Interoperable GNSS Space Service Volume (SSV)

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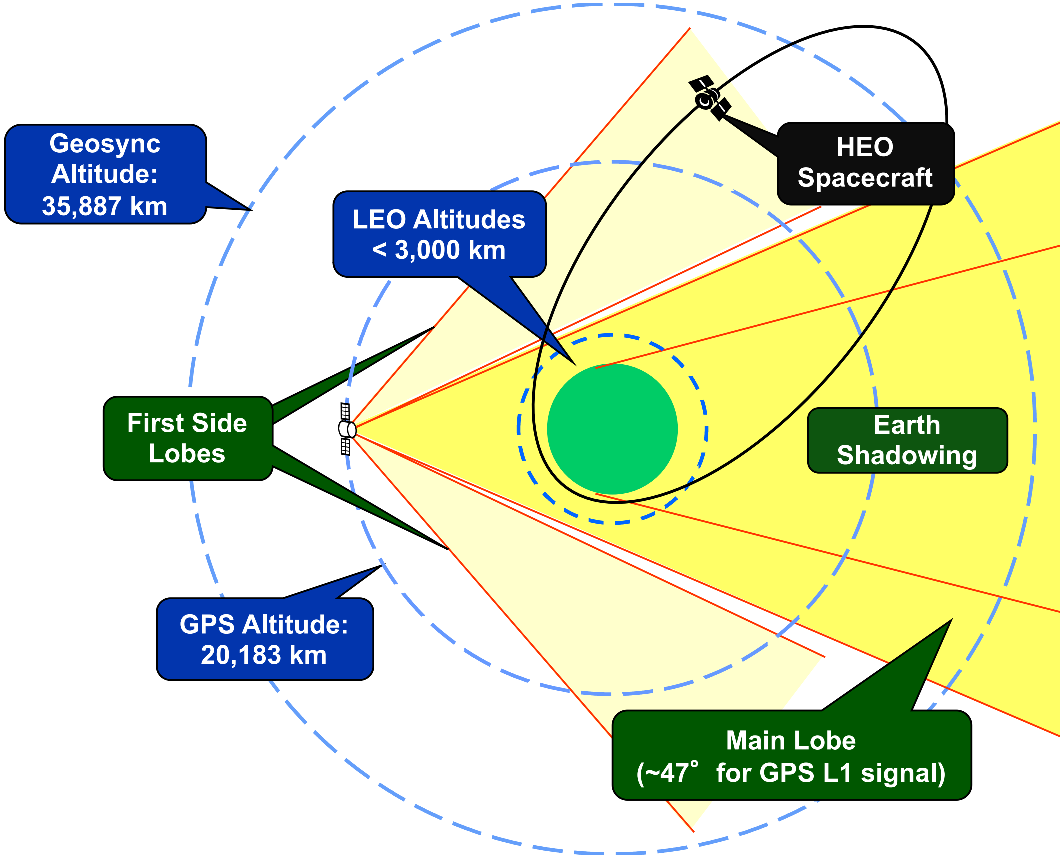
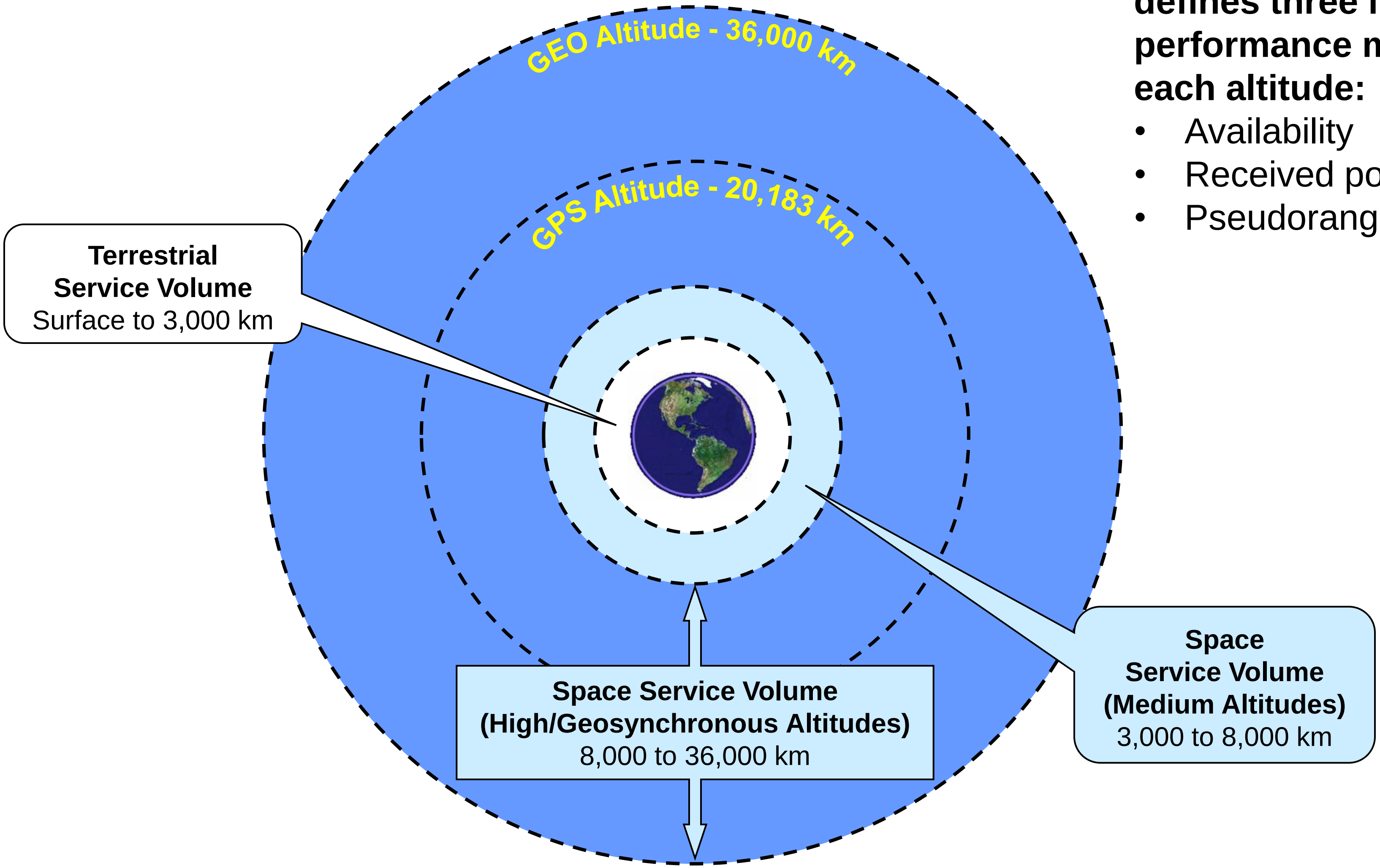
GNSS Signals in the Space Service Volume (SSV)

- The Terrestrial Service Volume (TSV) is defined as the volume of space including the surface of the Earth and LEO, i.e., up to 3,000 km
- The Space Service Volume (SSV) is defined as the volume of space surrounding the Earth from the edge of LEO to GEO, i.e., **3,000 km to 36,000 km altitude**
- The SSV overlaps and extends beyond the GNSS constellations, so use of signals in this region often requires signal reception from satellites on the opposite side of the Earth – main lobes and sidelobes
- Use of GNSS in the SSV increasing despite geometry, Earth occultation, and weak signal strength challenges
- Spacecraft use of GNSS in TSV & SSV enables:
    - reduced post-maneuver recovery time
    - improved operations cadence
    - increased satellite autonomy
    - more precise real-time navigation and timing performance



What is a Space Service Volume (SSV)?

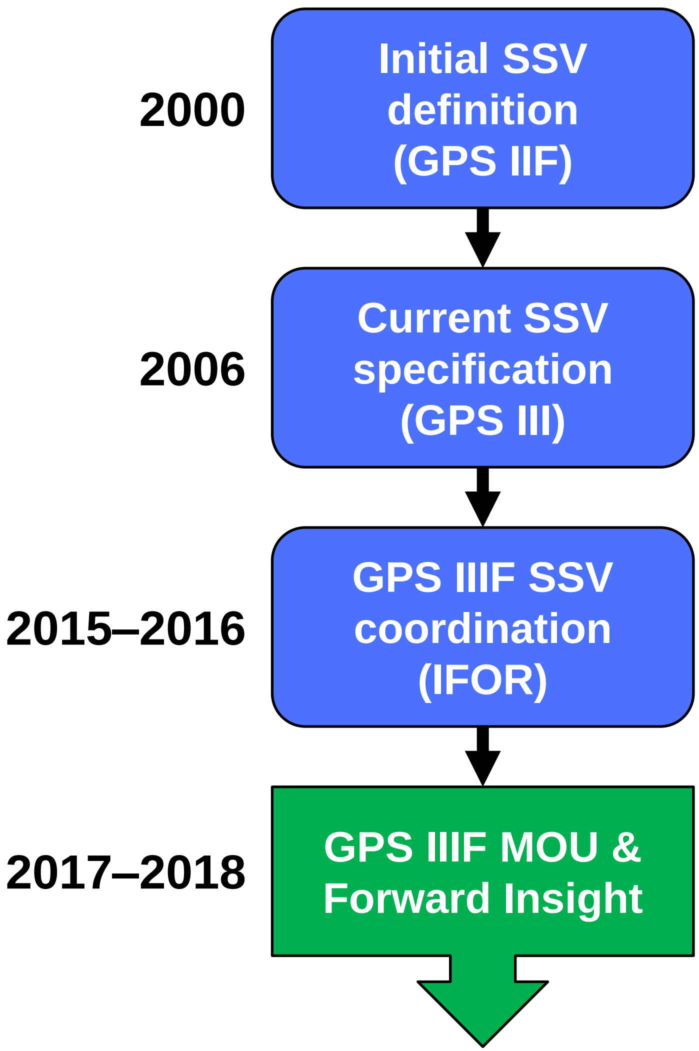


The Space Service Volume defines three interrelated performance metrics at each altitude:

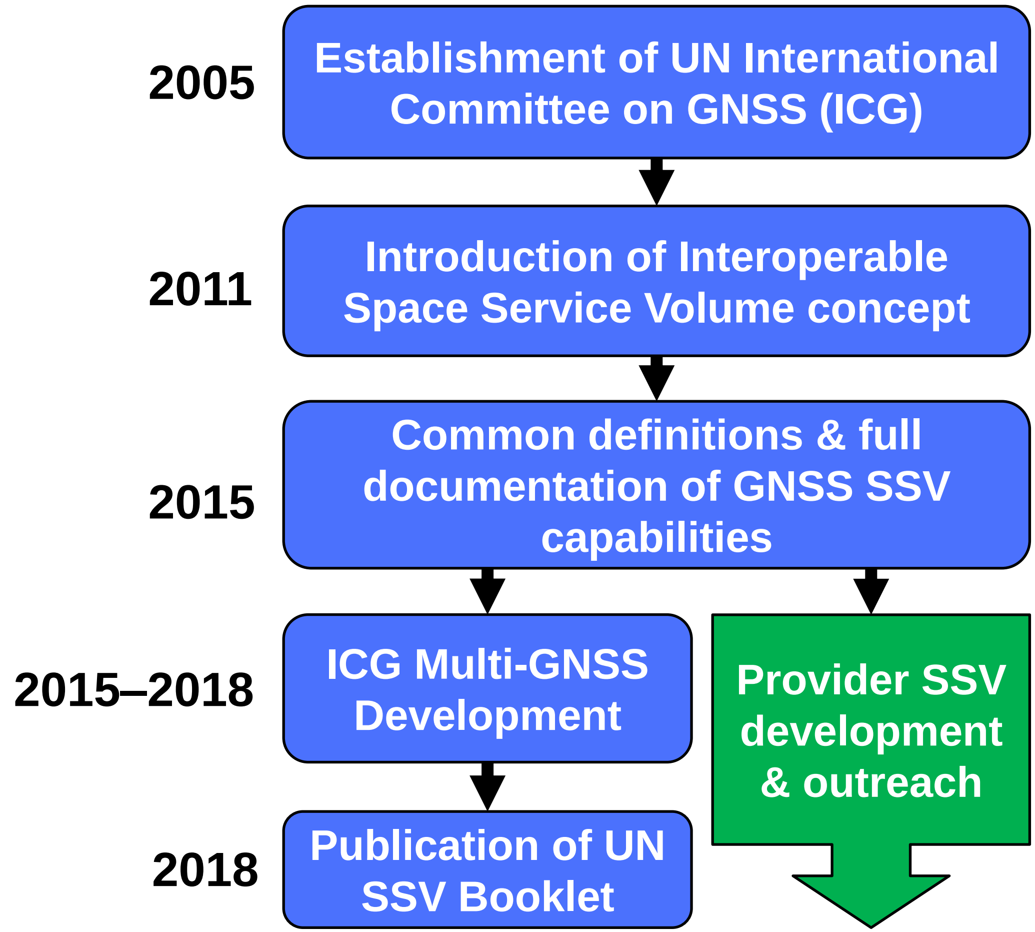
- Availability
- Received power
- Pseudorange accuracy

Past and Ongoing Development of the SSV

GPS SSV



Interoperable Multi-GNSS SSV



NASA-USAF SSV Collaboration

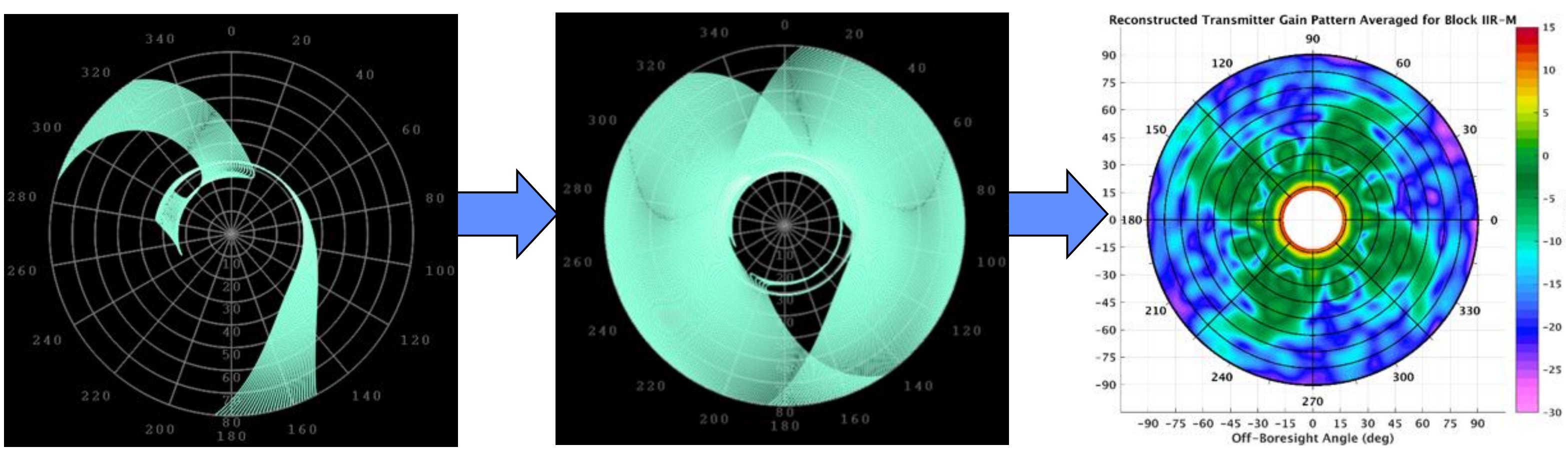
- **Oct 13 2017: Joint NASA-USAF Memorandum of Understanding (MOU) signed**
  - MOU addresses civil Space Service Volume (SSV) requirements
  - Scope relevant to GPS IIIF acquisition process
    - Civil space early insight into Block IIIF design relevant to SSV performance
    - Access to Block IIF, III, and IIIF technical data
- **MOU results to-date:**
  - US civil space rep. from NASA supported GPS IIIF source selection team as SSV technical expert
  - Built positive, collaborative relationships with IIIF acquisition team; provided civil space insight continuing through design and production
  - NASA received released GPS IIF antenna pattern measurements per MOU and to support NASA Space Launch System need

MOU supports SSV signal continuity goals for future space users

GPS Antenna Characterization Experiment

Objective: Complete first ever mapping of the GPS L1 sidelobes for all GPS satellites to determine signal availability for future missions in the Space Service Volume.

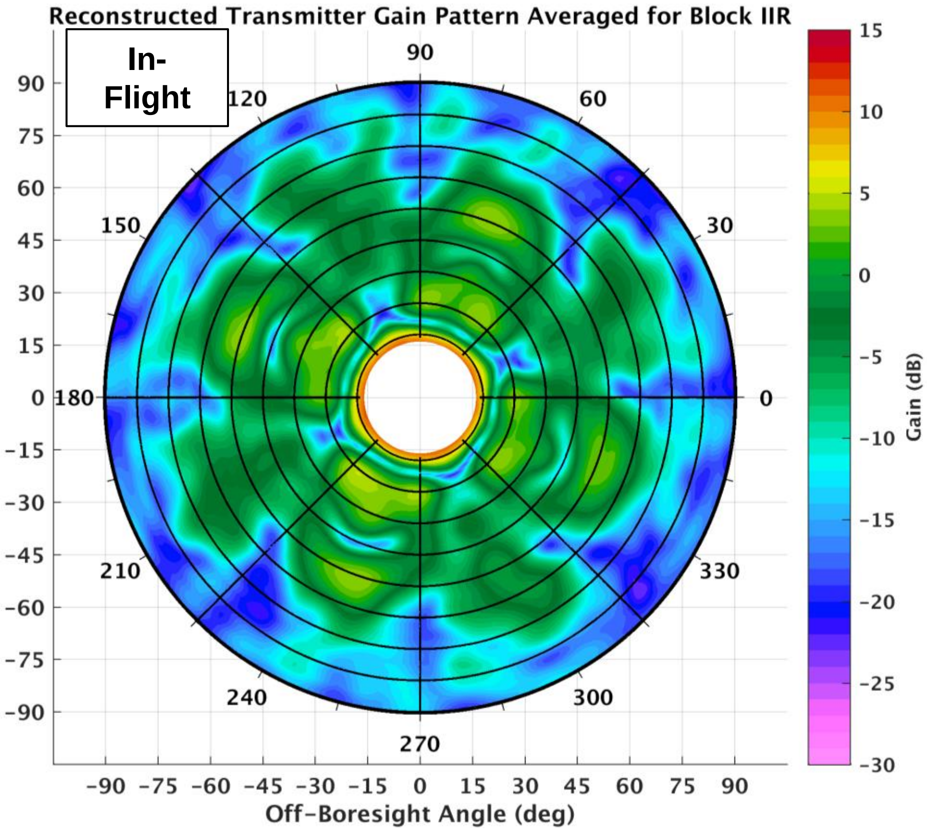
- **GPS ACE architecture permits tracking of extremely weak signals over long duration**
  - 24/7 GPS telemetry provides near continuous tracking of each PRN
- **First reconstruction of full GPS gain patterns from flight observations**
  - Block averages of IIR, IIR-M show remarkable consistency with ground patterns
    - Demonstrates value in extensive ground testing of antenna panel
  - Characterized full gain patterns from Blocks IIA, IIF for the first time
  - Patterns permit more accurate simulations of GPS signal availability for future HEO missions
- **Additional analysis of pseudorange deviations indicate usable measurements far into side lobes**

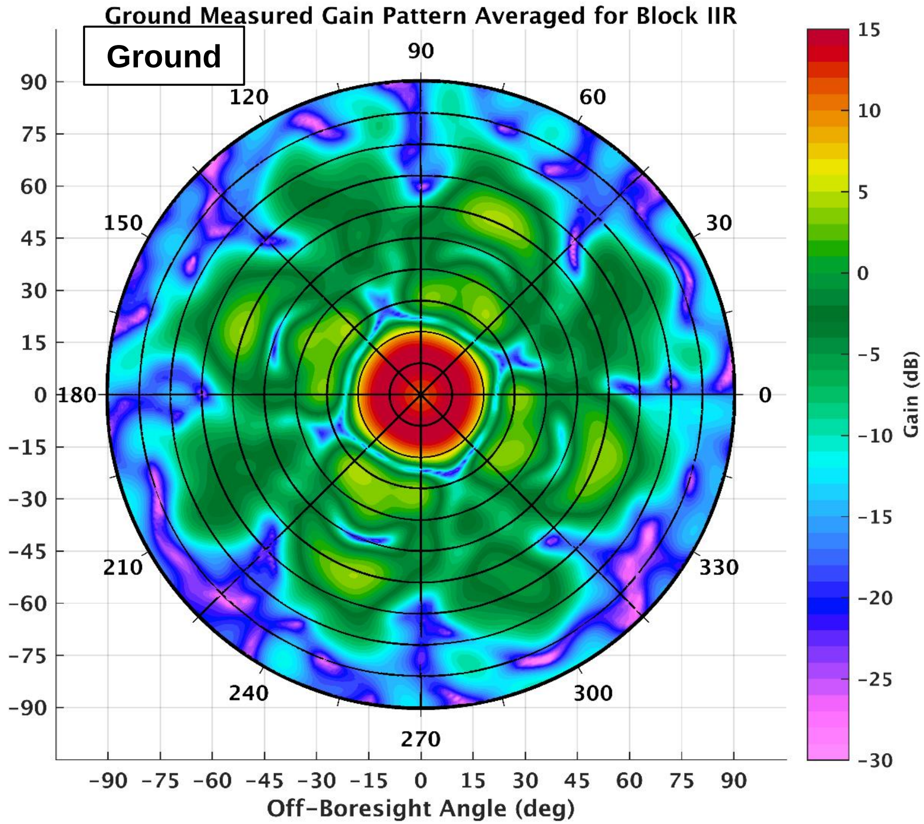


Dataset available at: https://esc.gsfc.nasa.gov/navigation

ACE Results: Average Transmit Gain – Block IIR

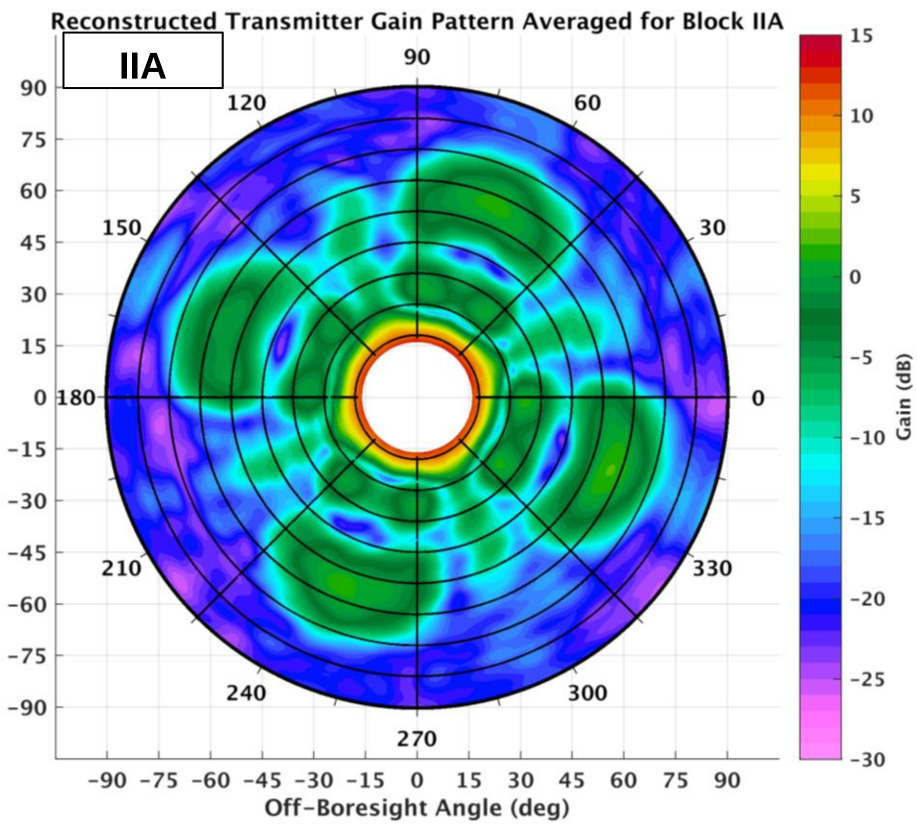
- In-flight averaged over all SVNs in block in 1 deg x 1 deg bins
- Remarkable similarity between average flight and ground measurements
  - Note matching patterns in nulls around outer edge

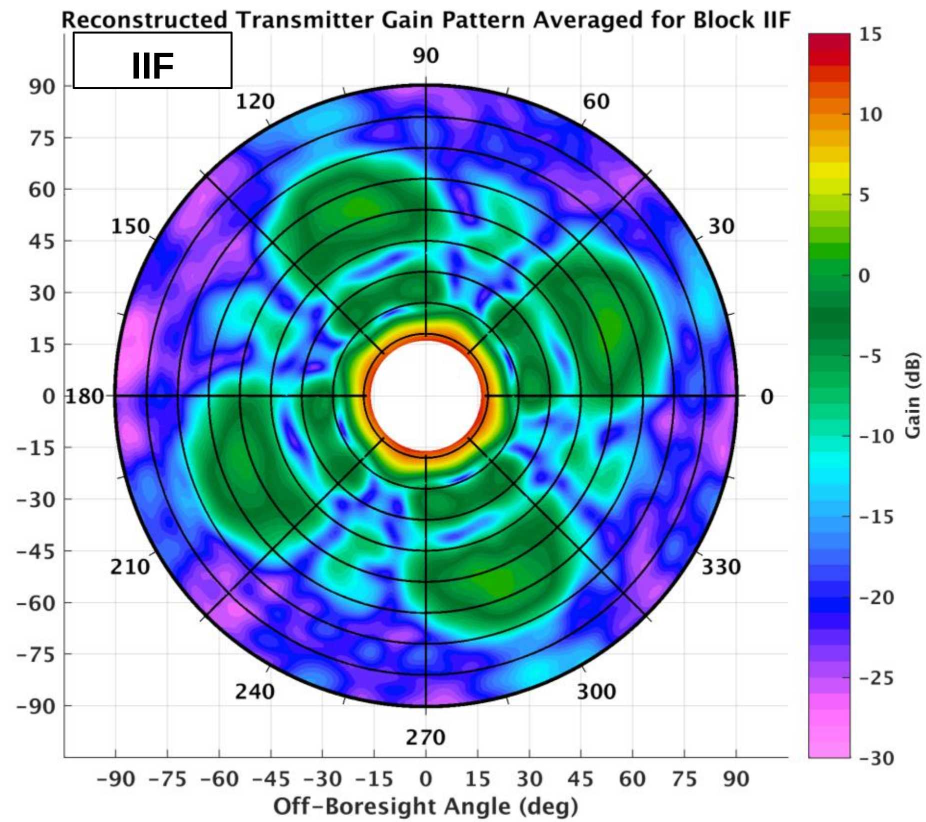




ACE Results:
Average Transmit Gain – Block IIA/IIF

- Averaged over all SVNs in block in 1 deg x 1 deg bins
- IIF side lobes are shifted 45 deg in azimuth from other blocks
- First full-pattern characterization of blocks IIA & IIF





Multi-GNSS activities in the ICG WG-B

As amended in 2015, the ICG WG-B work plan directs it to:

> *"continue the implementation of an interoperable GNSS Space Service Volume and provide recommendations to Service Providers regarding possible evolution needs arising from users/application developers."*

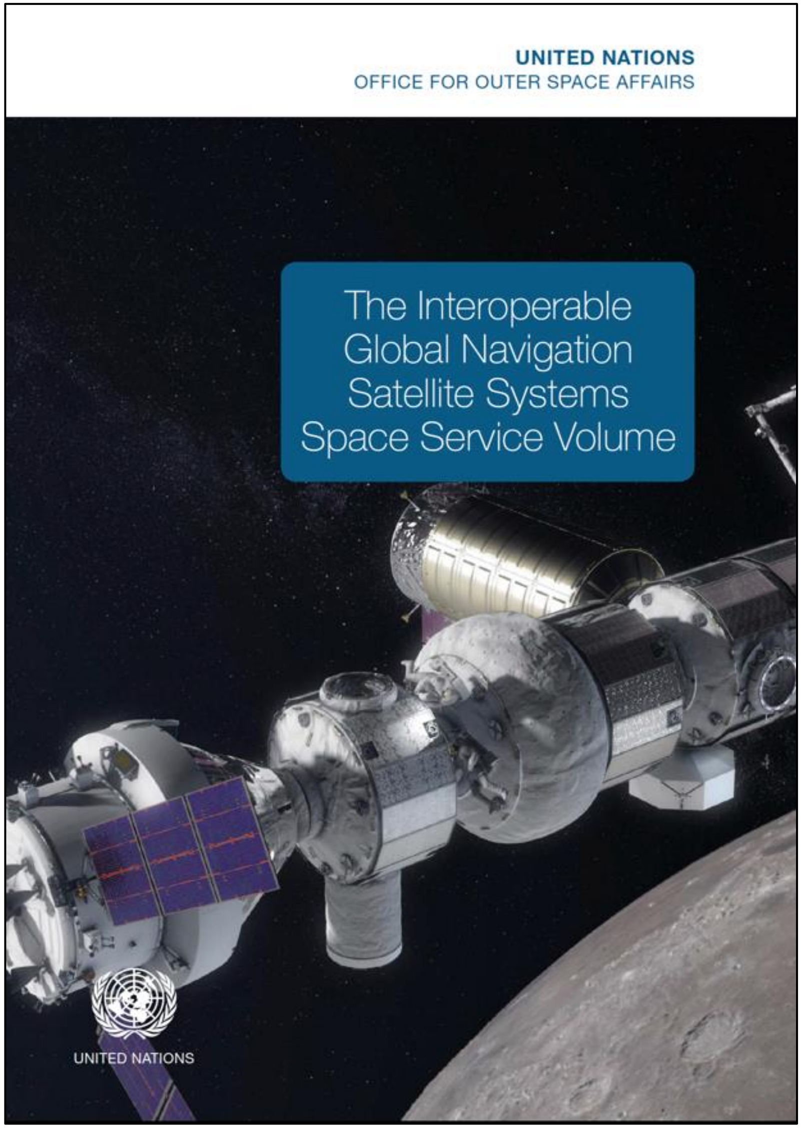
This is being accomplished via several initiatives:

	Status
• **SSV Definition/Assumption Maturation:** Adopting the formal definition of the Multi-GNSS SSV	Completed 2017
• **Constellation-Specific SSV Performance Data:** Publishing high-altitude performance characteristics for each GNSS constellation	Completed 2015
• **Multilateral SSV Analysis:** Conducting an internationally-coordinated analysis of simulated multi-GNSS SSV performance	Completed 2017
• **Multi-GNSS SSV Booklet:** Development of a formal UN publication defining the Multi-GNSS SSV, its characteristics, benefits, and applications	Published October 2018
• **SSV Capabilities Outreach:** Coordinating a joint international outreach activity to raise awareness of the final policy	Ongoing

GNSS SSV Booklet

Accomplishment: Publication of "The Interoperable GNSS Space Service Volume"

- UN publication ST/SPACE/75
- Culmination of three years of NASA & ESA-led international analysis & coordination
- First formal publication of SSV performance data from all constellations
- Establishes baseline performance characteristics for high-altitude mission planning



Available:

http://www.unoosa.org/oosa/en/ourwork/icg/documents/publications.html

GNSS SSV Performance Characteristics

Expected performance data (extracted sample shown here) was requested via a “template” for each:

- **GNSS constellation**
- **Civil signal**
- **SSV characteristic**

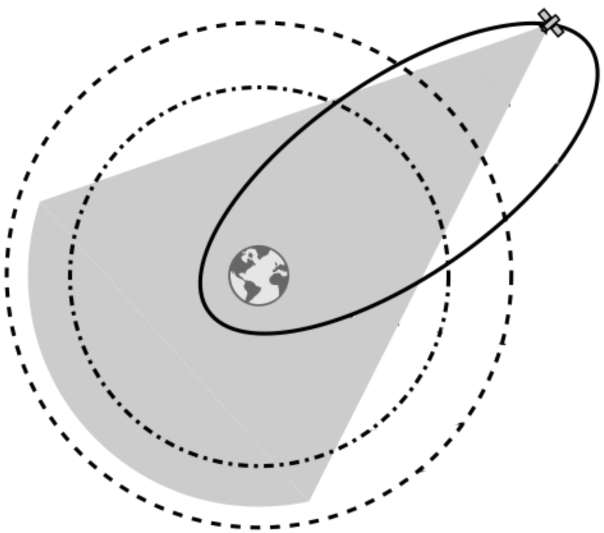
Data was requested for nominal constellations, and for primary main lobe signals only.

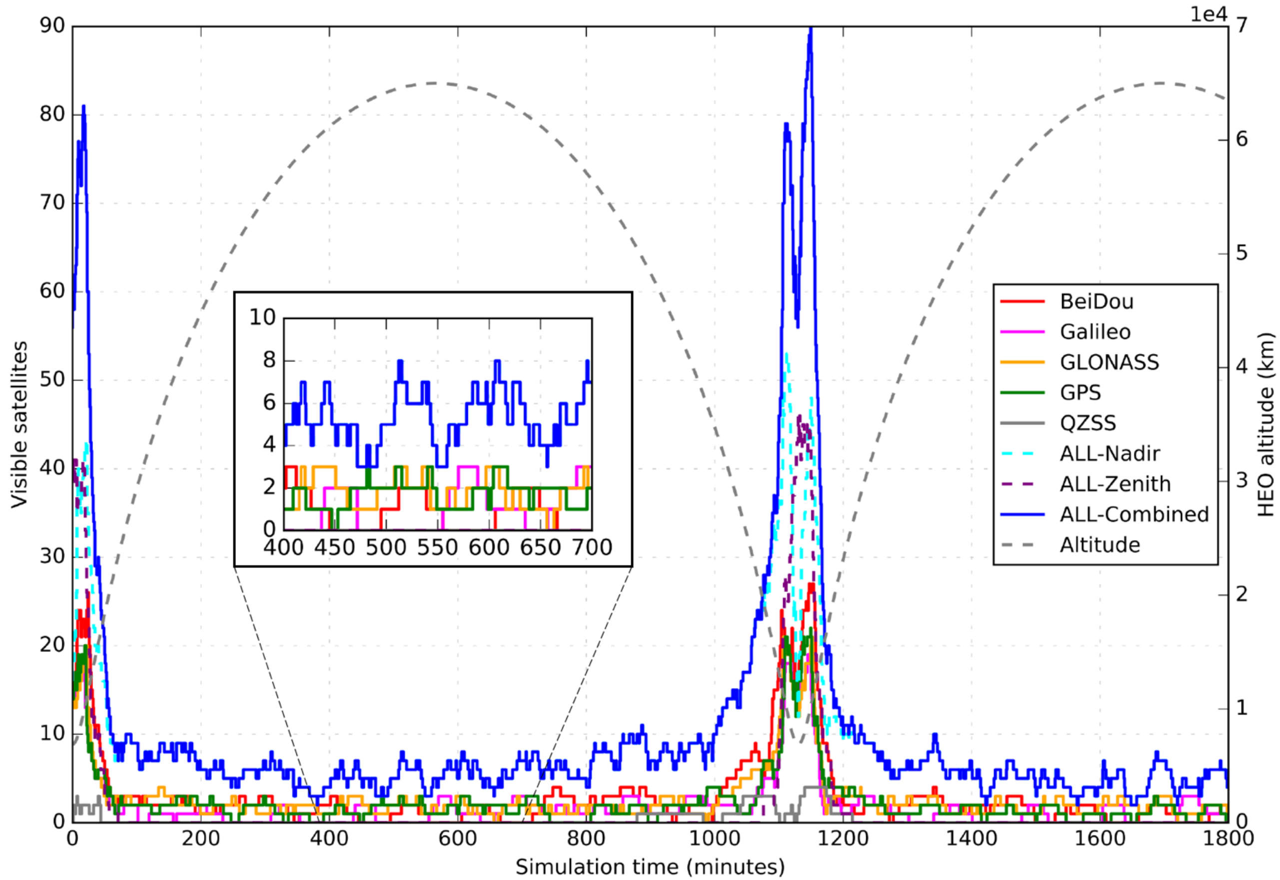
Supplied data represents minimum performance expectations for each signal; specification and requirement status varies by provider.

Data is intended to provide a conservative baseline performance level for mission planning activities. See the SSV Booklet for details constellation-specific information.

Band	Constellation	Minimum Received Civilian Signal Power	
		0dBi RCP antenna at GEO (dBW)	Reference off-boresight angle (°)
L1/E1/B1	GPS	-184 (C/A) -182.5 (C)	23.5
	GLONASS	-179	26
	Galileo	-182.5	20.5
	BDS	-184.2 (MEO) -185.9 (I/G)	25 19
	QZSS	-185.5	22
L5/L3/E5/B2	GPS	-182	26
	GLONASS	-178	34
	Galileo	-182.5 (E5b) -182.5 (E5a)	22.5 23.5
	BDS	-182.8 (MEO) -184.4 (I/G)	28 22
	QZSS	-180.7	24
	NavIC	-184.54	16

Example: Multi-GNSS SSV Benefits to Highly-Elliptical Mission Performance





- Simulated visibility for highly-elliptical trajectory, 500km x 60,000 km altitude, nadir + zenith-pointing antenna
- Single-signal availability from individual constellations is nearly continuous throughout the trajectory. Combined, it is fully continuous.
- At apogee, nearly-continuous four-signal availability is only achieved when combined signals are used.

Benefits of Development and Utilization of the Multi-GNSS SSV

- **Improve navigation performance:**
  - Increase number of usable signals over individual constellations alone
  - Improve geometric diversity by using multiple constellations in different regimes
  - Reduce or eliminate periods of outage, reducing the need for highly stable on-board clocks

- **Enable new mission types and operations concepts:**
  - Improved availability of navigation signals enables increased satellite autonomy, reducing the need for ground interactions and enabling reduced operations costs.
  - Increase operational robustness via diversity of independent constellations, signals, geometries, etc.
  - Reduce the navigation burden on ground-based communications assets, simplifying mission architectures.

- **Encourage development of the high-altitude GNSS user community:**
  - Adoption of the Multi-GNSS SSV indicates GNSS provider support for the high-altitude user community, encouraging development of specialized receivers and new mission applications.
  - Established UN ICG process provides a forum for further development.

Image: Southeastern USA at night, from ISS (NASA)

NASA Lunar GPS Visibility Simulation*

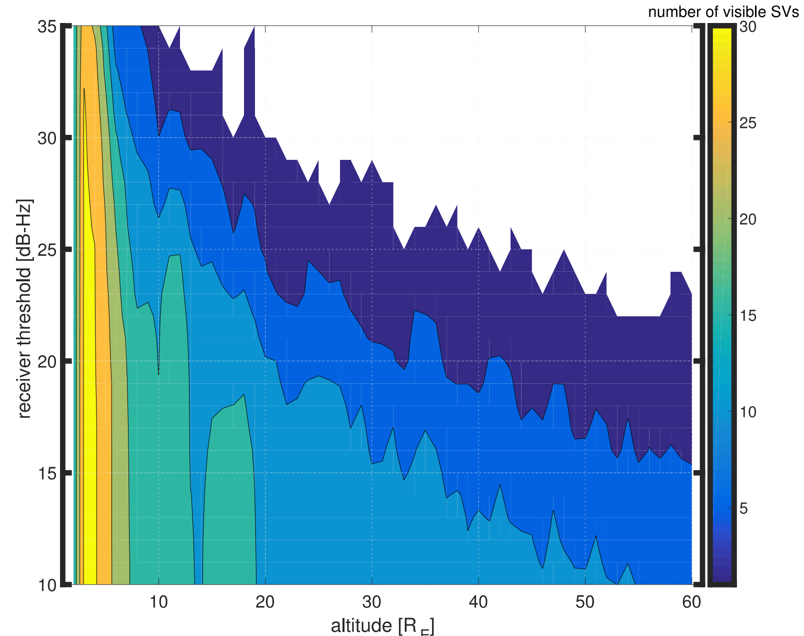
*B. Ashman, F. Bauer, J. Parker, J. Donaldson

Lunar Simulation Results

- Outbound lunar NRHO GPS receiver reception with 22 dB-Hz acq/trk threshold

Peak Antenna Gain	1+	4+	Maximum Outage
7 dB	63%	8%	140 min
10 dB	82%	17%	84 min
14 dB	99 %	65%	11 min

- *A modest amount of additional antenna gain or receiver sensitivity increases coverage significantly*



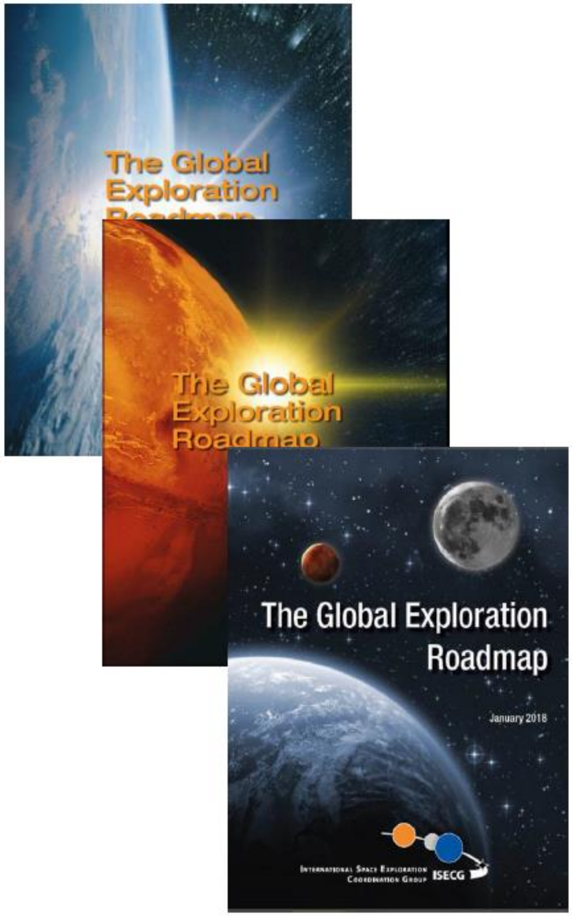
Number of satellites visible by altitude and receiver threshold

Conclusions

- GOES and MMS data have enabled the development of high altitude GPS simulation models that match flight data to within a few percent in overall visibility metrics
- These results show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven* receiver technology
- A modest increase in antenna gain or receiver sensitivity increases visibility significantly
- Future work must extend these specific studies to full navigation analysis of cis-lunar spacecraft, including effects of DOP, and utilizing the *full capability* of multi-GNSS signals
- ICG WG-B is a natural forum for these discussions and analyses, in keeping with the ICG-12 recommendation for analysis for cis-lunar missions and beyond.

Global Exploration Roadmap

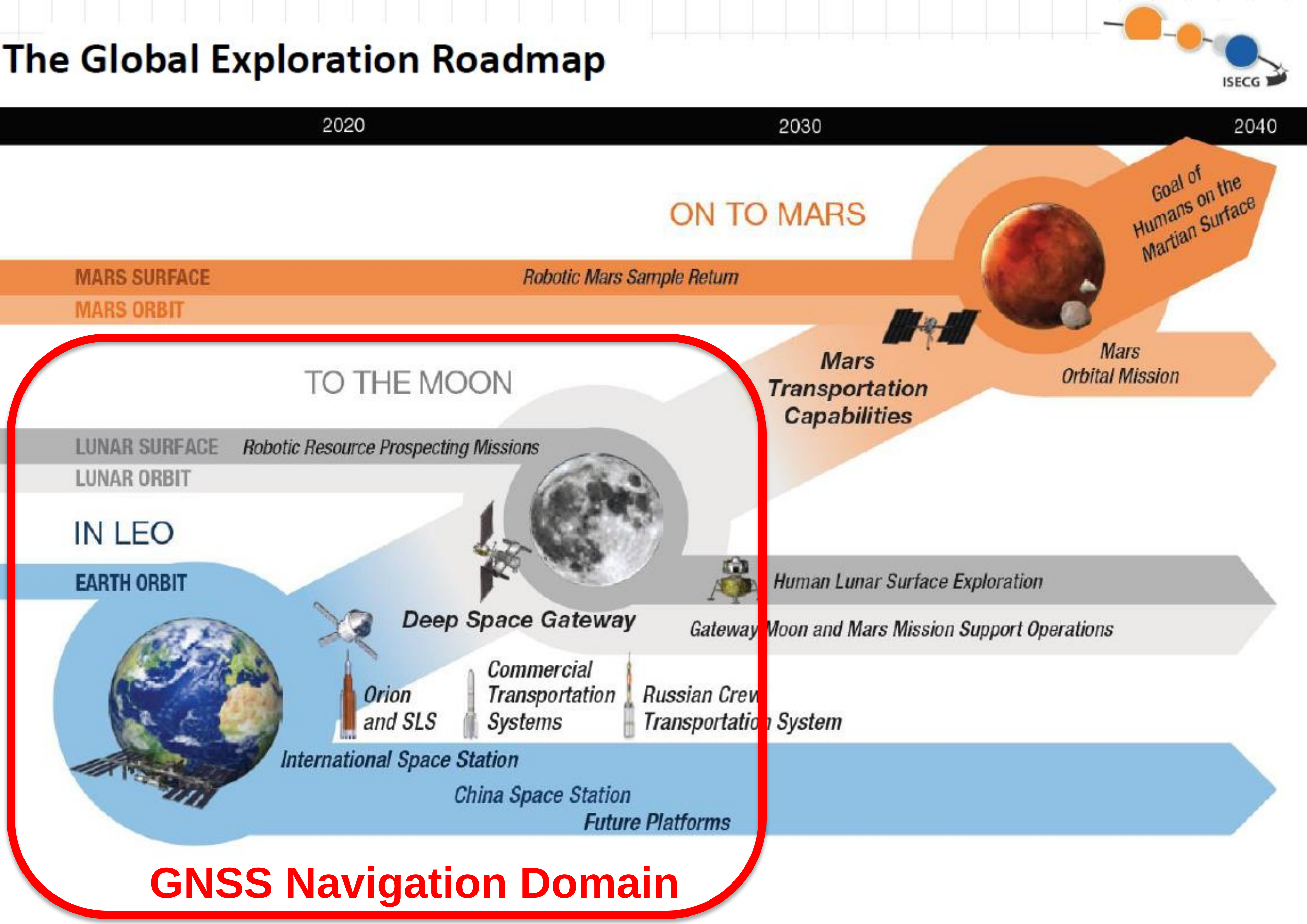
- **The GER is a human space exploration roadmap developed by 14 space agencies participating in the International Space Exploration Coordination Group (ISECG)**
  - First released in 2011. Updated in 2013 and 2018.

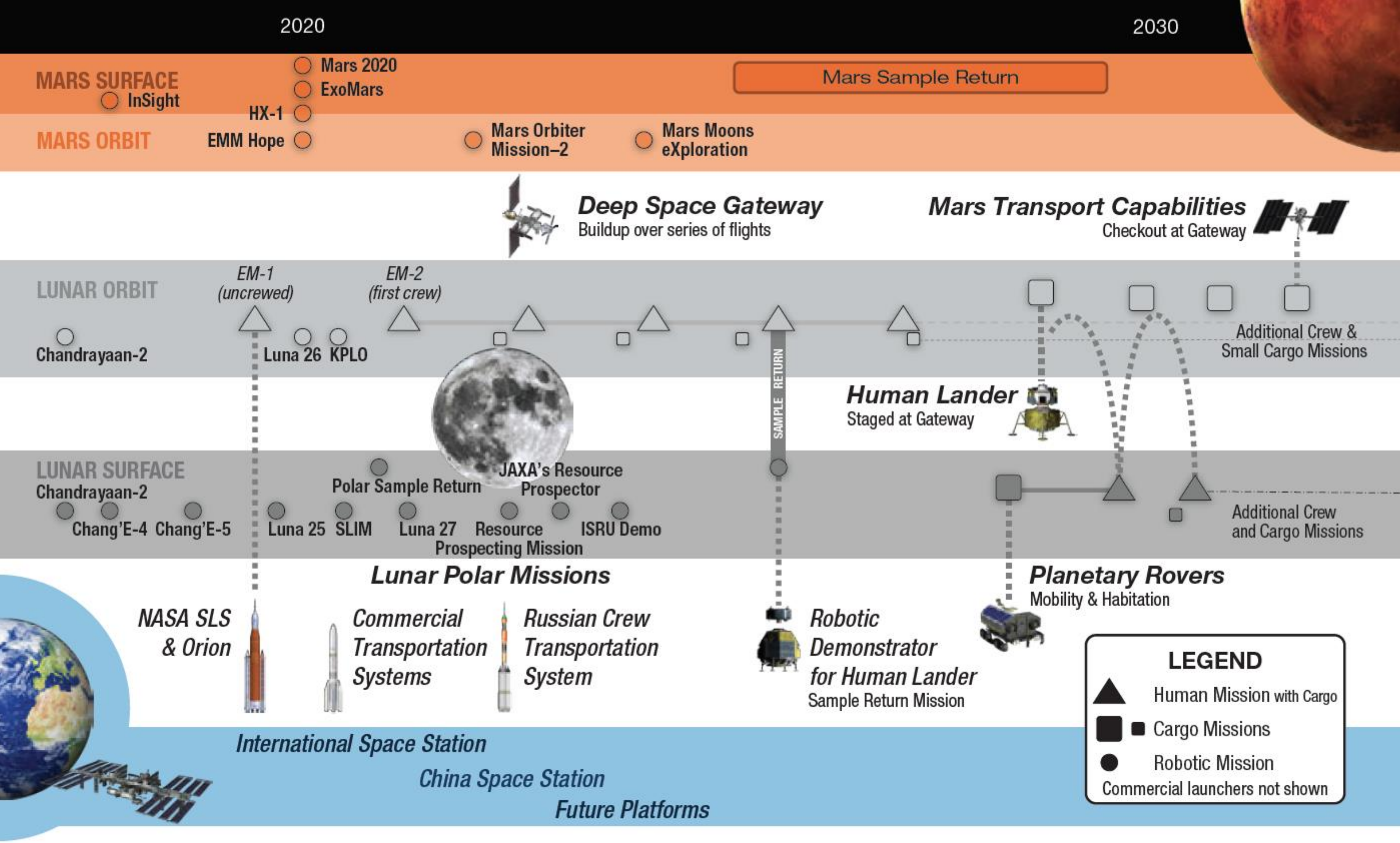


- **The non-binding strategic document reflects consensus on expanding human presence into the Solar System, including**
  – Sustainability Principles, spaceflight benefits to society
  – Importance of ISS and LEO
  – The Moon: Lunar vicinity and Lunar surface
  – Mars: The Driving Horizon Goal

www.globalspaceexploration.org
www.nasa.gov/isecg

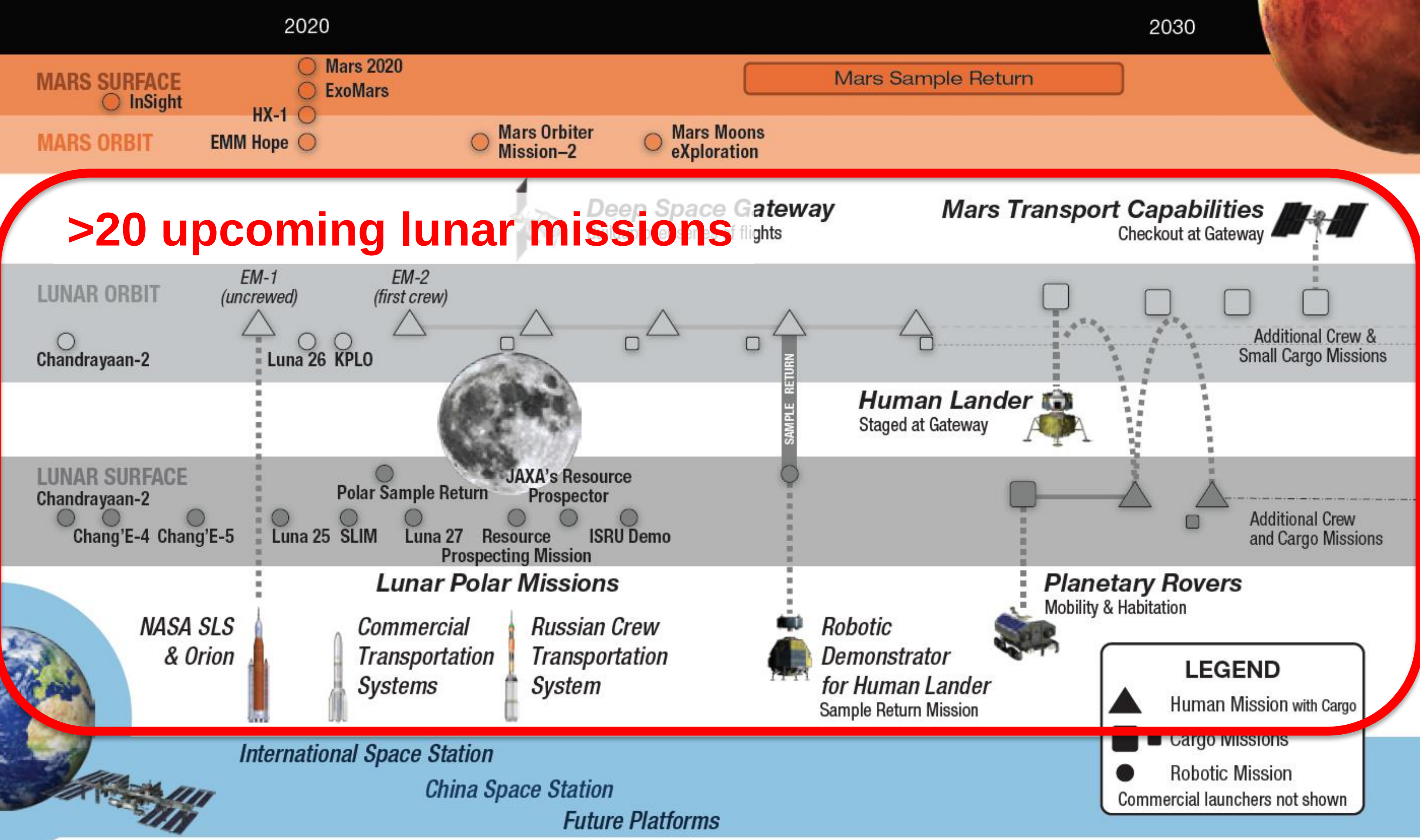
The Global Exploration Roadmap





Relevant GNSS Advanced Technology Needs:

- Autonomous Vehicle System Management
- Autonomous rendezvous & docking
- Proximity ops; Relative Navigation
- Beyond LEO Crew Autonomy
- Lunar Lander (100 m accuracy)
- In-space Timing and Navigation



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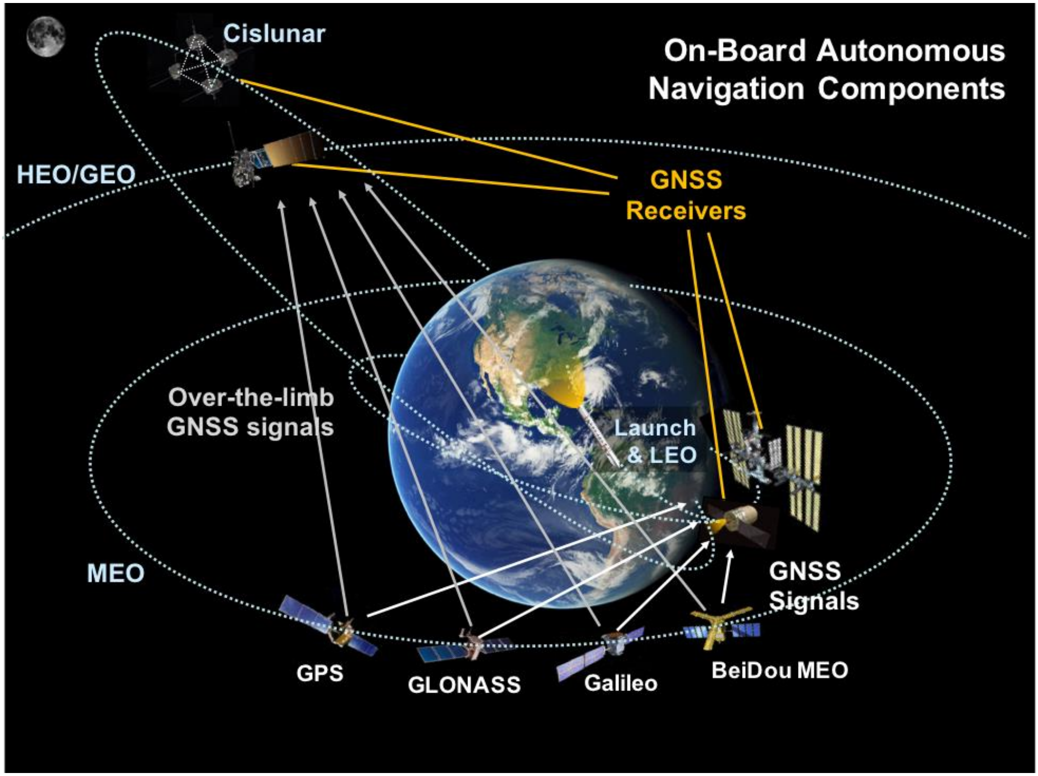
Conclusions

- The SSV, **continues to evolve** to meet user needs. **GPS has led the way**, starting with GPS IIF.
- Current and future space missions within the SSV are **enabled and enhanced** by near-continuous GNSS availability; **mission use is expanding into cislunar space**
- Today, we **continue to work** to ensure that the SSV keeps pace with user demands:
  - For **GPS**, we are working with the Air Force to understand how future GPS designs will continue to support the needs of emerging GPS-only users like the Geostationary Operational Environmental Satellite - R Series (GOES-R)
  - In partnership with foreign GNSS providers, we are working 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 and complementary. A robust GPS capability enables and enhances GPS-only applications; an interoperable GNSS SSV improves on-board PNT resilience & ensures that wider capabilities are available
- NASA and the U.S. Government are **proud to work** with the GNSS providers to contribute making GNSS services more accessible, interoperable, robust, and precise for all users, for the **benefit of humanity**. We encourage all providers to continue to support this essential capability

Backup

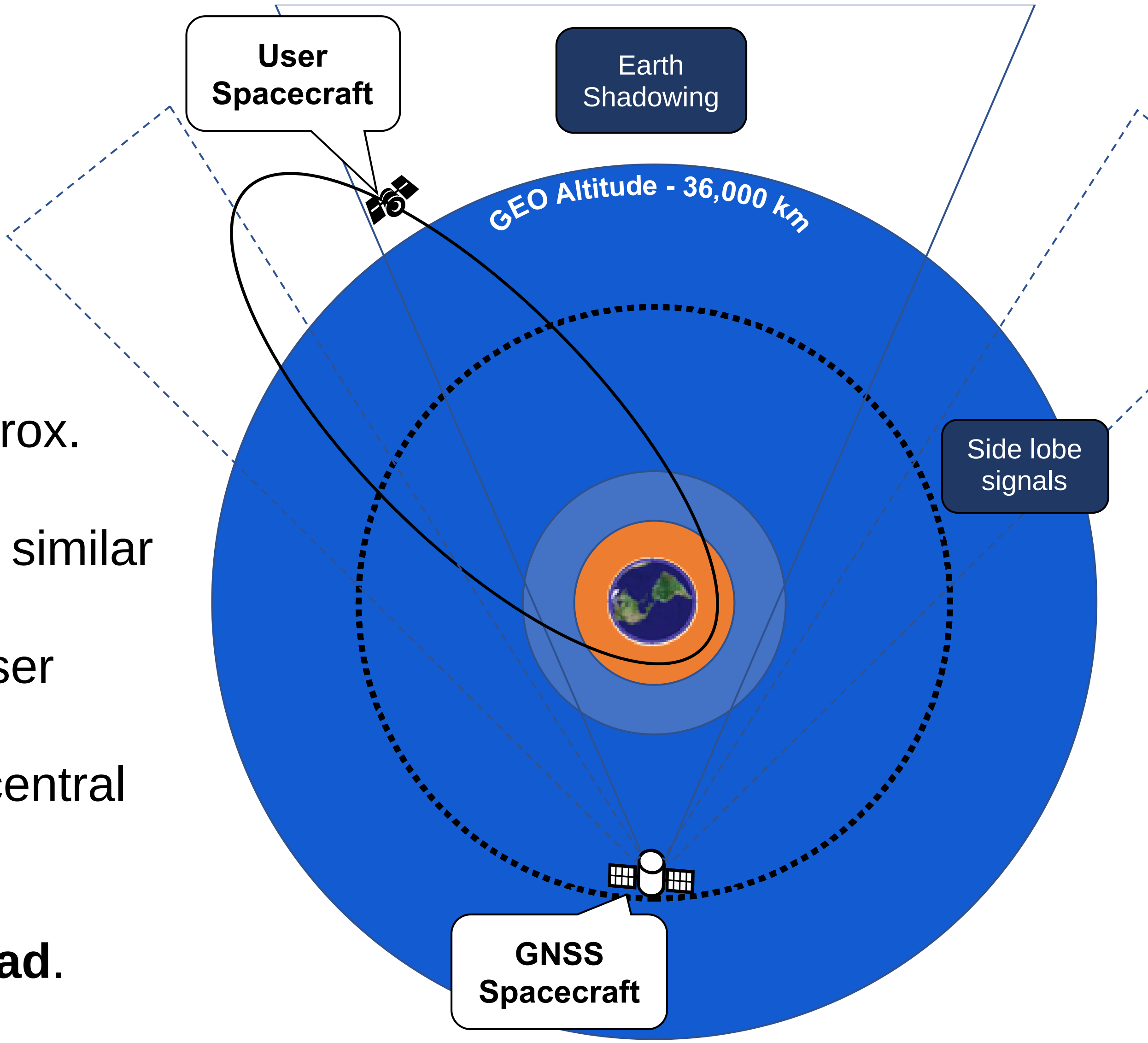
Space Uses of Global Positioning System (GPS) & Global Navigation Satellite Systems (GNSS)

- **<u>Real-time On-Board Navigation:</u>** Precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **<u>Earth Sciences:</u>** GPS as a measurement for atmospheric and ionospheric sciences, geodesy, and geodynamics
- **<u>Launch Vehicle Range Operations:</u>** Automated launch vehicle flight termination; providing safety net during launch failures & enabling higher cadence launch facility use
- **<u>Attitude Determination:</u>** Some missions, such as the International Space Station (ISS) are equipped to use GPS/GNSS to meet their attitude determination requirements
- **<u>Time Synchronization:</u>** Support precise time-tagging of science observations and synchronization of on-board clocks



GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

The Challenges of High-Altitude Space Use of GNSS



Low altitudes (below approx. 3,000 km):

- Signal reception largely similar to terrestrial
- Major factor is higher user velocities
- Signal reception is via central main lobe signals

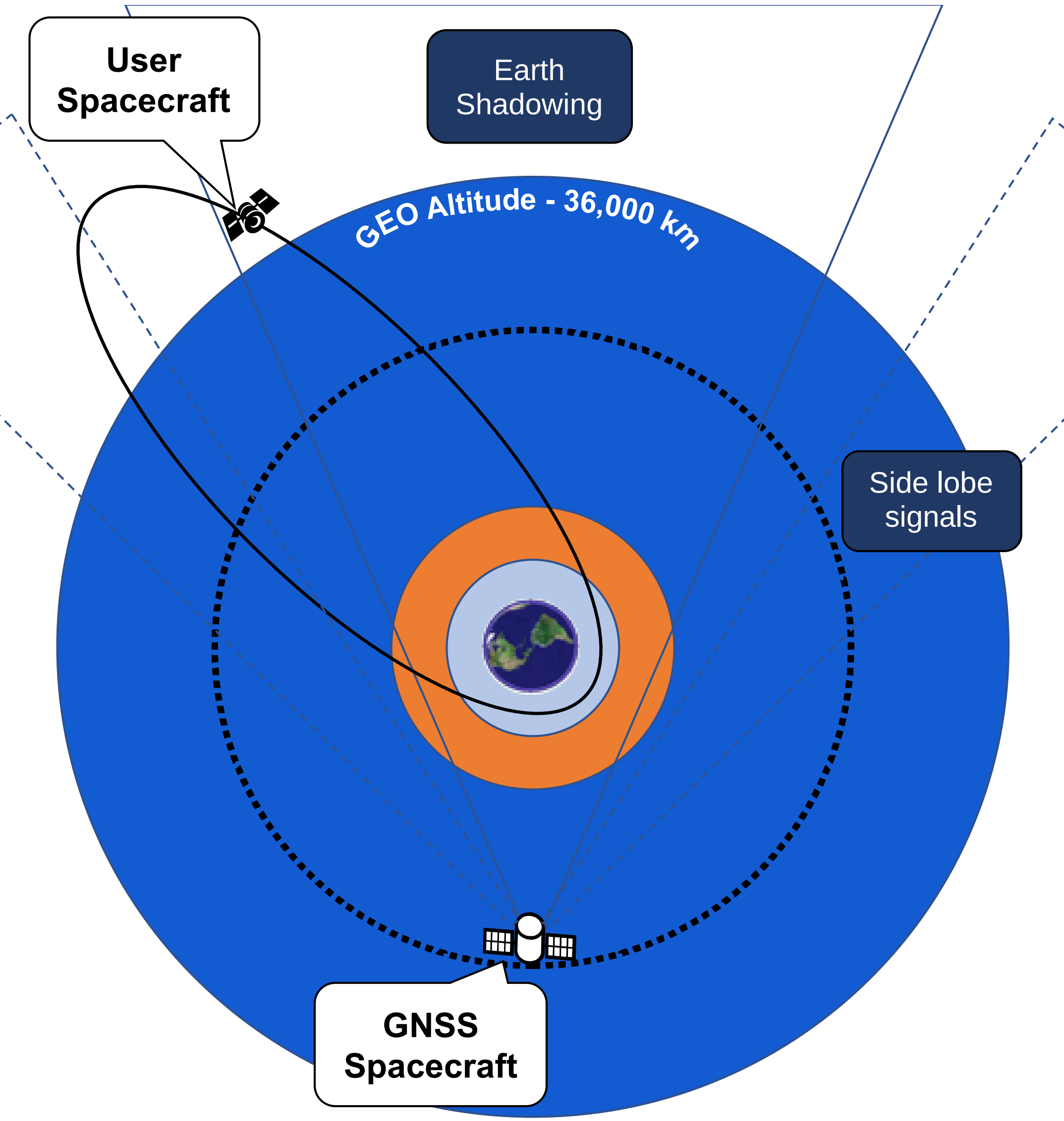
GNSS usage is **widespread**.

The Challenges of High-Altitude Space Use of GNSS

Medium altitudes (3,000 to 8,000 km):

- Decreased reception of primary main-lobe signals via zenith antenna
- Spillover signals can increase overall signal reception with omni-directional or additional nadir-pointing antenna.
- Signal reception is via direct and spillover main lobe signals.

GNSS usage is **operational**.

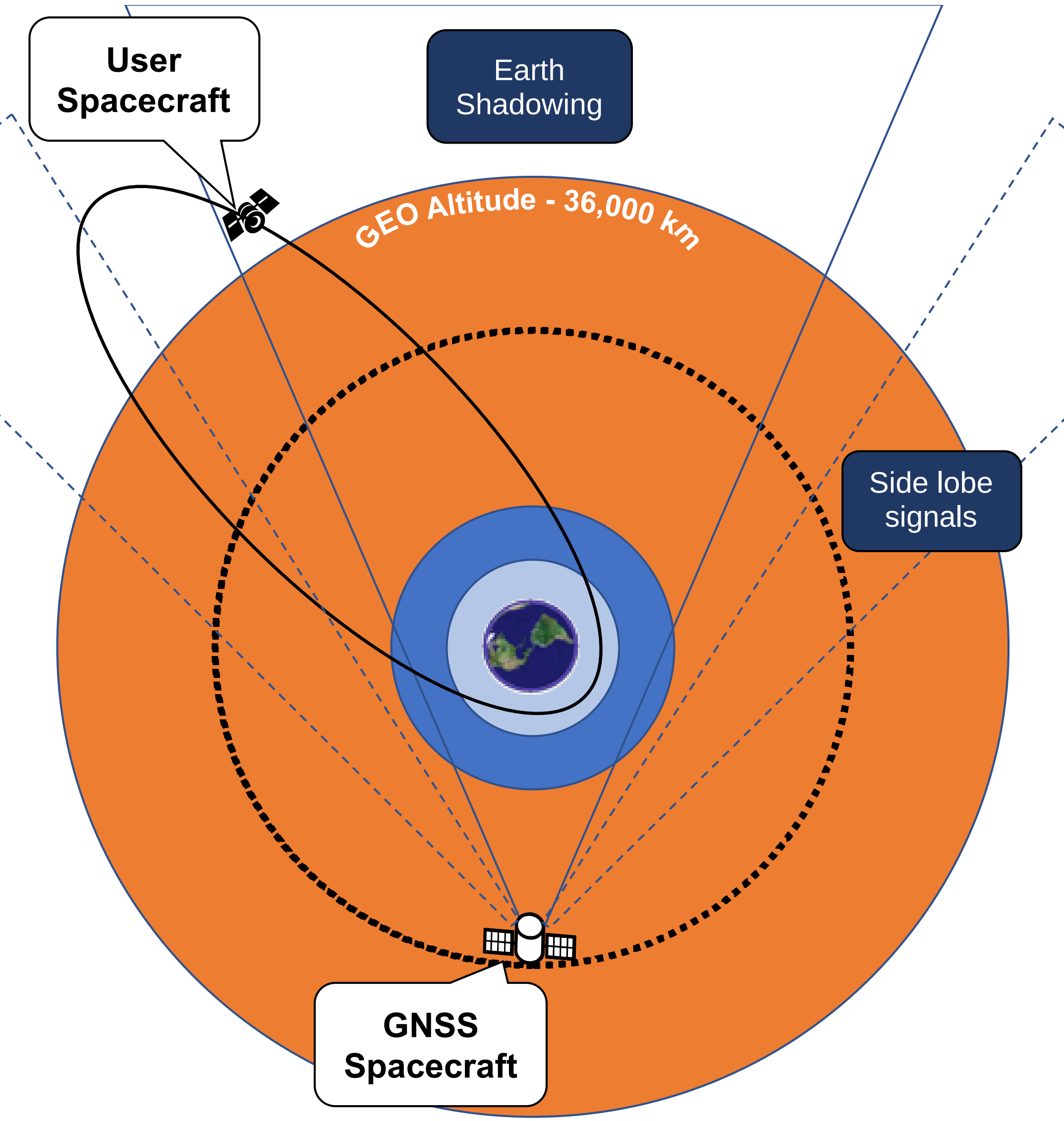


The Challenges of High-Altitude Space Use of GNSS

High altitudes (8,000 to 36,000 km):

- Signal reception is primarily via spillover signals and side lobe signals.
- Signals are much weaker due to additional distance traveled
- Signal availability is reduced due to signal power and narrower beamwidths in spillover signal
- Receivers typically employ navigation filter algorithms to allow processing of individual measurements.

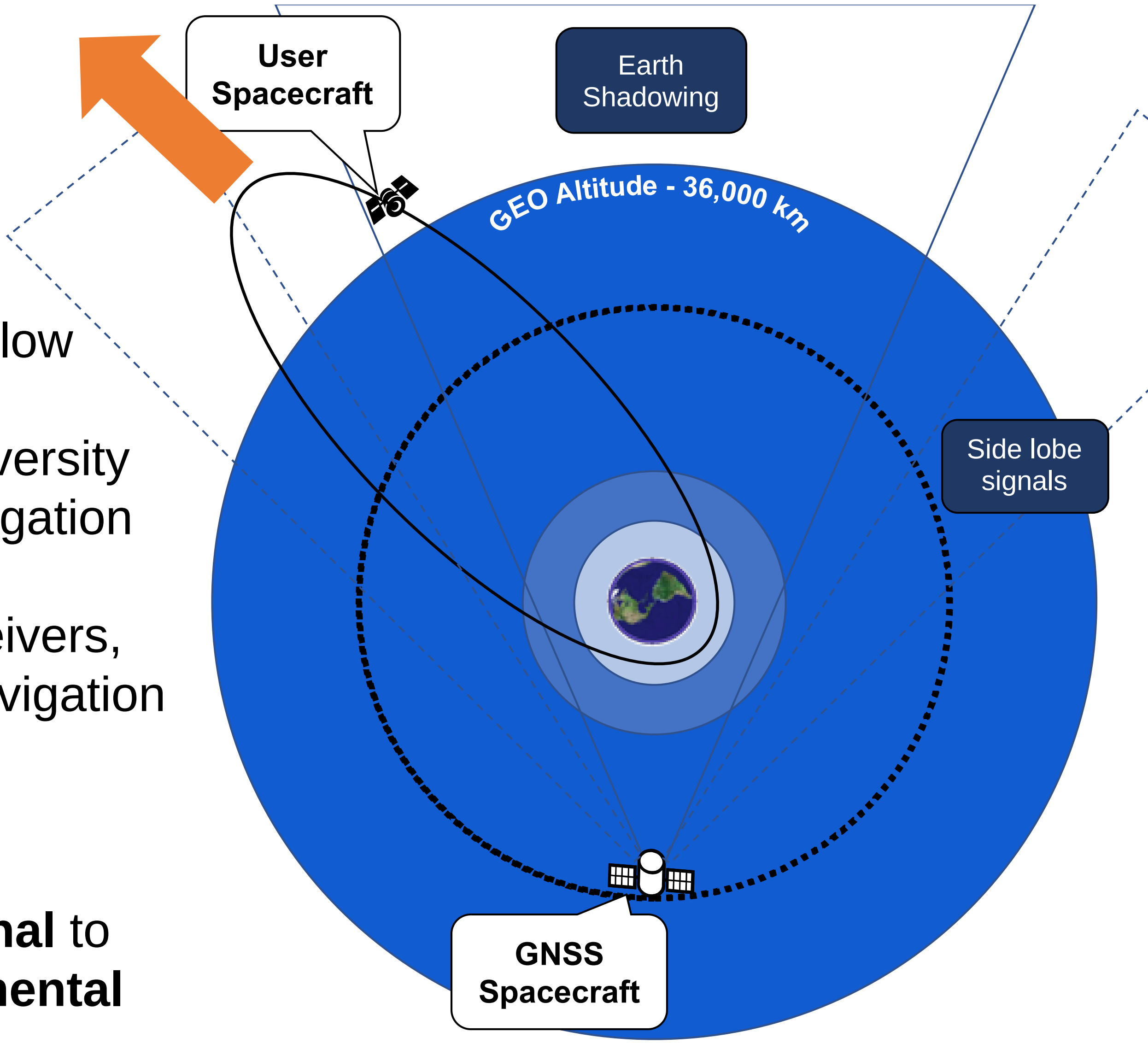
GNSS usage is **operational** but **emerging**.



The Challenges of High-Altitude Space Use of GNSS

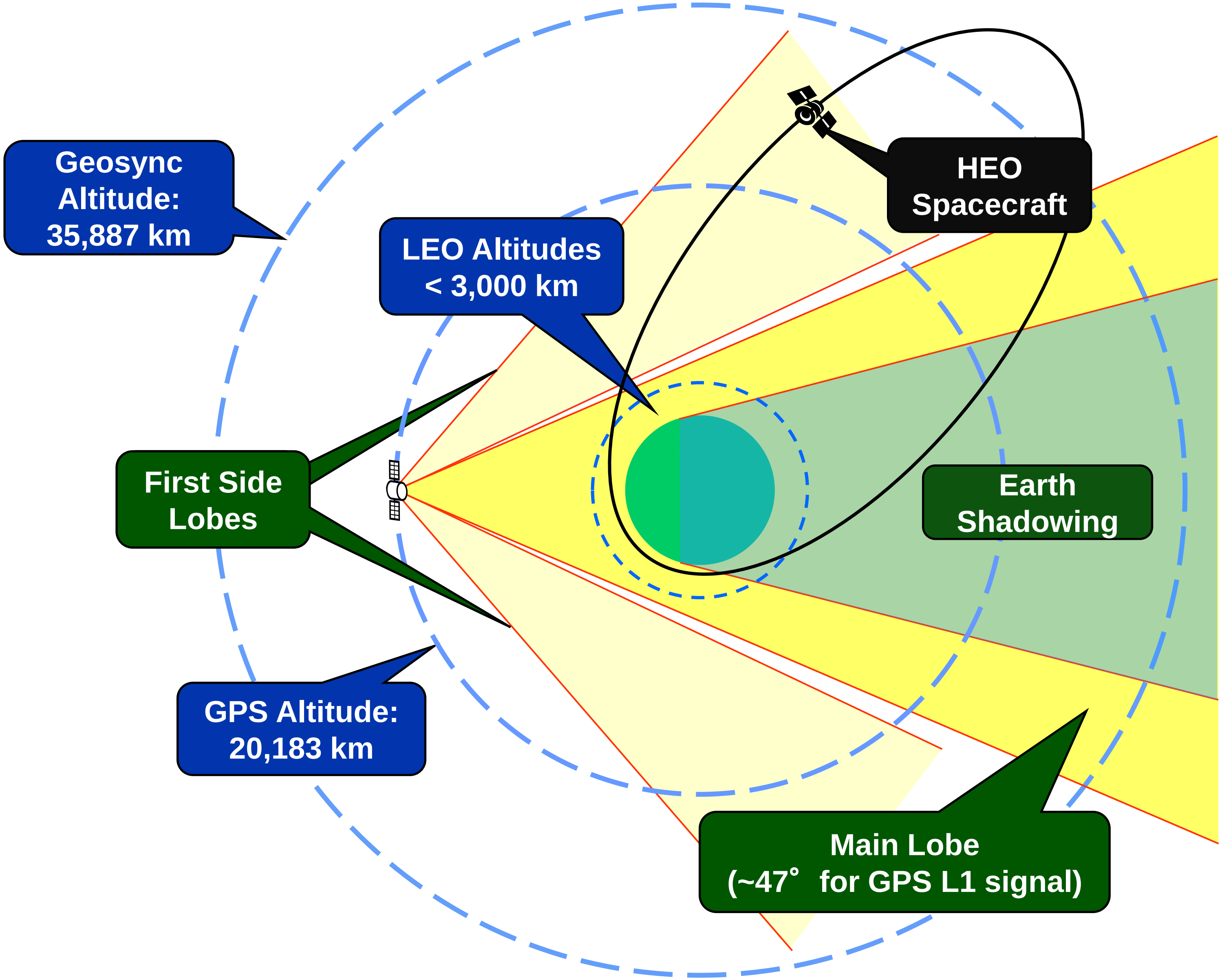
Beyond-GEO altitudes (36,000+ km):

- Very weak signals and low availability
- Very poor geometric diversity leads to increased navigation uncertainty
- Use of specialized receivers, high-gain antennas, navigation filters critical.



GNSS usage is **operational** to 150,000 km, and **experimental** beyond.

GPS Signals in the Space Service Volume (SSV)



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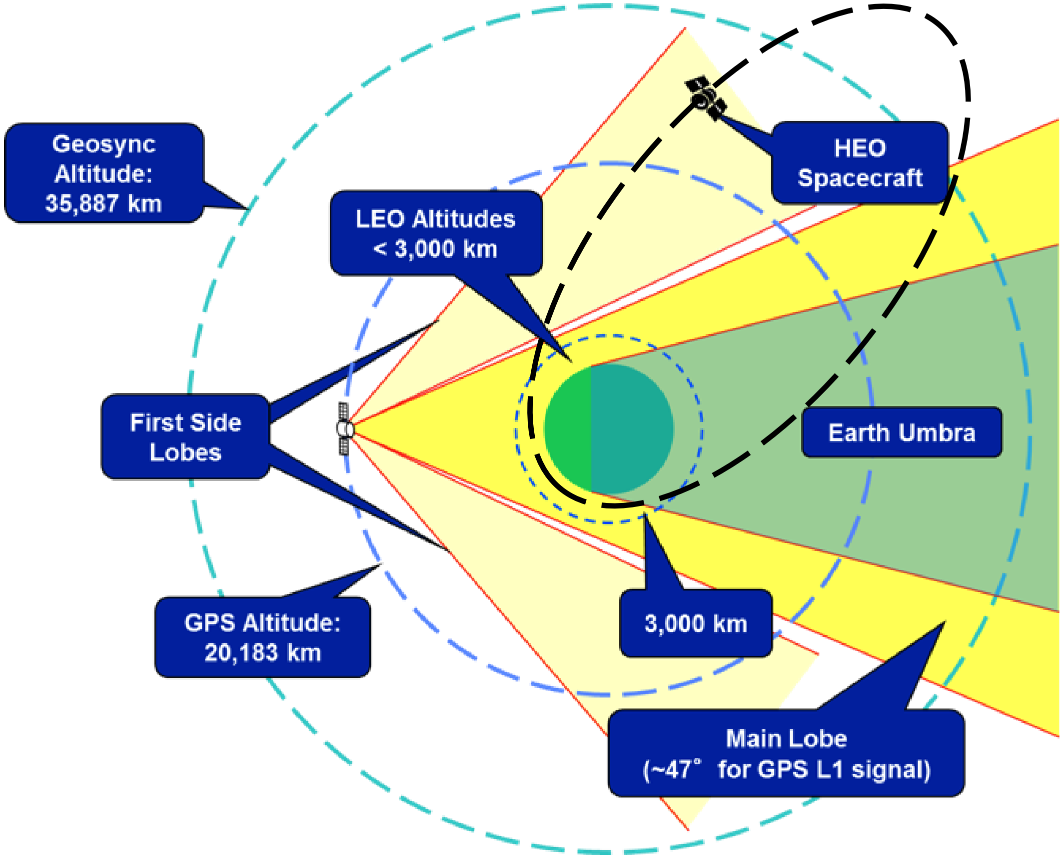
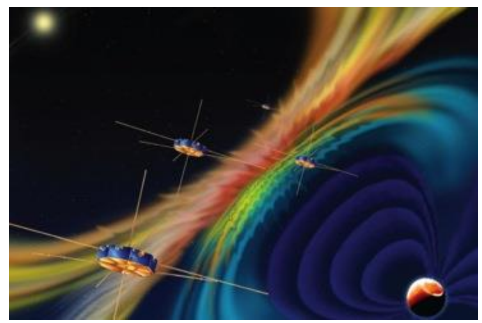


The Promise of using GNSS for Real-Time Navigation <u>inside</u> the SSV

Benefits of GNSS use inside the 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:

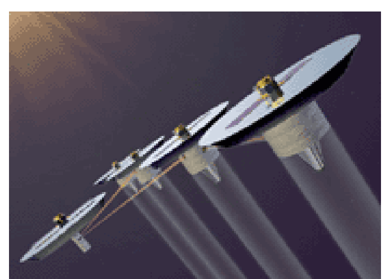
Earth Weather Prediction using Advanced Weather Satellites



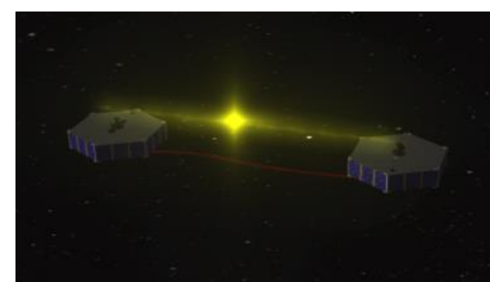
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



Formation Flying, Space Situational Awareness, Proximity Operations



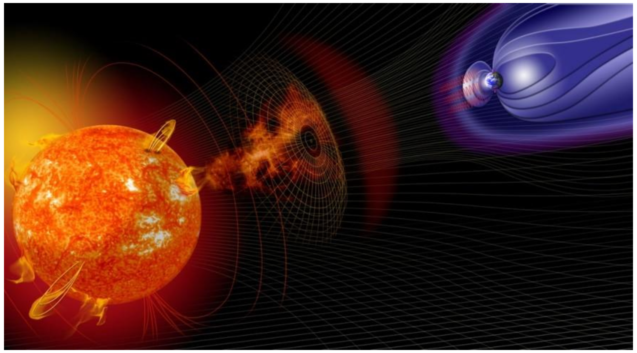
Precise Position Knowledge and Control at GEO

The Promise of using GNSS for Real-Time Navigation beyond the SSV

Benefits of GNSS use beyond the SSV:

- **Supports <u>real-time</u> navigation performance** (from: *no real time* to: real-time 1 km – 100 m position, µsec timing)
  - Improved performance with (pseudo-) satellite and clock augmentations
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- **Near-continuous navigation signals reduces DSN navigation support**
- **Increased satellite autonomy & robotic operations**, lowering ops costs (savings up to $500-750K/year)
- Supports vehicle autonomy, new/enhanced capabilities and better performance for Cis-Lunar & Gateway **mission scenarios,** including:

Earth Observations beyond GEO



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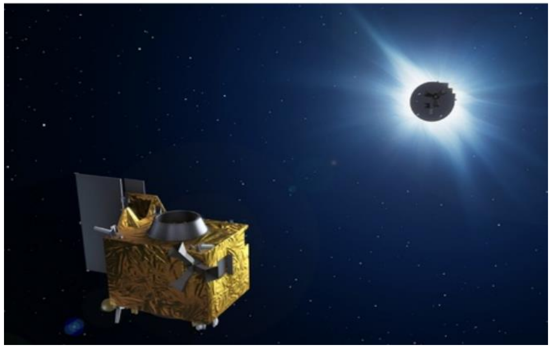
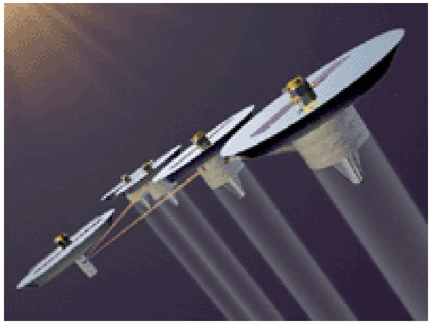


Precise Relative Positioning

Launch Vehicle Upper Stages & Cislunar applications



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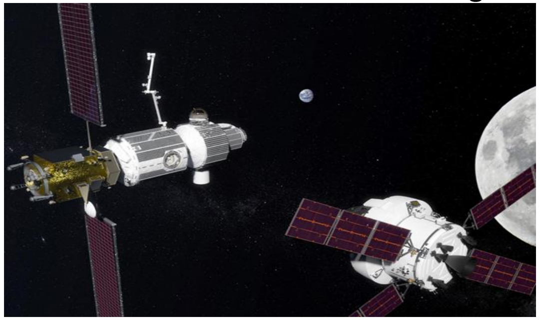
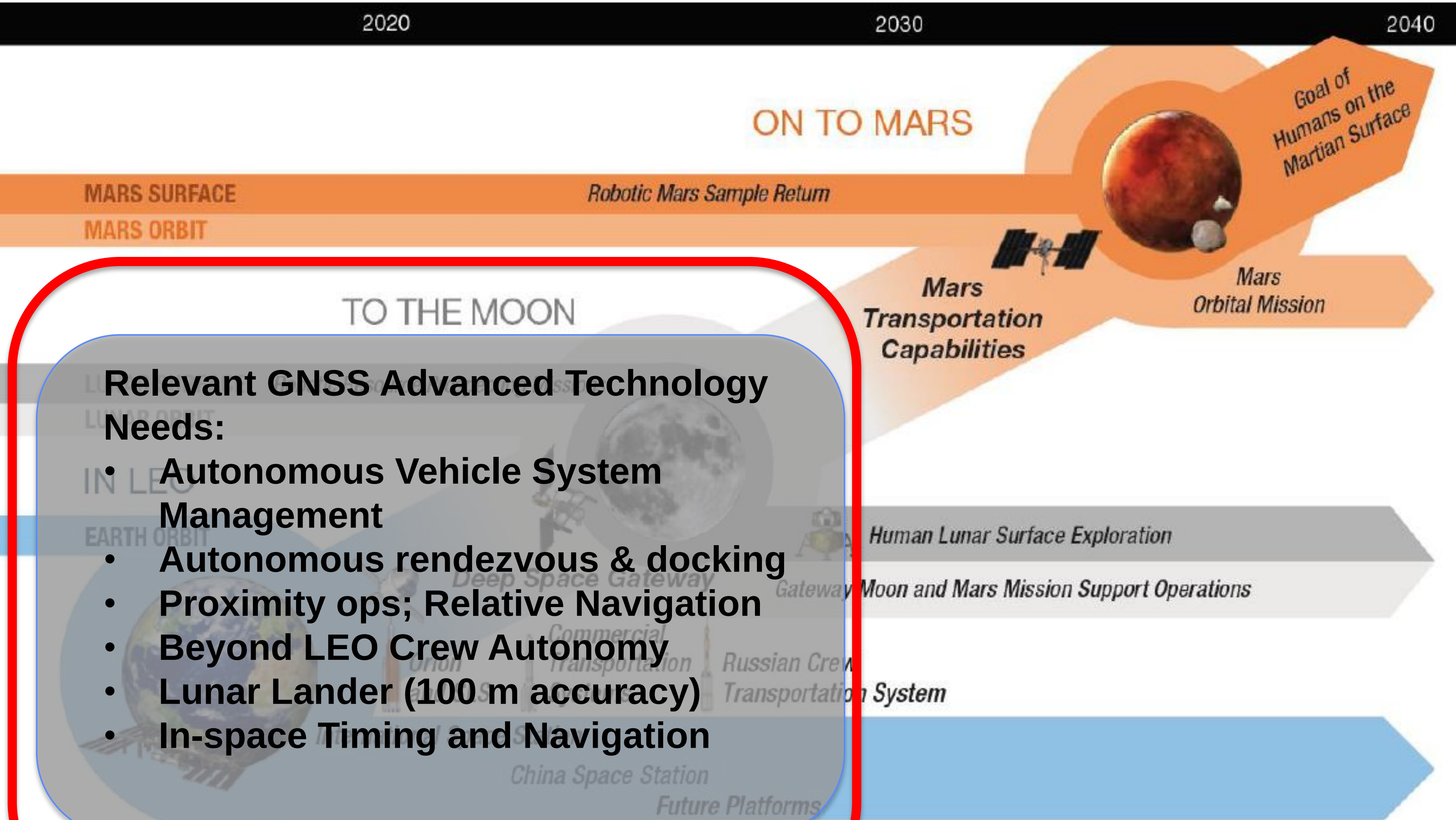


Lunar Orbiting Platform-Gateway Human & Robotic Space Applications

Operational Challenges, Mitigations and Use of GPS/GNSS in Space

Ops Scenario	Altitude Range (km)	Challenges & Observations (Compared to previous scenario)	Mitigations	Operational Status
Terrestrial Service Volume	100-3,000	Acquisition & Tracking: Higher Doppler, faster signal rise/set; accurate ephemeris upload required; signal strength & availability comparable to Earth use	Development of Space Receivers; fast acquisition algorithm eliminates ephemeris upload	Extensive Operational use
SSV Medium Altitudes	3,000-8,000	More GPS/GNSS signals available; highest observed Doppler (HEO spacecraft)	Max signals require omni antennas; receiver algorithms must track higher Doppler	Operational (US & foreign)
SSV High-GEO Altitudes	8,000-36,000	Earth obscuration significantly reduces main lobe signal availability; frequent ops w/ <4 signals; periods of no signals; weak signal strength due to long signal paths	Nav-Orbit Filter/Fusion algorithms (e.g. GEONS) enables ops w/ <4 signals and flywheel through 0 signal ops; use of signal side lobes and/or other GNSS constellations; higher gained antennas, weak signal receivers	Operational (US & foreign)
Beyond	36,000-	Even weaker signals &	Use higher gain, small footprint	Operational to

The Global Exploration Roadmap



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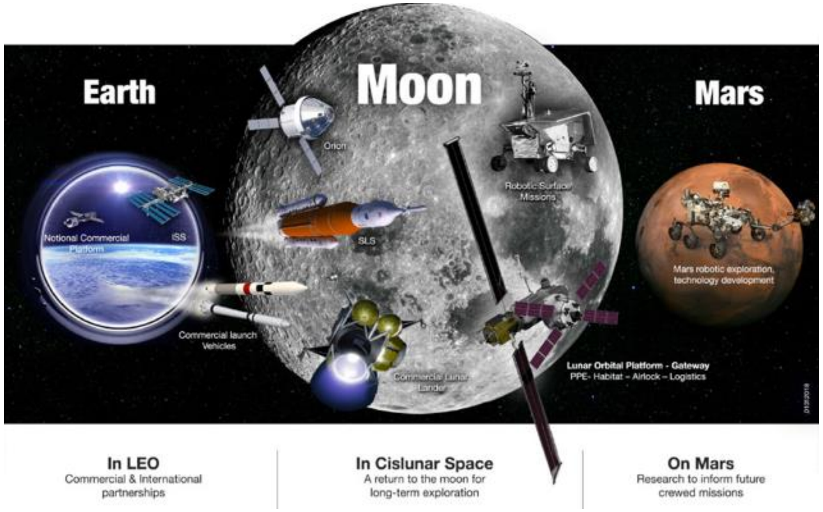
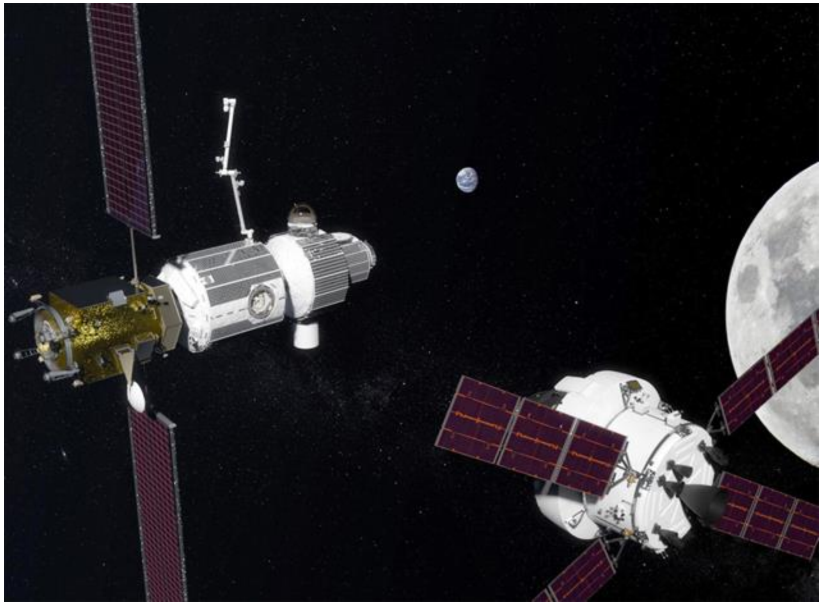
- **Autonomous Vehicle System Management**
- **Autonomous rendezvous & docking**
- **Proximity ops; Relative Navigation**
- **Beyond LEO Crew Autonomy**
- **Lunar Lander (100 m accuracy)**
- **In-space Timing and Navigation**

GNSS Navigation Domain

Potential Future Application: Lunar Orbital Platform - Gateway

- NASA Exploration Campaign: Next step is deployment and operations of US-led Lunar Orbital Platform – Gateway (previously known as Deep Space Gateway)
- Step-off point for human cislunar operations, lunar surface access, missions to Mars
- Features include:
  - Power and propulsion element (PPE) – targeted for 2022
  - Human habitation capability
  - Docking/rendezvous capability
  - Extended uncrewed operations (not continuously crewed)
  - Lunar near-rectilinear halo orbit (NRHO)
- Gateway conceptual studies are continuing with ISS partners
  - Requirements to be baselined in 2018
  - To be followed by Broad Agency Announcement for partnerships
- **Gateway represents a potential application for on-board GNSS navigation**
- NASA will continue providing updates to WG-B as plans develop.

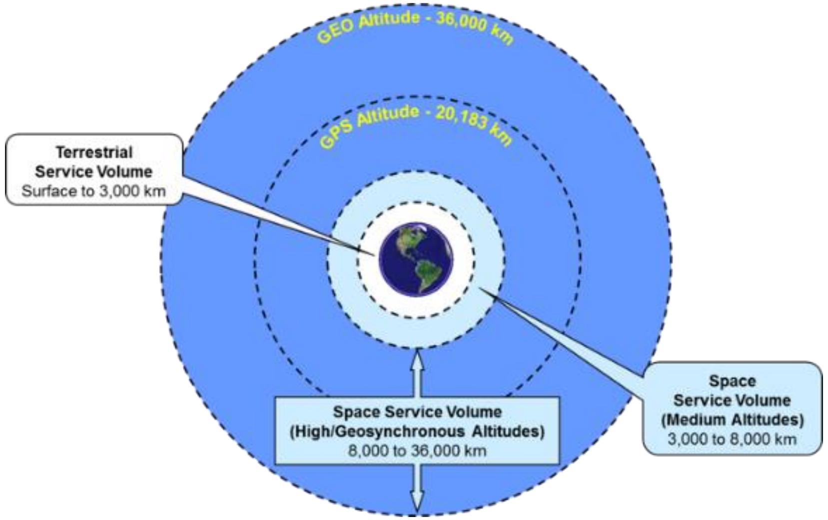


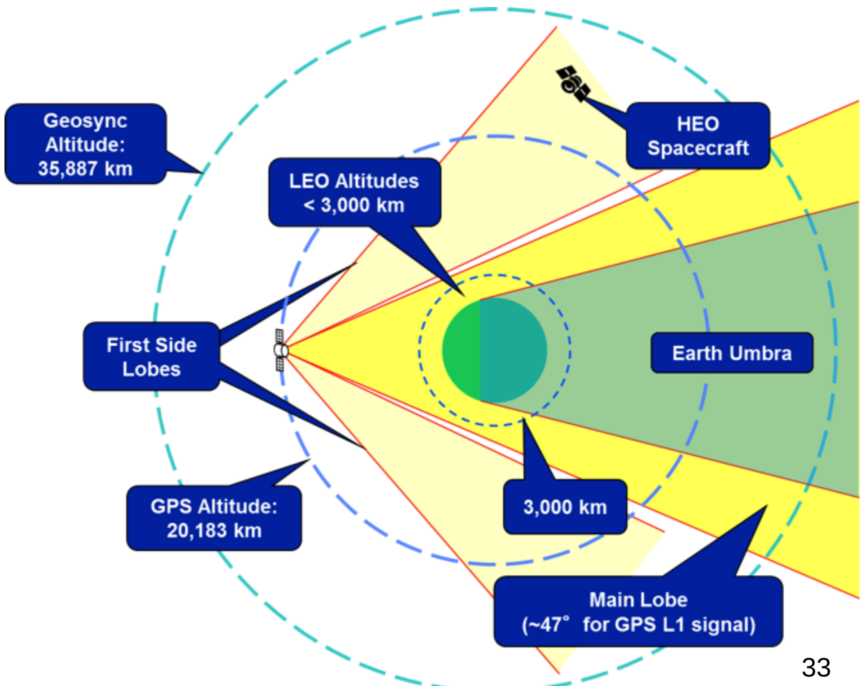


https://www.nasa.gov/feature/nasa-s-lunar-outpost-will-extend-human-presence-in-deep-space

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.

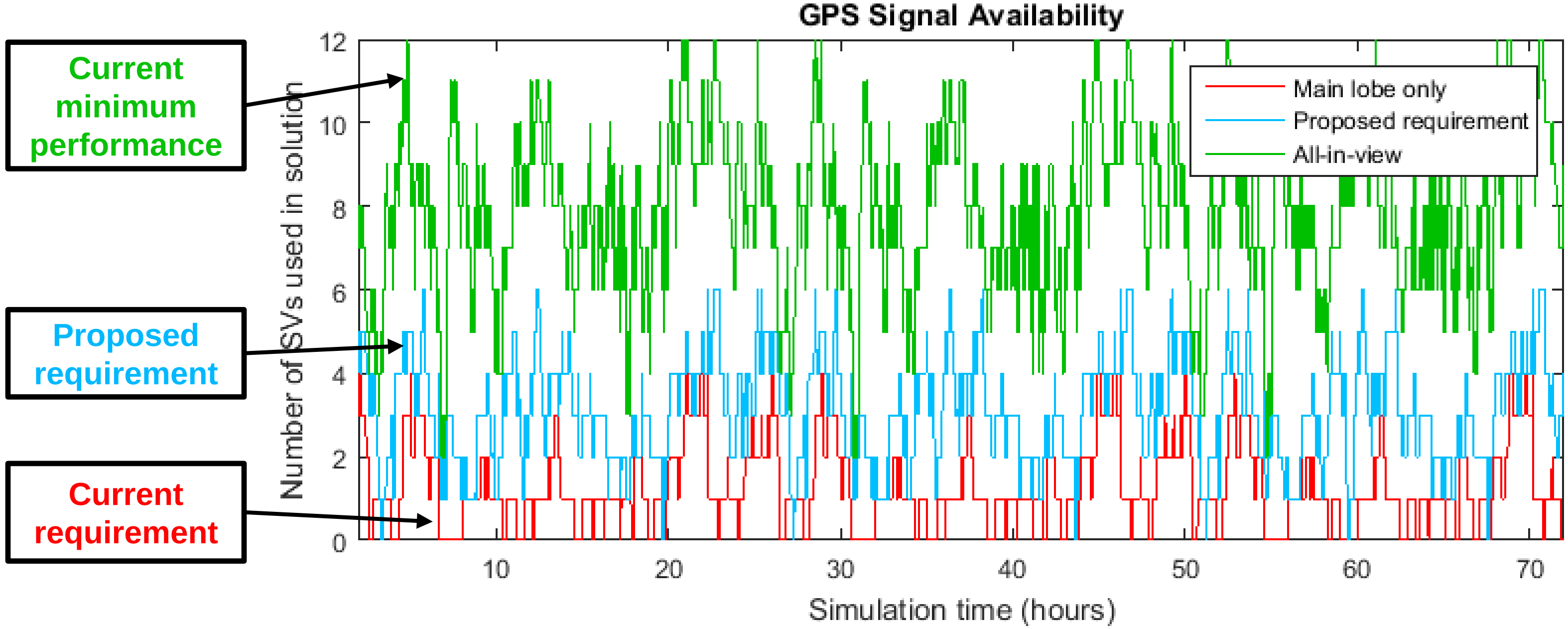
5X FASTER SCANS

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

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

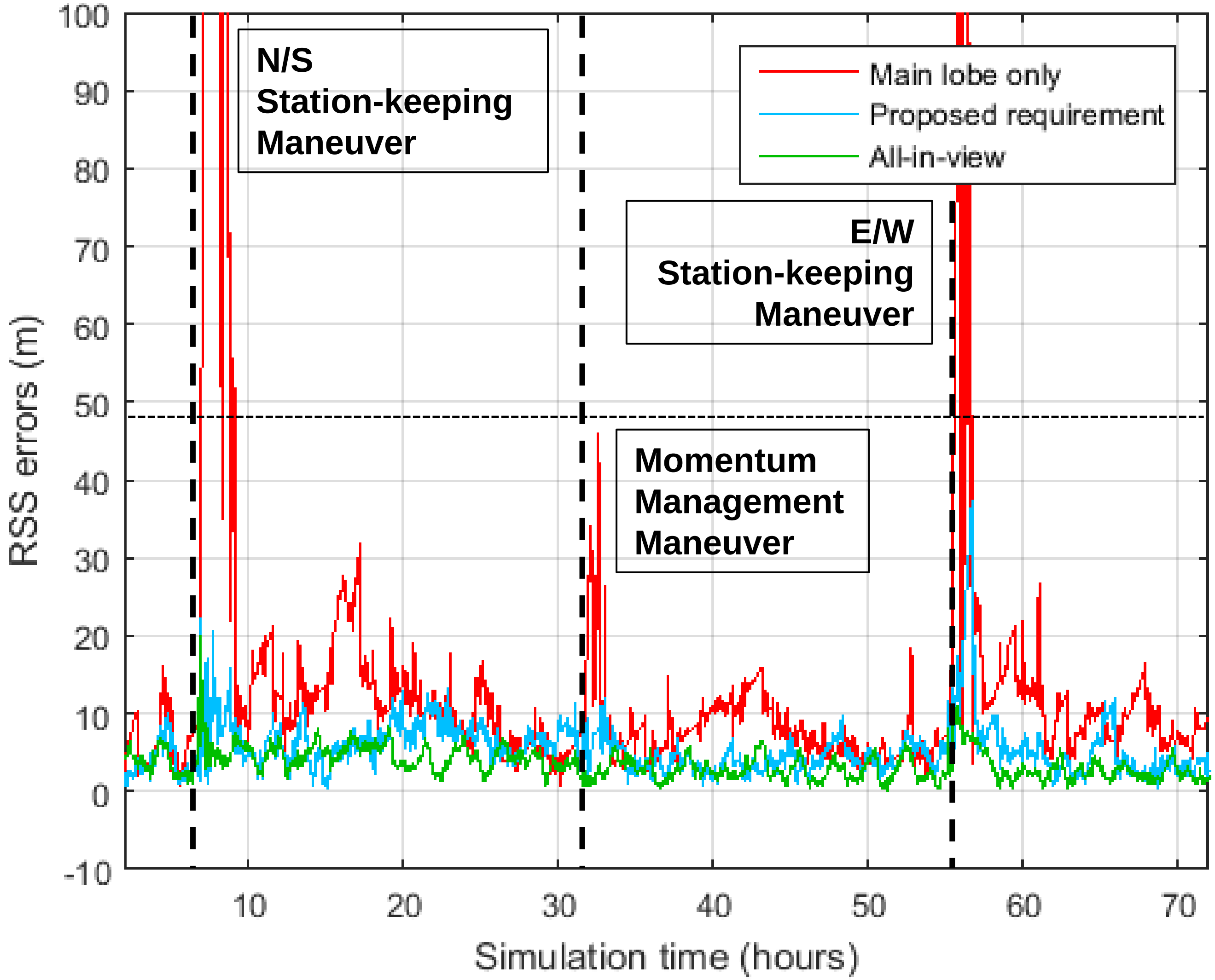
- **Proposed requirement adds second tier of capability specifically for HEO/GEO users**
  - Increased signal availability to nearly continuous for at least 1 signal
  - Relaxed pseudorange accuracy from 0.8m RMS to 4m RMS
  - No change to minimum received signal power
  - Applies to all signals (L1/L2/L5),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

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

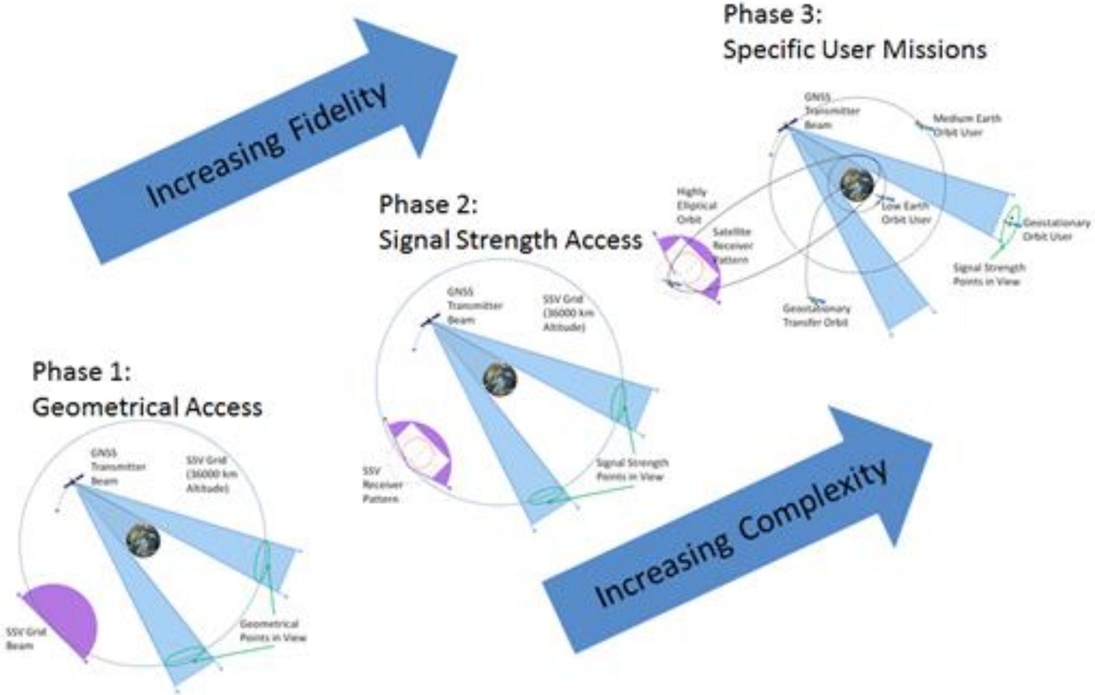
Summary of ICG Multi-GNSS SSV Development Efforts To-Date

- 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**

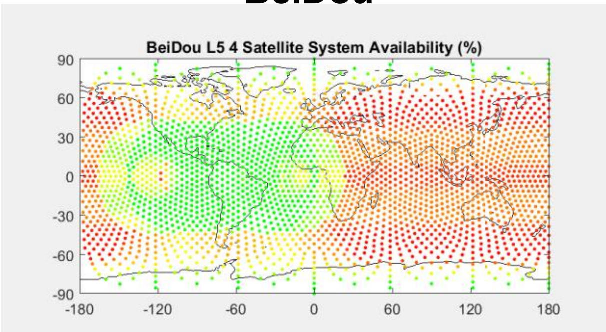
Multi-GNSS Simulation Overview



Multi-GNSS Simulation Video

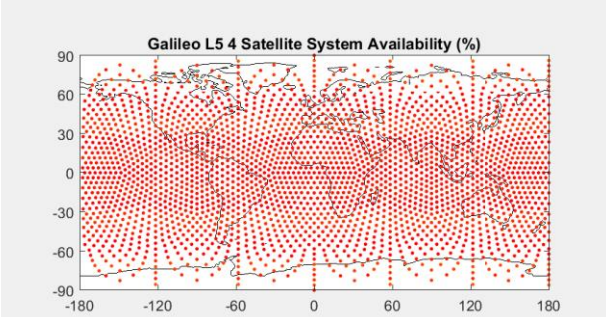
ICG WG-B Phase 1 Results:
4+ Signal Main-Lobe Availability

BeiDou



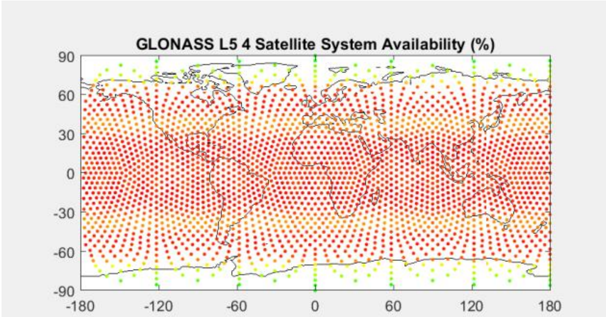
Average 45.4% availability

Galileo



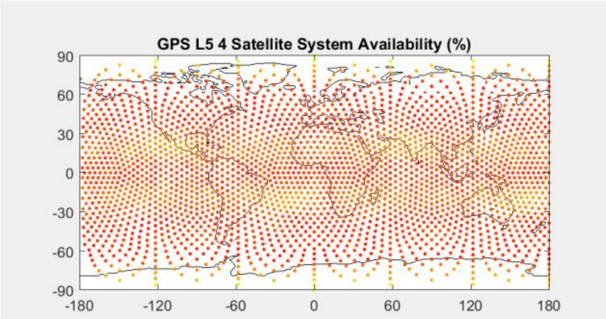
Average 4.2% availability

GLONASS



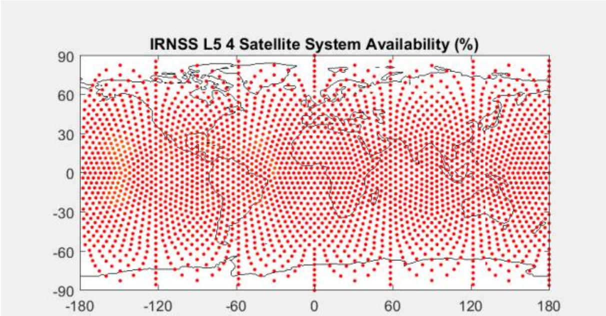
Average 14.5% availability

GPS



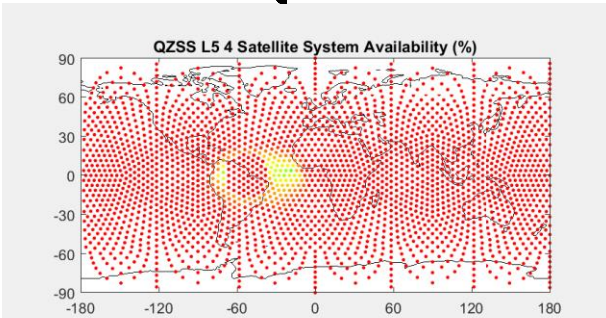
Average 15.6% availability

NAVIC



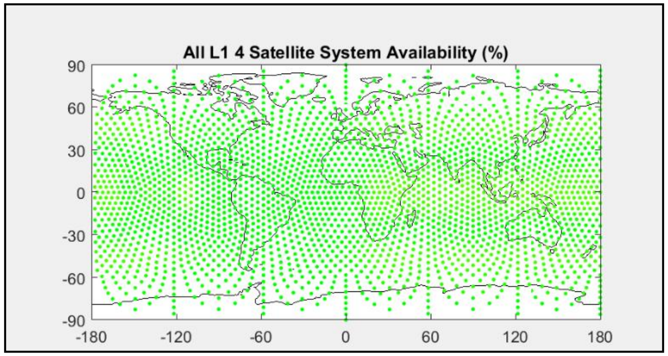
Average 0.6% availability

QZSS



Average 1.5% availability

Interoperable GNSS achieves <u>100%</u> 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

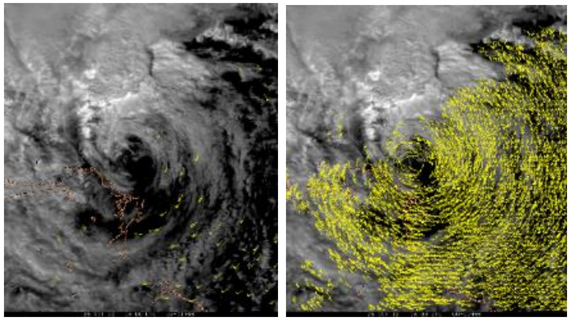
- The Space Service Volume, first defined for GPS IIF in 2000, **continues to evolve** to meet high-altitude user needs.
- **GPS led the way** with a formal specification for GPSIII, requiring that GPS provides a core capability to space users.
- Today, we **continue to work** in parallel tracks to ensure 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.

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**