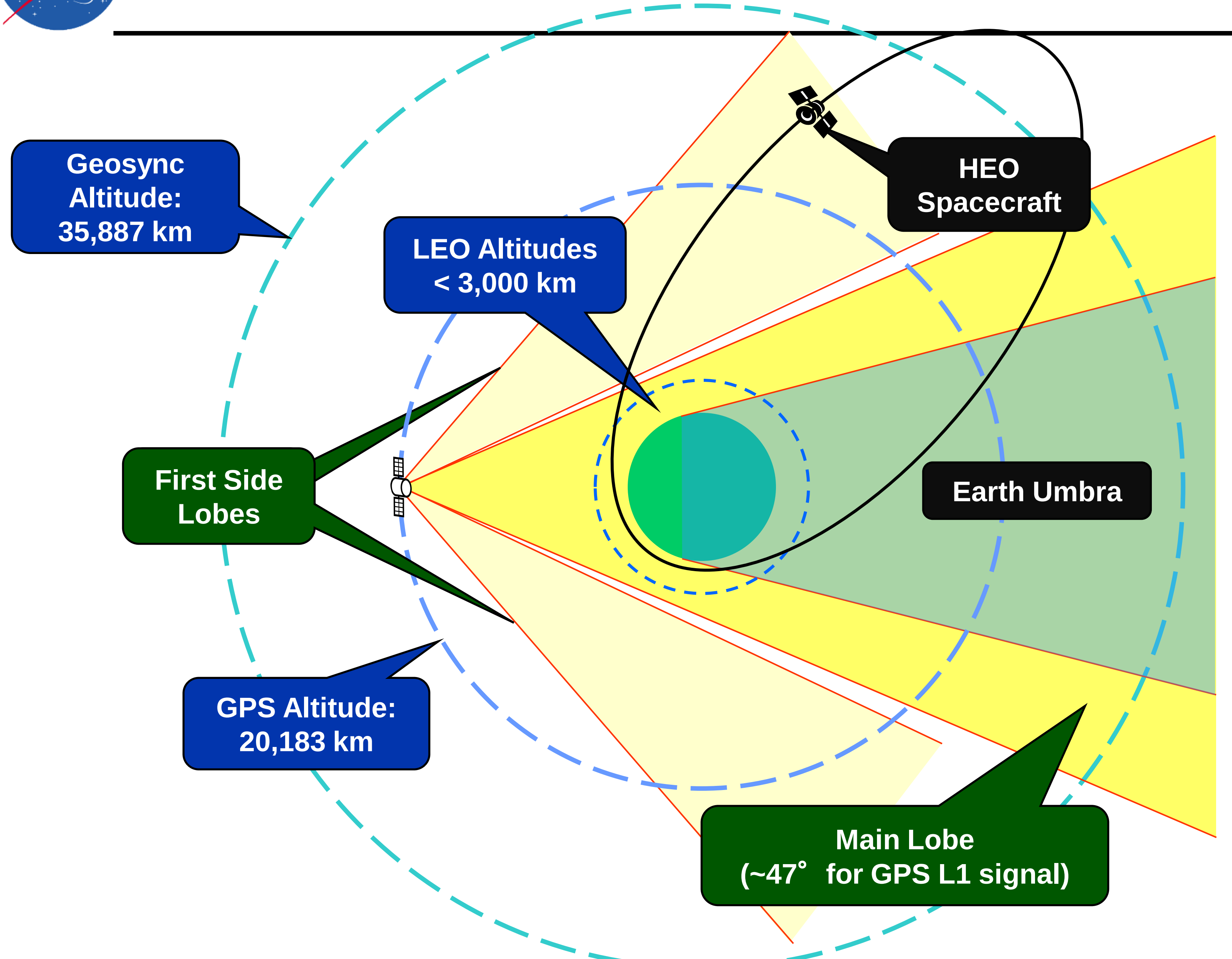
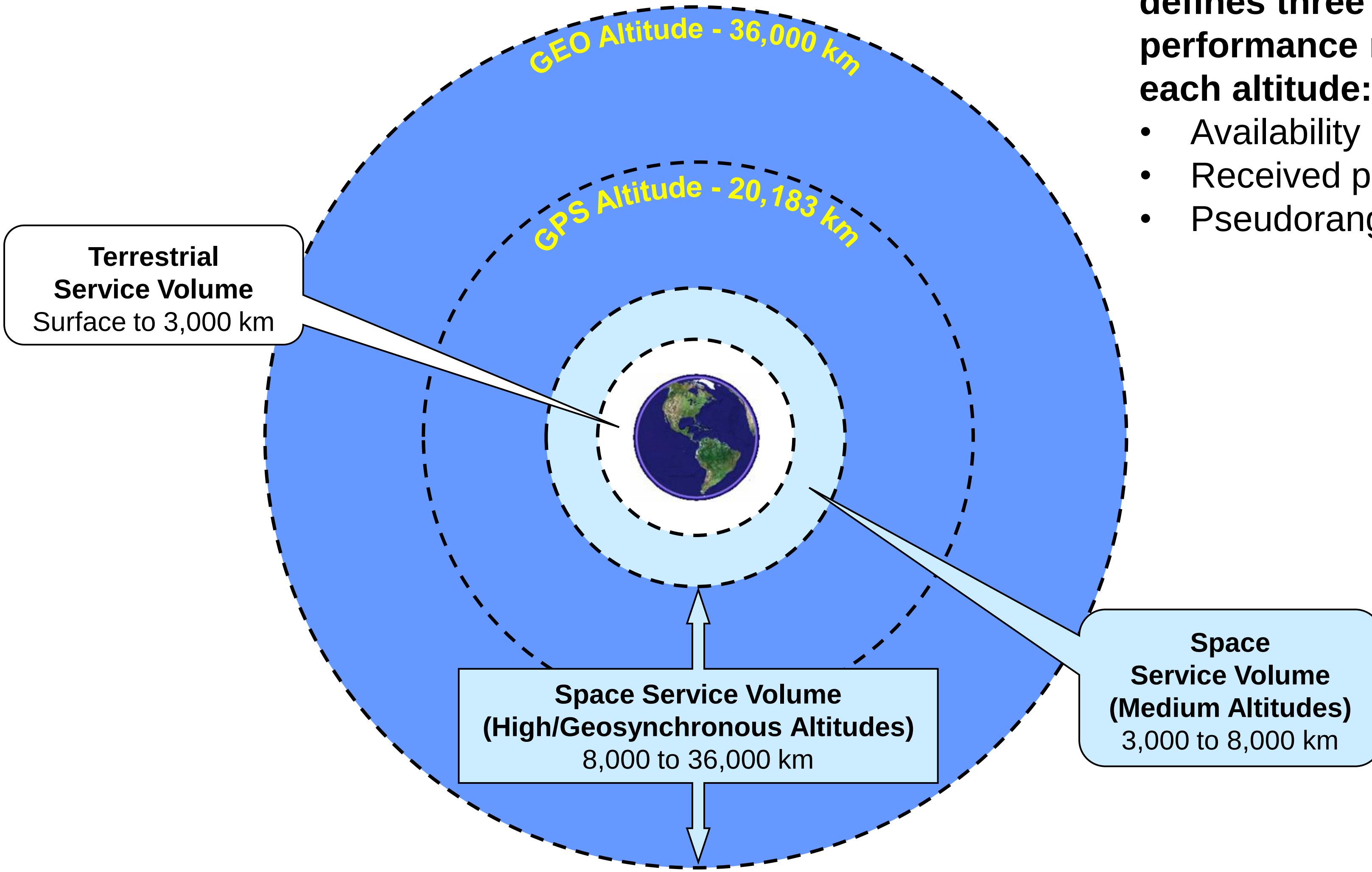
Before We Begin…

- **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?

Reception Geometry for GPS Signals in Space



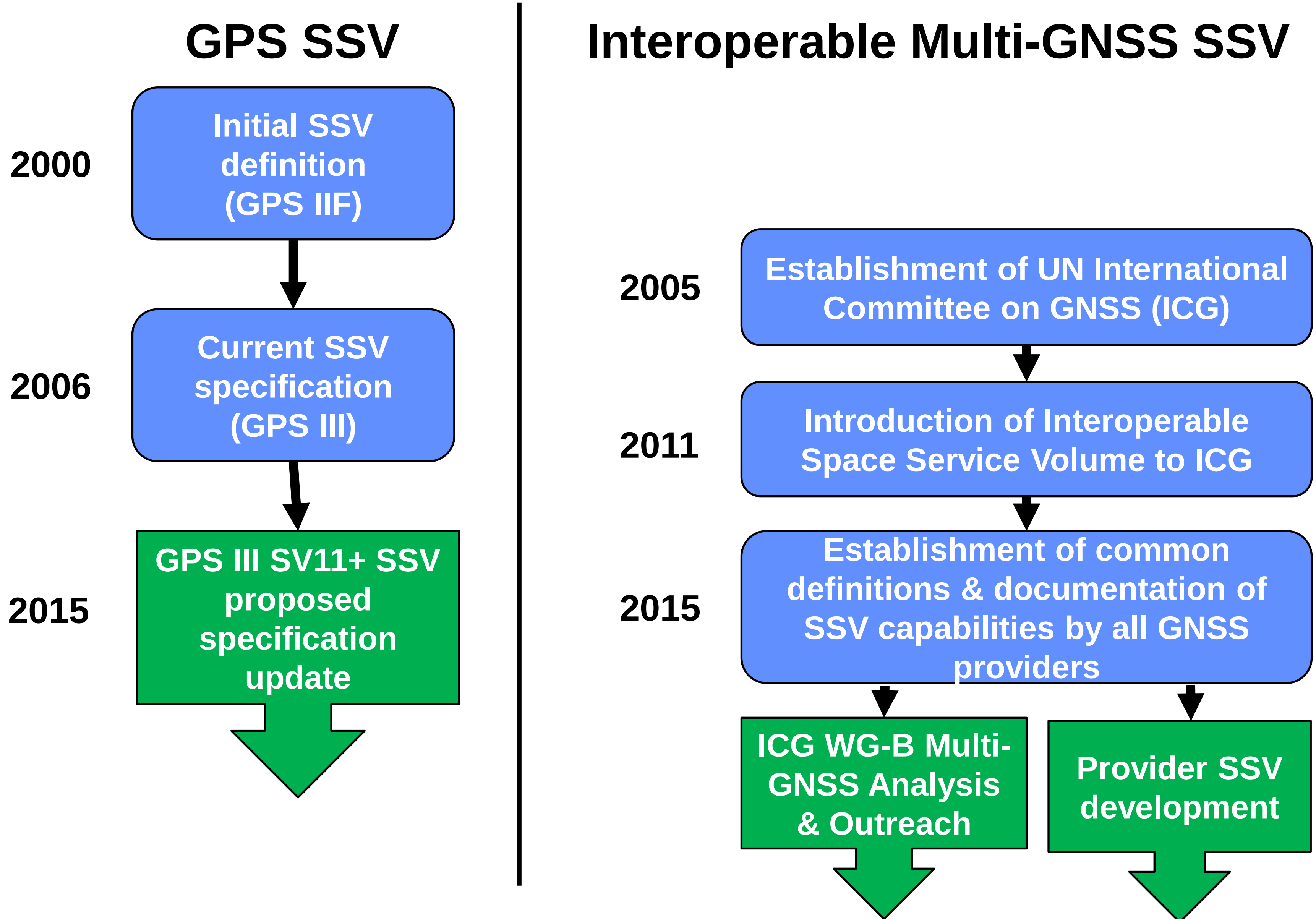
What is a Space Service Volume (SSV)?



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

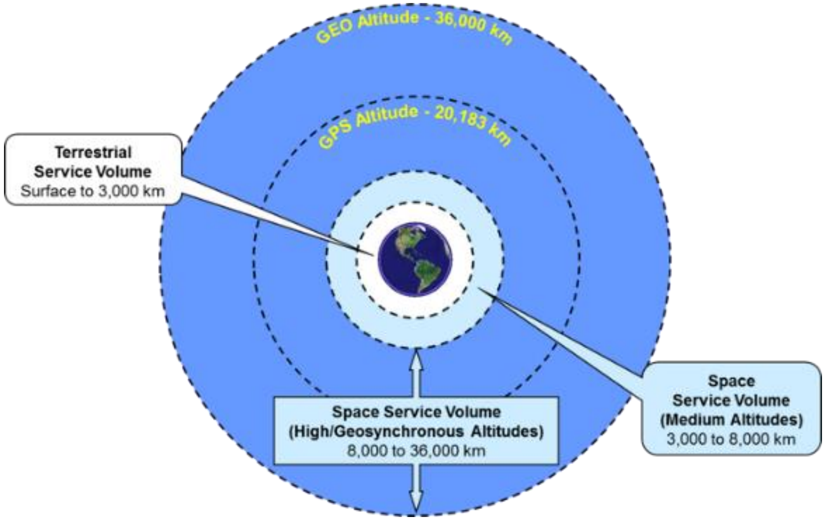
- Availability
- Received power
- Pseudorange accuracy

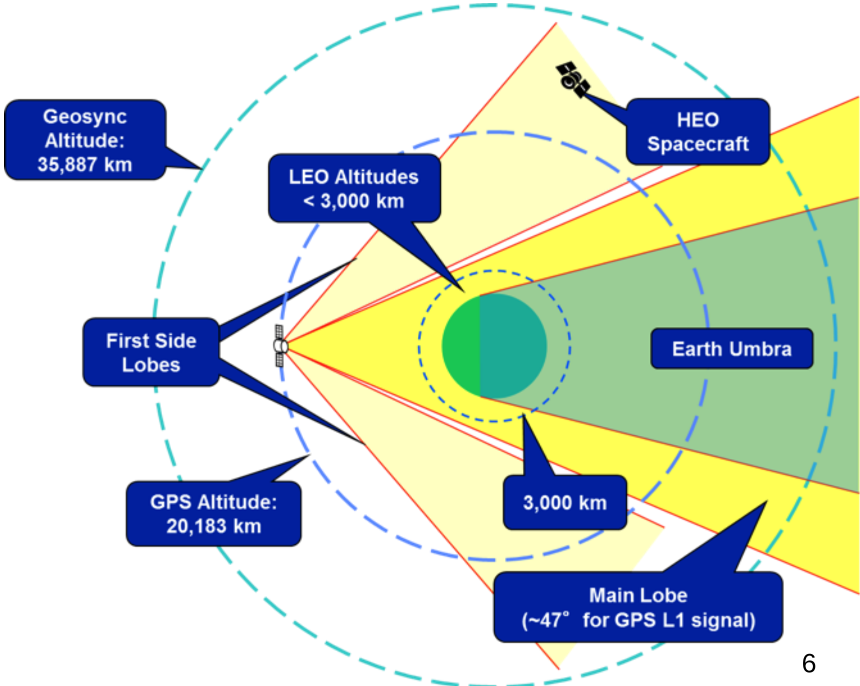
Past and Ongoing Development of the SSV



GPS 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





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.

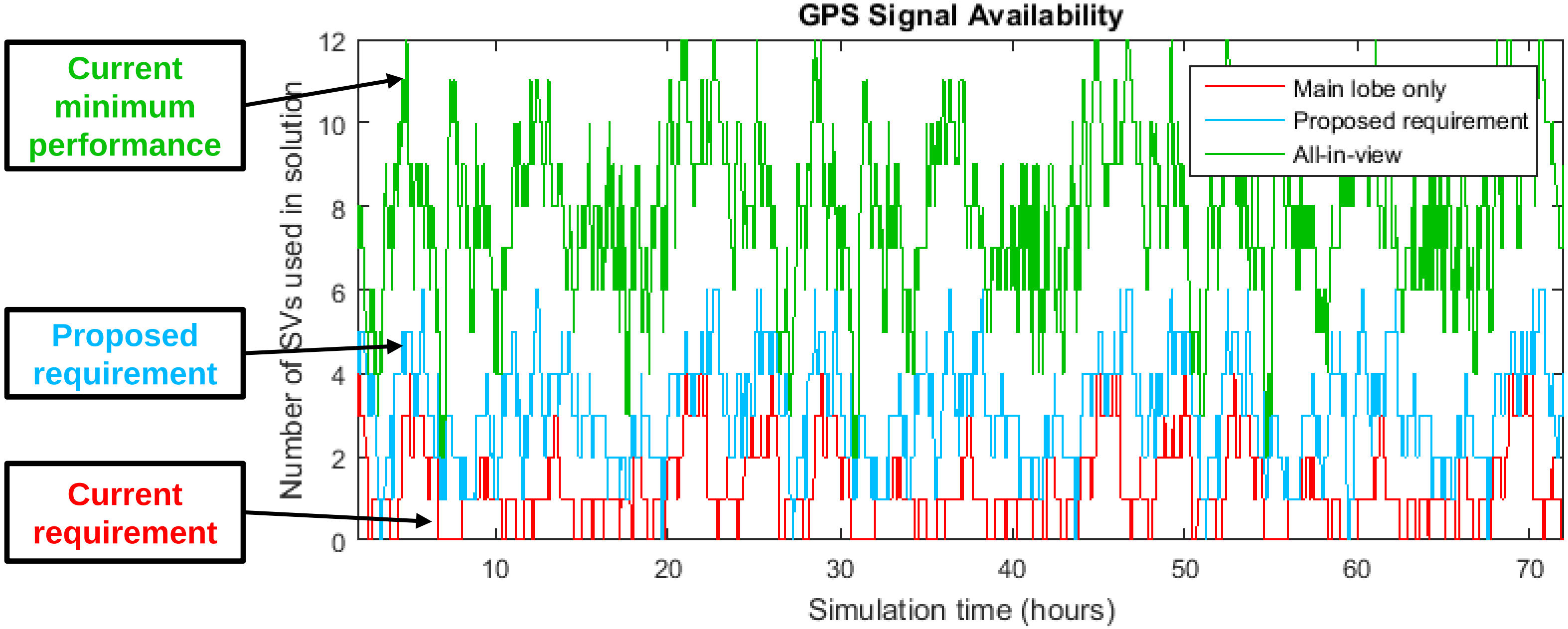
4X BETTER RESOLUTION

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.

Proposed GPSIII SV11+ SSV Requirement



Signal Availability for GOES-R-class GEO Mission

Independent of pseudorange accuracy

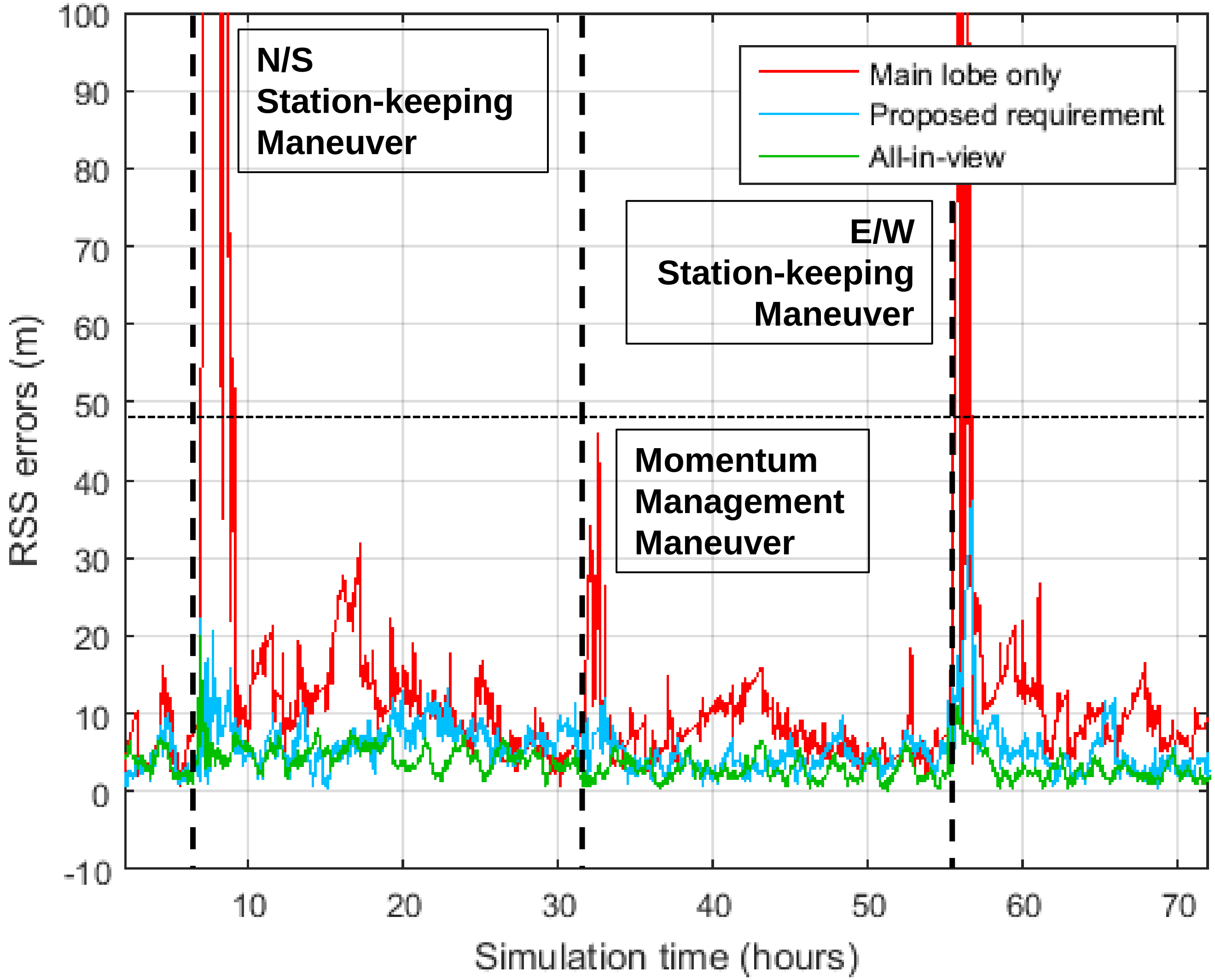
- **Proposed requirement adds second tier of capability specifically for HEO/GEO users**
  - Increased signal availability to nearly continuous for at least 1 signal
  - Relaxed pseudorange accuracy from 0.8m RMS to 4m RMS
  - No change to minimum received signal power
  - Applies to all signals (L1/L2/L5),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

IFOR Current Status

- **Key participants:**
  - NASA, USAF (user side)
  - SMC/GPV4 (GPS side)
  - AFSPC/A5M (IFOR side)
- **Original proposed recommendation from IFOR (Mar):**
  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
- **New proposed recommendation after HPT (Apr):**
  - 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.

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

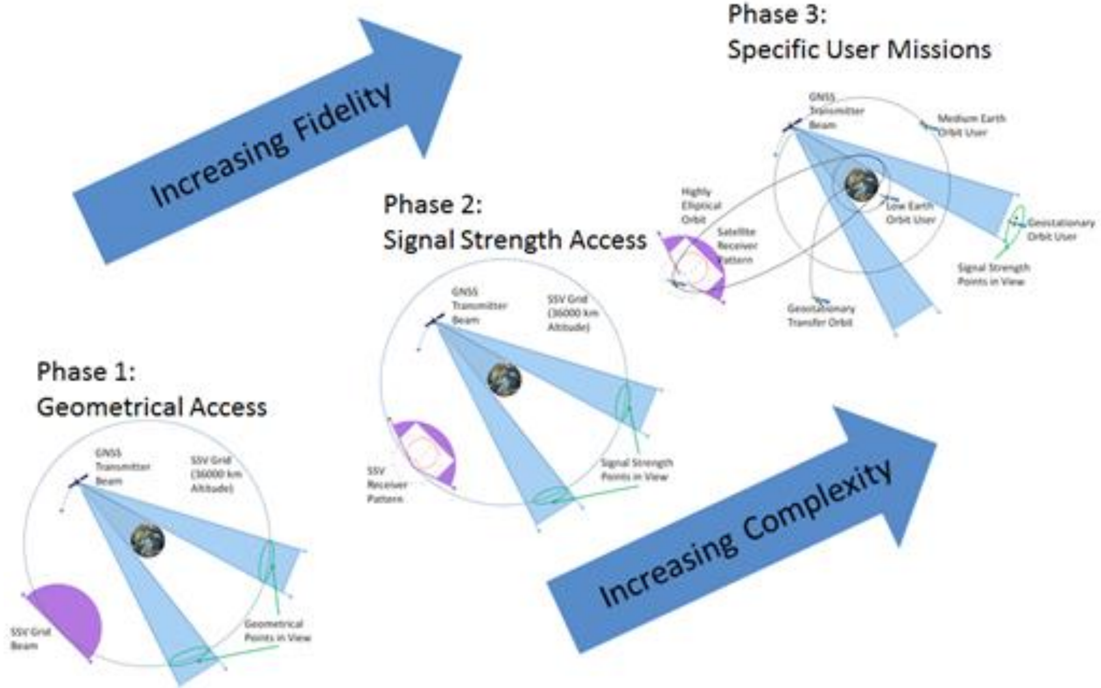
Summary of ICG Multi-GNSS SSV Development Efforts To-Date

- 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**

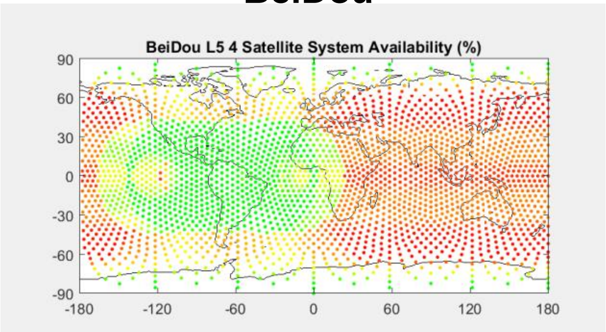
Multi-GNSS Simulation Overview



Multi-GNSS Simulation Video

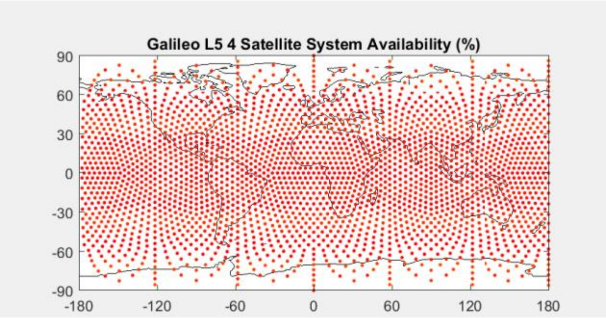
ICG WG-B Phase 1 Results:
4+ Signal Main-Lobe Availability

BeiDou



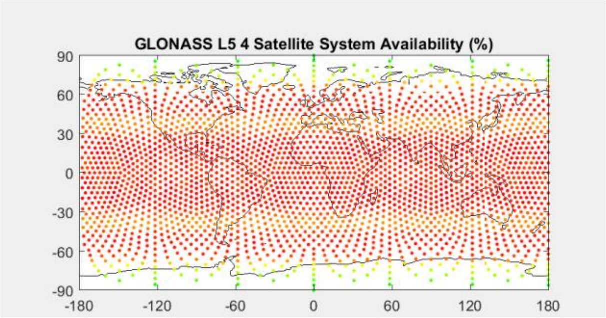
Average 45.4% availability

Galileo



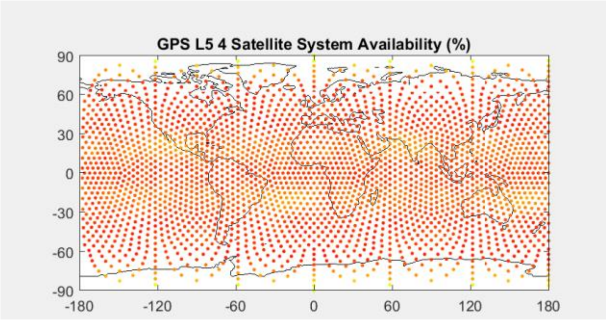
Average 4.2% availability

GLONASS



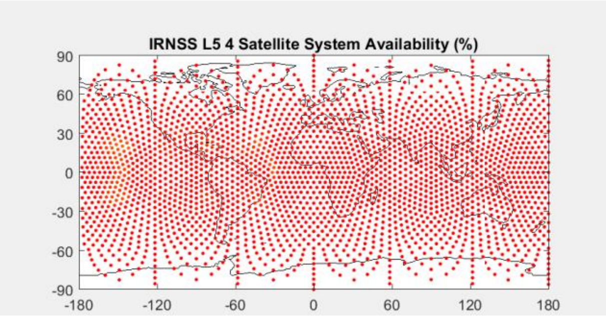
Average 14.5% availability

GPS



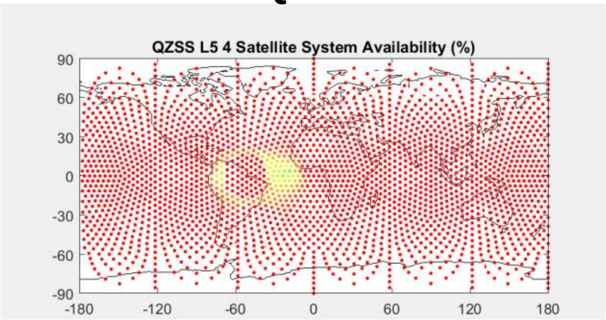
Average 15.6% availability

NAVIC



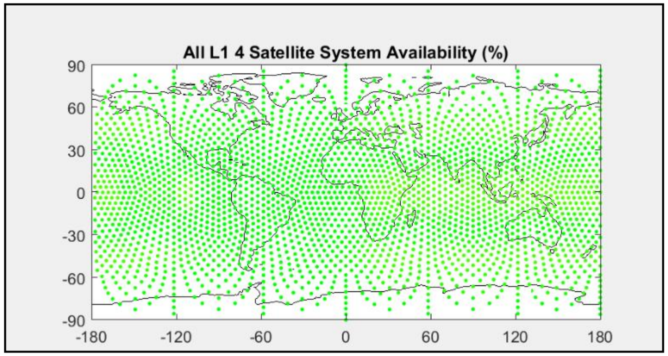
Average 0.6% availability

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.

A Continuing Discussion

- **15 Feb 2017: "Workshop on Emerging Technologies for Autonomous Navigation"**
- A one-day workshop on spacecraft navigation technologies.
- Public attendance welcome
- Hosted in Washington, DC by NASA Space Communications and Navigation (SCaN)
- Topics include:
  - Needs and Technology Drivers for Autonomous Navigation
  - GPS & Multi-GNSS SSV
  - Proximity Operations, Relative Navigation, Formation Flying
  - Autonomous Entry Descent & Landing
  - Clocks & Timing
  - Signal Diversity & Data Fusion
  - Optical Navigation Technologies
- We are currently seeking talks and presenters.
- Contact:
  Joel J. K. Parker, joel.j.k.parker@nasa.gov
  JJ Miller, jj.miller@nasa.gov

Backup

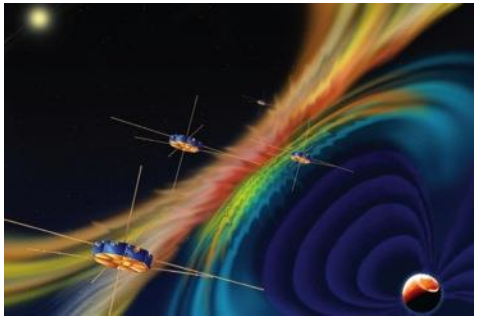
The Promise of using GPS for Real-Time Navigation in the Space Service Volume

Benefits of GPS use in SSV:

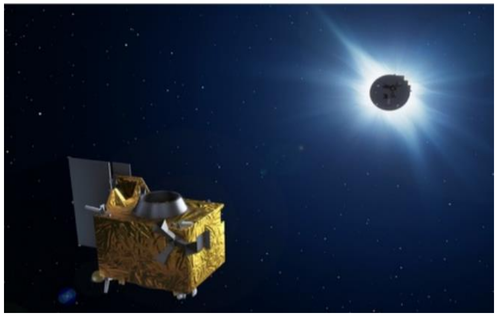
- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- GPS timing **reduces need for expensive on-board clocks** (from: $100sK-$1M to: $15K–$50K)
- Supports **increased satellite autonomy**, lowering mission operations costs (savings up to $500-750K/year)

- Enables new/enhanced capabilities and better performance for **HEO and GEO missions,** such as:

Earth Weather Prediction using Advanced Weather Satellites

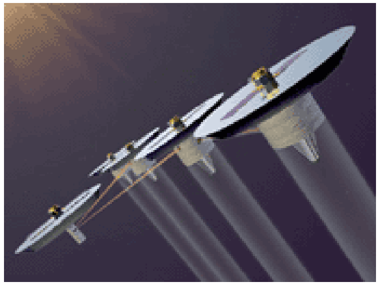


Space Weather Observations

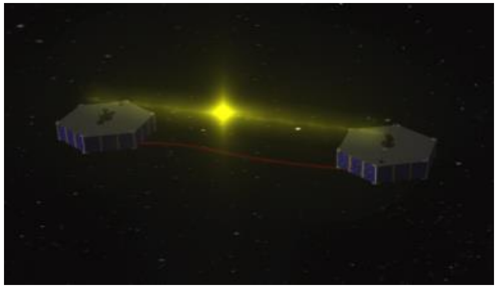


Precise Relative Positioning

Launch Vehicle Upper Stages & Beyond-GEO applications



Formation Flying, SSA, ProxOps



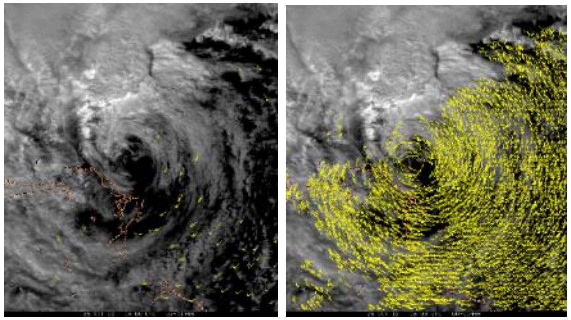
Precise Position Knowledge & Control at GEO

Statement of Need: GOES-R Spacecraft Series Issue Summary

- GOES-R-U series operational weather satellites of national importance, protecting people and property through weather prediction and severe event warnings
- New, improved Imager (ABI) combined with IFOR-improved GPS PNT will have **game-changing** societal benefits with enhanced temporal, spatial, spectral & radiometric attributes
- GPS/GOES nav. stability & geolocation requirements critical to derive first & second derivative wind measurements, significantly improving wind velocity estimations
- Safety of people/property data products **requiring** the NASA-proposed (improved) SSV specification include:
  - Improved wind vector measurements—significantly enhancing convective (severe) storm prediction & danger zone warning time
  - Exact location & volume of mountain downpours—improves flash flood warnings
  - Timely, precise location of wild fires—enables safe placement of firefighters & equipment
  - More accurate prediction of early morning fog for aviation
  - Better prediction of mountain weather where radar is ineffective
  - Blending GEO-sat (high temporal resolution), LEO-sat (high spatial resolution) & ground-based radars for more accurate prediction
  - **Improved weather forecasting from 3-5 days (now) to 5-7 days (GOES-R)**

Assembled GOES-R Spacecraft

Wind Vector Measurements Hurricane Sandy



Current GOES-R

Safety of People/Property Data Products Will Not Be Operationally Delivered if GPS Degrades Capability to Current GPS SSV Spec; Minimally Met Through Proposed SSV Spec

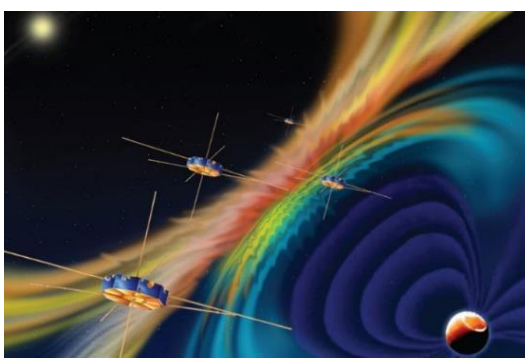
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

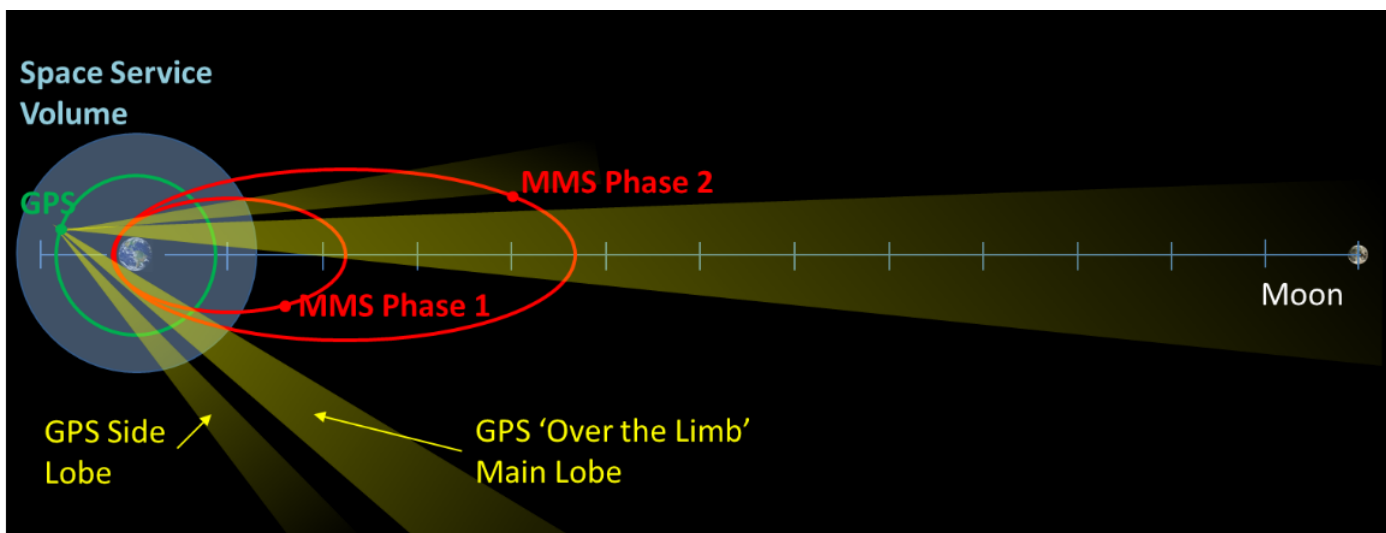
Magnetospheric Multi-Scale (MMS)

- **Launched March 12, 2015**
- **Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)**
- **Four spacecraft in highly eccentric orbits**
  - Phase 1: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - Phase 2: Extends apogee to 25 Re (~150,000 km)

MMS Navigator System

- **GPS enables onboard (autonomous) navigation and near autonomous station-keeping**
- **MMS Navigator system exceeds all expectations**
- **At the highest point of the MMS orbit Navigator <u>set a record for the highest-ever reception</u> of signals and onboard navigation solutions by an operational GPS receiver in space**
- **At the lowest point of the MMS orbit Navigator <u>set a record as the fastest operational GPS receiver</u> in space, at velocities over 35,000 km/h**



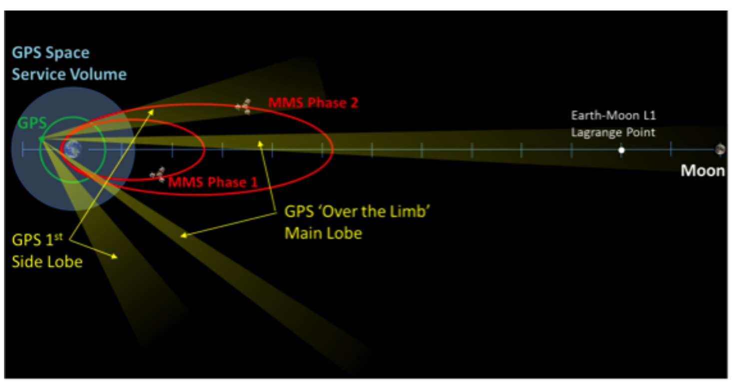


Example Performance: Side Lobe Signal Availability

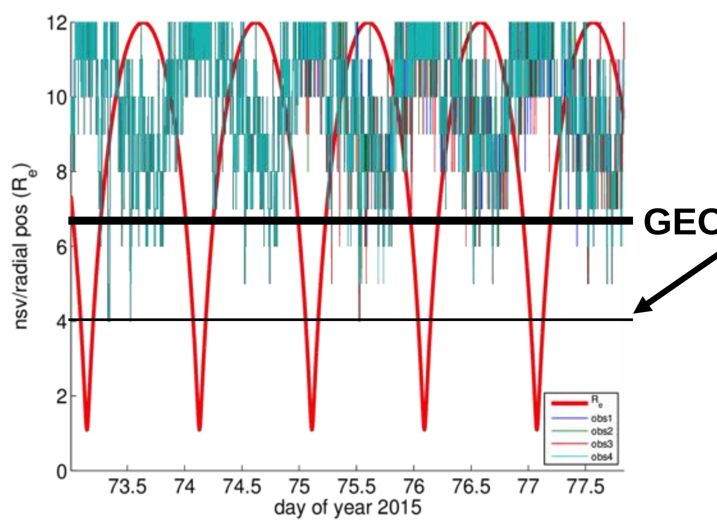
Signal Availability Contributed by Side Lobes (Assumes 24 Satellite Constellation)		
L1 Signal Availability	**Main Lobe Only**	**Main and Side Lobes**
4 or More SVs Visible	**Never**	**99%**
1 or More SVs Visible	59%	100%
No SVs Visible	41%	Never

Current Spec (L1 Signal Availability): 4 or more SVs visible: >1%

Recent Flight Data From Magnetosphere Multi-Scale (MMS) Mission



MMS Phase 1: **1.2 × 12 Re orbit**
(7,600 km × 76,000 km)



Current spec: Four or more PRs shall be available more than or equal to 1% of the time.

MMS is seeing **100%.**

GPS Space Service Volume Specification History

- **Mid-1990s**—efforts started to develop a formal Space Service Volume
  - –Discussion/debate about requiring "backside" antennas for space users
  - –Use of main lobe/side-lobe signals entertained as a no cost alternative
- **1997-Present**—Several space flight experiments, particularly the AMSAT-OSCAR-40 experiment demonstrated critical need to enhance space user requirements and SSV
- **February 2000**—GPS Operational Requirements Document (ORD), released with first space user requirements and description of SSV
  - –Shortcomings
    - ➢ Did not cover mid-altitude users (above LEO but below GPS)
    - ➢ Did not cover users outside of the GEO equatorial plane
    - ➢ Only specified reqts on L1 signals (L2 and L5 have wider beam-width and therefore, better coverage)
- **2000-2006**—NASA/DoD team coordinated updated Space User reqmnts
  - – Worked with SMC/GPE, Aerospace support staff & AFSPACE to assess impacts of proposed requirements to GPS-III
  - – Government System Spec (SS-SYS-800) includes threshold & objective reqmnts
  - – Shortcomings:
    - ➢ Developed with limited on-orbit experiment data & minimal understanding of GPS satellite antenna patterns
    - ➢ **Only specifies the main lobe signals, does not address side lobe signals**

IFOR Progress at a Glance

- **Spring 2015: GPS ACE & MMS performance definitively demonstrate benefits of sidelobes for space users – socialization begins with GOES-R as example**
- **Aug 2015: Maj Gen Thompson briefed, supports NASA updating GPS SSV requirement through IFOR**
  - As implemented, IFOR requires validated, documented mission need
- **Oct 2015–Feb 2016: NASA engages Air Force in IFOR coordination**
  - Monthly IFOR WG meetings w/ NASA, AFSPC, SMC (Aerospace as "honest broker")
  - Major deliverables provided by NASA: Requirement Language, Statement of Need, Analysis of Alternatives
  - NASA coordinating with interagency stakeholders for letters of support/commitment
- **9 Feb 2016: Final IFOR WG**
  - NASA delivered final products
  - SMC delivered ROM cost estimate for impact to GPS system
- **26 Feb 2016: SMC/SY endorsement**
- **22 Mar 2016: IFOR Co-Chair preliminary recommendation meeting**
  - SMC pushback on AoA and forward plan led to IFOR-requested HPT
- **12–14 Apr 2016: NASA/AFSPC/SMC HPT**
  - USAF/NASA MoA framework drafted
  - AoA GOES-R questions clarified
  - Agreement reached on forward engagement in SV11+ procurement process
- **19 Apr 2016: NOAA endorsement**
- **18 May 2016: Brief to PNT Advisory Board**
- **TBD: Final IFOR Co-Chair recommendation meeting**

Key Endorsements

USAF SMC/SY (Space Superiority Systems)

- Letter of endorsement signed by Col Garrant, 26 Feb 2016.
- SMC/SY has documented program requirement.
- Requirement is unfunded at this time.
- SY currently performing analyses to document their actual required capability levels as compared to NASA's proposed IFOR requirement.

NOAA

- Letter of endorsement from VADM Manson Brown (NOAA Deputy Administrator) to Gen Hyten & Maj Gen Thompson, 19 Apr 2016
- Confirms that GOES-R is reliant on GPS signals as captured in NASA's proposed IFOR requirement
- Additionally, identifies EUMETSAT (EU) and Japanese weather satellites as reliant on increased signal availability

(See letters in backup)

SMC/SY Endorsement

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SPACE AND MISSILE SYSTEMS CENTER (AFSPC)
LOS ANGELES AIR FORCE BASE, CALIFORNIA

26 February 2016

MEMORANDUM FOR GLOBAL POSITIONING SYSTEMS DIRECTORATE

FROM: SMC/SY
483 N. Aviation Blvd
El Segundo CA 90245-2808

SUBJECT: Statement of Need for Global Positioning System (GPS) Signal Availability at Geosynchronous Orbit (GEO) Altitudes

1. GPS capabilities are a force multiplier for terrestrial and space operations. Department of Defense and Intelligence Community users rely upon the robust Position, Navigation and Timing (PNT) architecture created by the GPS directorate to accomplish national objectives. While originally conceived as a service targeted for land, maritime, and airborne applications, GPS satellites provide critical capability to space-based missions as well.

2. Recently, NASA proposed an update to the Space Service Volume to preserve GPS signal performance for satellites in GEO. I share the concern that future Block III increment satellites, even if they nominally comply with official specifications for navigation signal characteristics, may provide significantly reduced performance relative to the signal seen today. SMC/SY supports NASA's request for a new requirement, as SMC/SY assets rely upon GPS signals at GEO; additional classified details are available upon request.

3. Although signal availability at GEO is currently unfunded, this requirement provides critical capability to National Security Space operations. We want to ensure that there are sufficient signal availability, power, and accuracy levels at GEO to conduct current and future space control missions.

PHILIP A. GARRANT, Colonel, USAF
Director
Space Superiority Systems Directorate

NOAA Endorsement

From: Manson Brown - NOAA Federal <manson.brown@noaa.gov>
Date: April 19, 2016 at 18:19:52 EDT
To: <john.hyten@us.af.mil>, <david.thompson@us.af.mil>
Cc: Stephen Volz - NOAA Federal <stephen.m.volz@noaa.gov>, "Thomas Burns - NOAA Federal" <thomas.burns@noaa.gov>, "Karen St. Germain - NOAA Federal" <karen.st.germain@noaa.gov>, Mark Mulholland - NOAA Federal <mark.f.mulholland@noaa.gov>, <harold.martin@gps.gov>, "MILLER, JAMES (HQ-CG000)" <jj.miller@nasa.gov>, "Christopher J. Scolese" <cscolese@nasa.gov>
Subject: NOAA Support of GPS Aggregate Signal Availability Requirement

General Hyten and Major General Thompson,

I am writing to convey NOAA's strong support for the NASA initiative to update the GPS Space Service Volume (SSV) requirements to insert an "aggregate signal availability" requirement in conjunction with your current procurement activities for future GPS spacecraft.

NOAA's new generation of geostationary weather satellites, the GOES-R series, relies upon precision GPS signals to successfully perform its mission, including the performance provided by the side lobe signal strength from the GPS. While presently expected performance and power levels are adequate, we assess that a documented "aggregate signal availability" requirement is needed to ensure that current capabilities of the GPS constellation continue into the future.

Further, because the recent DoD Space-Based Environmental Monitoring (SBEM) Analysis of Alternatives places reliance upon civil, international and commercial sources of satellite-based environmental data, the "aggregate signal availability" requirement is critical for NOAA's European and Asian mission partners which also fly GPS-dependent weather satellites. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) provides geostationary weather data for U.S. forces in the CENTCOM, EUCOM, and AFRICOM AORs. A Japanese geostationary weather satellite provides data in the PACOM AOR.

Thanks for your consideration. I welcome any questions or concerns you may have. I can be reached at (202) 482-6236. Our staff POC is Mark Mulholland (301) 713-7325, mark.f.mulholland@noaa.gov.

Best Regards,
Manson

Manson K. Brown, VADM, USCG (Ret)
Assistant Secretary of Commerce
for Environmental Observation & Prediction
And NOAA Deputy Administrator

Progress on Key Issues

- **Ensuring navigation resiliency**
  - NASA-proposed requirement is intended to protect use of critical GPS capabilities for space users in HEO/GEO
  - Effort is not intended to establish GPS as a space user's only navigation solution
  - Resiliency is ensured through space vehicle applications of complementary PNT solutions – RF, optical, INS, etc.
- **Ensuring military flexibility**
  - NASA-proposed requirement is not intended to constrain military terrestrial use of GPS
  - SSV user is "second priority" during short-lived warfighter-support scenarios

Risk-Based Impact Assessment

- **NASA & SMC acknowledge:**
  - There exist no direct full-pattern pseudorange accuracy maps for the current GPS III design
  - There exist two risks in adopting the requirement:
    1. Risk that the current GPS III design will not meet the proposed requirement.
    2. Risk that the new design(s) selected during Phase 1 for follow-on SV11 production (3Q FY16) will not meet the requirement.
- **NASA & SMC differ in likelihood assessment:**
  - NASA analysis of antenna group delay on contractor-provided antenna panel measurements for GPS IIF and IIIA (eng. model) provides strong indication that pseudorange accuracy meets proposed 4m requirement with margin.
  - Furthermore, in-flight experiments such as MMS and GPS ACE provide direct evidence for good pseudorange accuracy for on-orbit designs.
  - NASA: 2/5 likelihood, 5/5 consequence
  - SMC: 4/5 likelihood, 5/5 consequence
- **See backup for risk charts.**

Risk that proposed SSV requirement not met by legacy GPS system

Risk Description

- If the proposed SSV signal accuracy of four meters is not met by legacy GPS antenna designs, space vehicle hardware and software impacts may be incurred for GPS SVs 11+.

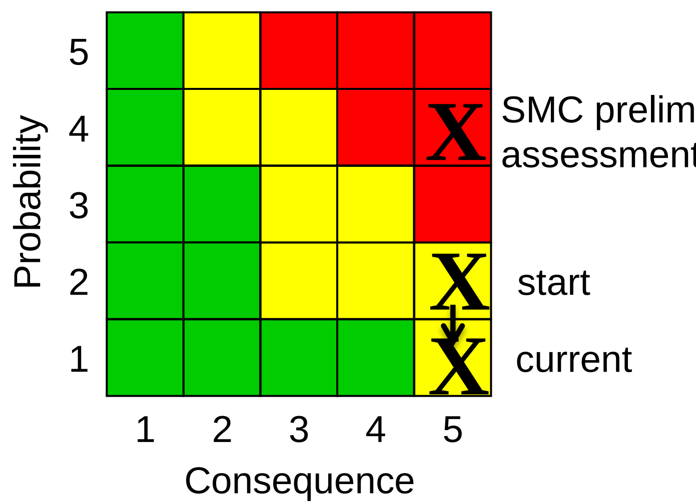
Mitigation

- **Mitigations to date:**
  1. Group delay analysis performed using Block IIF and Block III EM antenna measurements (performed by NASA)
  2. Analysis of measurement residuals of side lobe signals recorded on operational missions (NASA, Aerospace, and other organizations)
- **Proposed mitigations:**
  3. SMC/GP-led analysis to verify NASA analysis of IIF and III EM data.
  4. Additional analysis of phase delay and other channel distortions.
  5. Repeat analysis using antenna pattern measurements from IIR/IIR-M, IIIA flight hardware.

Mitigation Results

1. NASA analysis of antenna contribution to range error in the sides lobes suggests there is significant margin with respect to four meter requirement
2. Analysis of on orbit measurements from GPS ACE and other currently operating GEO missions suggest measurement errors in side lobes are consistent with those indicated by antenna analysis.
3. In steps 3-5, verification of NASA analysis by Air Force technical support personnel would close the risk.

NASA Standard 5X5 Risk Matrix



Risk of Space Vehicle/System Impact from SSV requirements

Risk Description

- If future SSV contractors implement an Earth-coverage antenna design that differs significantly from legacy GPS space vehicles, then design changes may be required to meet proposed SSV availability and accuracy requirements.

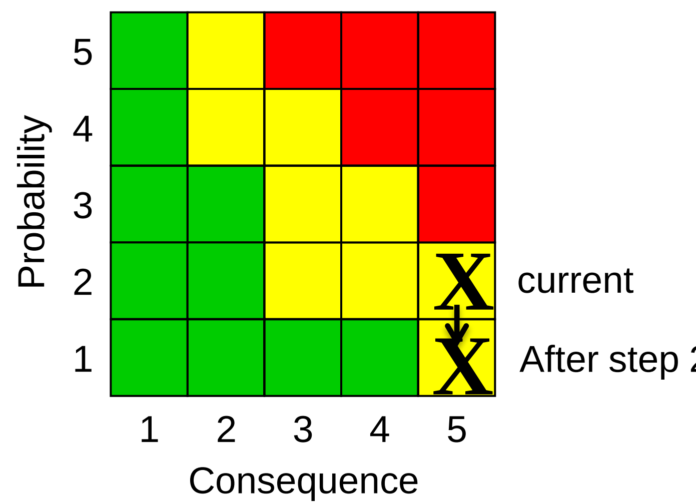
Mitigation

- **Mitigations to date:**
  1. Formulate the SSV availability and accuracy requirements in a manner that allows some flexibility on the part of the design implementation (completed as part of IFOR discussions in Dec 2015)
  2. Analysis of proposed requirement against antenna measurements from legacy GPS satellites (initiated)
- **Proposed mitigations:**
  3. Engage GPS SV11+ prime contractor in assessment of proposed requirement following contract award

Mitigation Results

1. Working together through the IFOR process, NASA, SMC, and AFPSC personnel have come up with a revised formulation of the requirements that increases the flexibility the contractor will have in implementing the requirement.
2. Determining that the legacy GPS satellites meet the requirement and quantifying margin reduces the likelihood that future antenna designs would be impacted. This analysis has been initiated and can be feasibly completed even before the IFOR process is complete (but requires engagement by SMC/GP).
3. As in any procurement/development activity, if the contractor's analysis of the requirements indicates a risk of exceedance, a modification or re-formulation of the requirement may be all that is necessary to remove the impact. At this point the risk would be closed.

NASA Standard 5X5 Risk Matrix

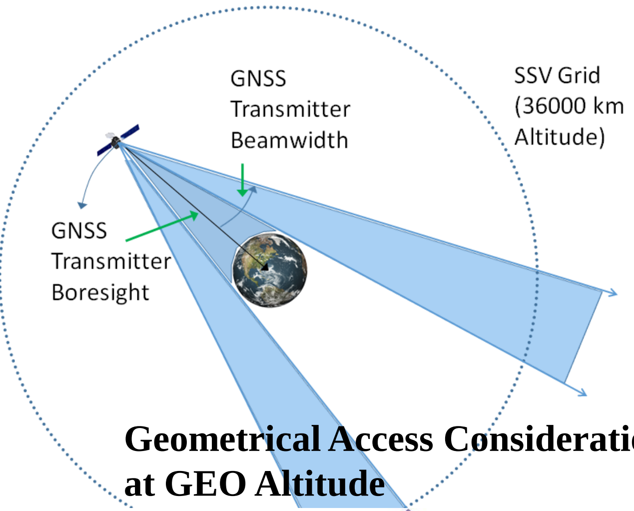


U.S. Objectives in Working with other GNSS Service Providers

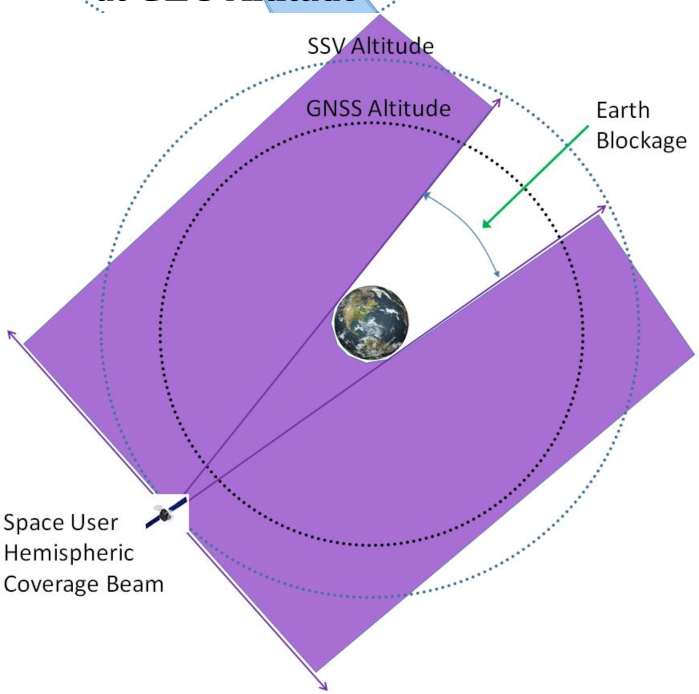
Pursue through Bilateral and Multilateral Cooperation

- **Ensure compatibility — ability of U.S. and non-U.S. space-based PNT services to be used separately or together without interfering with each individual service or signal**
  - Radio frequency compatibility
  - Spectral separation between M-code and other signals
- **Achieve interoperability – ability of civil U.S. and non-U.S. space-based PNT services to be used together to provide the user better capabilities than would be achieved by relying solely on one service or signal**
- **Promote fair competition in the global marketplace**

ICG WG-B
Phase 1 Results (1)



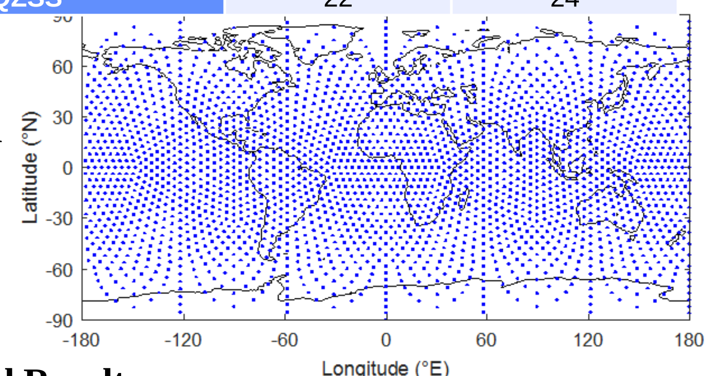
Geometrical Access Considerations at GEO Altitude



Beamwidth Assumptions

GNSS Constellation	L1 Beamwidth (°)	L5 Beamwidth (°)
BeiDou	25 (MEO) 19 (GEO/IGSO)	28 (MEO) 22 (GEO/IGSO)
Galileo	20.5	23.5
GLONASS	20	28
GPS	23.5	26
NAVIC	Not Applicable	16
QZSS	22	24

Analysis performed over equal area-based grid of points at GEO and MEO altitudes



L5 Frequency Band Results

Figure of Merit	BeiDou	Galileo	GLONASS	GPS	NAVIC	QZSS	All
1 Satellite System Availability (%)	99.9	93.4	98.3	96.9	36.9	30.5	100
4 Satellite System Availability (%)	45.4	4.2	14.5	15.6	0.6	1.5	99.9
1 Satellite Maximum Outage (minutes)	7	55	35	77	Max SD	Max SD	0
4 Satellite Maximum Outage	644	Max SD	2252	1180	Max SD	Max SD	35

GNSS Mission Areas (1):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 21, 2016 Version (Updated for ICG-11 & and IOAG-20a)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
1	ASI	COSMO SKYMED (CSK)	GPS	L1/L2 C/A, P(Y)	Precise Orbit Determinatin (POD), Time	Es	2007, 2008, 2010	4 satellites
2	ASI	COSMO SKYMED SECOND GENERATION (CSG)	GPS, Galileo Ready	L1/L2/L2C (GPS) ready for E1 (Galileo)	Precise Orbit Determinatin (POD), Time	Es	2018 1st SAT, 2019 2nd SAT	2 satellites
3	ASI	AGILE	GPS	L1 C/A	Orbit, Time	Ee	2007	
4	ASI	PRISMA	GPS		Orbit, Time	Es	2018	
5	CNES	CALIPSO	GPS	L1 C/A	Orbit, Time	Es	2006	CNES controls the in flight satellite .
6	CNES	COROT	GPS	L1 C/A	Orbit, Time	Ep (90°)	2006	CNES controls the in flight satellite .
7	CNES	JASON-2	GPS*	L1 C/A	Orbit, Time	Ei (66°)	2008	CNES controls the in flight satellite in case of emergencey on behalf of NASA/NOAA or EUMETSAT.* GPS on Bus + GPSP on Payload (NASA)
8	CNES	SMOS	GPS	L1 C/A	Orbit, Time	Es	2009	Launch was Nov 02, 2009. CNES controls the satellite in routine operations ; ESA operates the mission.
9	CNES	ELISA	GPS	L1 C/A	Orbit, Time	Es	2011	The system is with four satellites launched in Dec 2011. Receiver: MOSAIC
10	CNES	JASON-3	GPS*	L1 C/A	Orbit, Time	Ei (66°)	2015	CNES controls the in flight satellites in case of emergencey on behalf of NASA/NOAA or EUMETSAT.* GPS on Bus + GPSP on Payload (NASA)
11	CNES	MICROSCOPE	GPS, Galileo	L1 C/A, E1	Precise Orbit Determinatin (POD), Time	Es	2016	One satellite to be launched in 2016 Receiver: SKYLOC
12	CNES	CSO-MUSIS	GPS, Galileo	L1 C/A, L2C, L5 E1, E5a	Orbit, Time	Es	2017	The system is with three satellites to be launched from 2017. Receiver : LION
13	CNES	MERLIN	GPS, Galileo	L1 C/A, E1	Orbit, Time	Es (TBC)	2018	Receiver : not yet decided
14	CNES	SWOT	GPS, Galileo (to be decided)	GPS L1 C/A, other (to be decided)	Orbit, Time	Ep (77,6°)	2020	Receiver : not yet decided
15	CSA	Scisat	GPS		Orbit, Time	LEO	2003	
16	CSA	Radarsat-2	GPS		Orbit, Time	LEO	2007	
17	CSA	Neossat	GPS		Orbit, Time	LEO	2013	
18	CSA	M3MSat	GPS		Orbit, Time	LEO	2016	
19	CSA	RCM	GPS		Orbit, Time	LEO	2018	3 satellites

GNSS Mission Areas (2):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 21, 2016 Version (Updated for ICG-11 & and IOAG-20a)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
20	DLR	TSX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	15-Jun-2007	
21	DLR	TDX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	21-Jun-2010	
22	DLR	TET	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	22-July-2012	
23	DLR	TET NOX experiment	GPS	GPS L1 C/A, L1/L2 P(Y)	Experiment (POD, RO)	Ep	22-July-2012	
24	DLR	BIROS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	2015	
25	DLR	HAG-1	GPS	GPS L1 C/A	Experiment (navigation)	G	2014	GPS used for on-board experiment
26	DLR	Eu:CROPIS	GPS	GPS L1 C/A	navigation, flight dynamics	Ep	2016	
27	DLR	ENMAP	GPS			Ep	2017	
28	DLR/NASA	GRACE_FO	GPS GLO/GAL?)	GPS L1 C/A, L1/L2 P(Y), (others?)	Navigation, POD	Ep	2018	Joint mission with NASA.
29	DLR	DEOS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support), relative navigation (formation flight/ rendezvous)	Ep	2017	
30	DLR	Electra	GPS		orbit determination	G	2018	
31	DLR	PAZ	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD	Ep	2014	Same as TSX
32	ESA	ADM / Aeolus	GPS		GPS (single frequency)		2017	Lidar for wind profiles
33	ESA	SAOCOM / CS	GPS		GPS + Galileo Dual Frequency, Receiver + POD		2019	Bistatic SAR Payload
34	ESA	GOCE	GPS	GPS, dual frequency L1, L2 Codephase and carrierphase	Navigation (PVT), Precise Orbit Determination (POD)	LEO	2009	Earth Gravity Mission
35	ESA	SWARM	GPS	GPS, dual frequency, L1, L2 Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2013	Magnetosphere, 3 spacecraft
36	ESA	Earth Care			Orbit	LEO	2018	
37	ESA	BIOMASS					2020	SAR
38	ESA	Sentinel S1	GPS	GPS, dual frequency L1, L2 Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2014 / 16	SAR, 2 spacecraft

GNSS Mission Areas (3):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 21, 2016 Version (Updated for ICG-11 & and IOAG-20a)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
39	ESA	Sentinel S2	GPS	GPS, dual frequency L1, L2 Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2015	Imager, 2 spacecraft
40	ESA	Sentinel S3	GPS	GPS, dual frequency L1, L2 Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2015	Altimetry & Imager, 2 spacecraft
41	ESA	Sentinel S4				LEO		UV Spectrometry
42	ESA	Proba 2			Orbit	LEO	2009	Tech Demo
43	ESA/NASA	ISS	GPS and Galileo	Galileo: E1 and E5a, GPS: L1 and L5, Codephase and Carrierphase for GPS and Galileo	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	1017	Joint demonstration mission with NASA, using NASA's SCAN Testbed on-board the ISS
44	ESA	Proba 3	GPS and Galileo	Galileo: E1 and E5a, GPS: L1 and L5, Codephase and Carrierphase for GPS and Galileo	Navigation (PVT), Precise Orbit Determination (POD), Formation Flying relative POD Time	HEO	2019	FF Demo, 2 spacecraft
45	ESA	Small GEO	GPS	single Frequency, L1	Navigation (PVT)	GEO	2015	Telecom
46	ESA	FLEX				LEO	2022	Clorofile Explorer (GPS similar to GPS & Galileo)
47	ESA	JASON-CS				LEO	2020 & 2026	Altimetry
48	ESA	METOP-A/B/C			Radio Occultation	LEO	2006 / 2012 / 18	Atmospheric Sounder, 2 spacecraft
49	ESA	MetOp-SG					2021/27/33	3 spacecraft
50	JAXA	GOSAT	GPS	L1	Orbit, time	LEO	2009-present	Remote Sensing
51	JAXA	GCOM-W1	GPS	L1	Orbit, time	LEO	2012-present	Remote Sensing
52	JAXA	GCOM-C1	GPS	L1	Orbit, time	LEO	2016	Remote Sensing
53	JAXA	ALOS-2	GPS	L1, L2	Precise orbit （3σ<1m), Orbit, time,	LEO	2013	Remote Sensing
54	JAXA	HTV-series	GPS	L1	Orbit(relative)	LEO	2009-present	Unmanned ISS transportation
55	JAXA	GOSAT-2	GPS	L1, L2 (TBD)	Orbit, time	LEO	2017	Remote Sensing
56	JAXA	ASTRO-H	GPS	L1, L2	Orbit, time	LEO	2015	Remote Sensing
57	NASA	ISS	GPS	L1 C/A	Attitude Dynamics	LEO	Since 1998	Honeywell SIGI receiver

GNSS Mission Areas (4):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 21, 2016 Version (Updated for ICG-11 & and IOAG-20a)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
58	NASA	COSMIC (6 satellites)	GPS	L1 C/A, L1/L2 semicodeless, L2C	Radio Occultation	LEO	2006	IGOR (BlackJack) receiver; spacecraft nearing end of life
59	NASA	IceSat	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2003	BlackJack receiver; mission retired 14 August 2010
60	NASA	GRACE (2 satellites)	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination, Occultation, precision time	LEO	2002	BlackJack receiver, joint mission with DLR
61	CNES/NASA	OSTM/Jason 2	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2008	BlackJack receiver
62	NASA	Landsat-8	GPS	L1 C/A	Orbit	LEO	2013	GD Viceroy receiver
63	NASA	ISS Commercial Crew and Cargo Program - Dragon	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+	
64	NASA	ISS Commercial Crew and Cargo Program: Cygnus	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+	
65	NASA	CONNECT / SCaN Test-Bed (ISS)	GPS	L1 C/A, L1/L2 semicodeless, L2C, L5, + option for Galileo & GLONASS	Orbit determination, time	LEO	2012	"Blackjack-based SDR. Monitoring of GPS CNAV testing began in June 2013. Development of Galileo E5a/GPS L5 waveform through agreement with ESA began in October 2016
66	NASA	GPM	GPS	L1 C/A	Orbit, time	LEO	2014	Navigator receiver
67	NASA	Orion/MPCV	GPS	L1 C/A	Orbit / navigation	LEO	2014 - Earth Orbit, 2017 Cislunar	Honeywell Aerospace Electronic Systems 'GPSR' receiver
68	NSPO/USAF/NASA	COSMIC IIA (6 satellites)	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2017	TriG receiver, 8 RF inputs, hardware all-GNSS capable, will track GPS + GLONASS at launch
69	NASA	DSAC	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Time transfer	LEO	2017	TriG lite receiver
70	CNES/NASA	Jason-3	GPS, GLONASS FDMA	L1 C/A, L1/L2 semicodeless, L2C	Precise Orbit Determination, Oceanography	LEO	2015	IGOR+ (BlackJack) receiver
71	NASA	MMS	GPS	L1 C/A	Rel. range, orbit, time	up to 30 Earth radii	2015	Navigator receiver (8 receivers)
72	NASA	GOES-R	GPS	L1 C/A	Orbit	GEO	2016	General Dynamics Viceroy-4
73	NASA	ICESat-2	GPS	-	-	LEO	2016	RUAG Space receiver
74	NASA	CYGNSS (8 sats)	GPS	-	GPS bi-scatterometry	LEO	2016	Delay Mapping Receiver (DMR), SSTL UK
75	NSPO/USAF/NASA	COSMIC IIB (6 satellites)	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2017	TriG receiver, digital beam steering
76	NASA/DLR	GRACE FO	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation, precision orbit, time	LEO	2018	TriG receiver with microwave ranging, joint mission with DLR

GNSS Mission Areas (5):
Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 21, 2016 Version (Updated for ICG-11 & and IOAG-20a)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes
77	NASA/ESA	Sentinel S6 (Jason-CS)	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Occultation, Precise Orbit Determination	LEO	2020	TriG receiver with 1553
78	NASA	GRASP	GPS, GLONASS FDMA, Beudou, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination	LEO	2017	Trig receiver (proposed)
79	NASA	GRACE FO	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Science	LEO	2020	Trig receiver (proposed)
80	NASA	NICER (ISS)	GPS	L1 C/A	Orbit	LEO	2016	Moog/Navigator receiver
81	NASA	Pegasus Launcher	GPS	L1 C/A	Navigation	Surface to LEO	Since 1990	Trimble receiver
82	NASA	Antares (formerly Taurus II) Launcher	GPS	L1 C/A	Integrated Inertial Navigation System (INS) & GPS	Surface to LEO	Since 2010	Orbital GPB receiver
83	NASA	Falcon-9 Launcher	GPS	L1 C/A	Overlay to INS for additional orbit insertion accuracy	Surface to LEO	Since 2013	
84	NASA	Launchers* at the Eastern and Western Ranges	GPS	L1 C/A	Autonomous Flight Safety System	Range Safety	2016*	(*) Including ULA Atlas V and Delta IV (GPS system: Space Vector SIL, uses a Javad receiver). (**) Estimated initional operational test.
85	NASA	NISAR	GPS, GLONASS, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination, timing	LEO	2020	TriG Lite receiver
86	NASA	SWOT	GPS, GLONASS FDMA	L1 C/A, L2C, L5, Galileo, GLONASS FDMA	Precise Orbit Determination - Real Time	LEO	2020	TriG Lite receiver with 1553
87	NASA/ISRO	(not available)	GPS, IRNSS	L1 C/A, L2C, semi-codeless P2, L5, IRNSS	Precise Orbit Determination, Occultation, Reflections (Scatterometry)	LEO	2018	TriG receiver with 1553
88	NASA	GEDI	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P1/P2, Glonass G1 & G2	Precise Orbit Determination	LEO/ISS	2018	Moog TriG-lite receiver
89	NASA	iSat	GPS	L1 C/A	Orbit Determination	LEO	2018	Iodine Satellite CubeSat. 1 Year LEO Mission.
90	NASA	MAPS	GPS	L1 C/A	Orbit Determination	LEO		
91	NASA	SLS - ICPS	GPS	L1 C/A	End-of-Mission Disposal	Ascent, LEO, Cislunar, EoM Disposal	2018	
92	NASA	SLS - EUS	GPS	L1/L2 C/A, P(Y) [I think P(Y)]	Ascent Range Safety, Orbit Determination	Ascent, LEO, Cislunar	2020	