The Multi-GNSS Space Service Volume (SSV): USA ICG Support and Space User Applications

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CGSIC
Munich Navigation Summit
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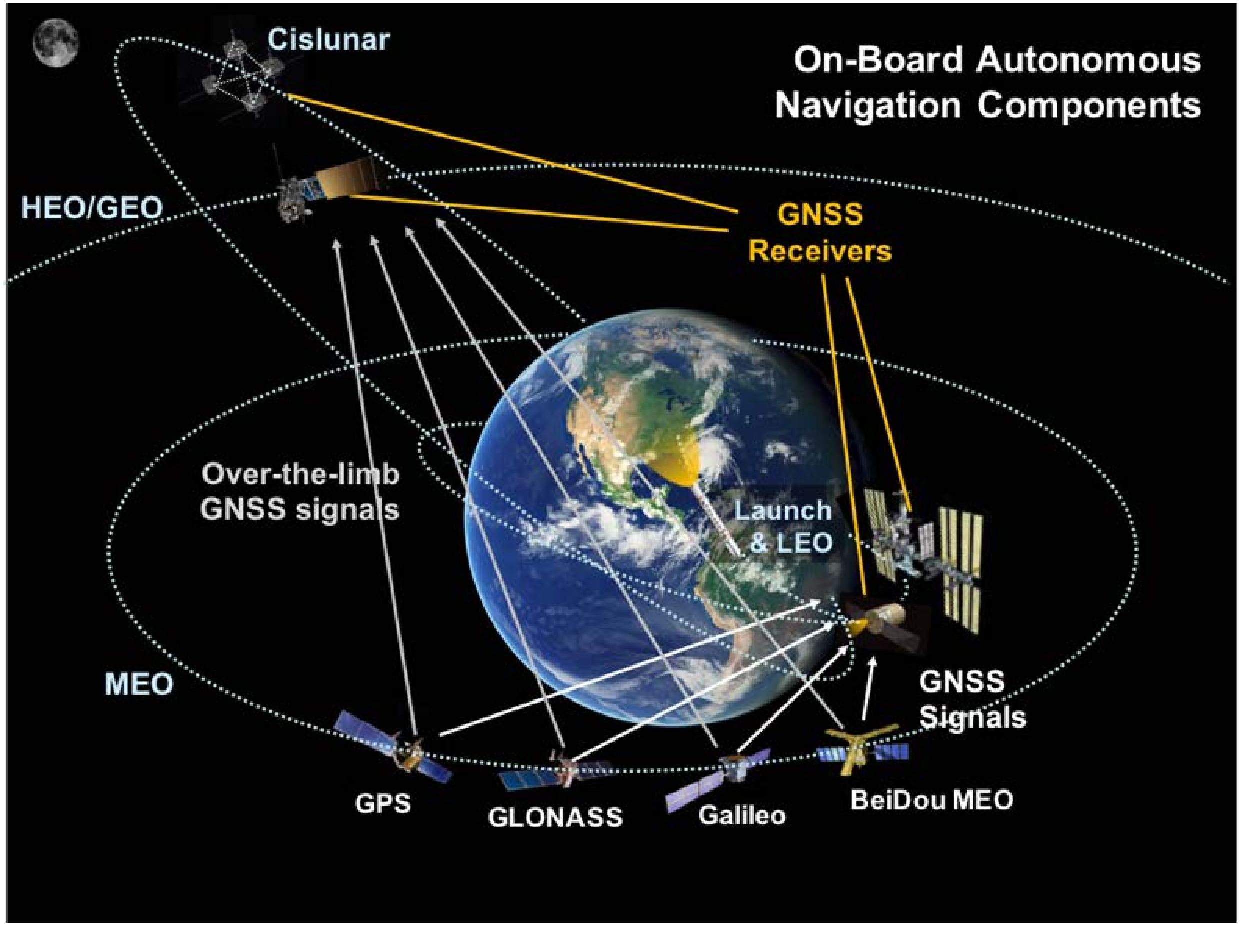
ICG Collaboration on GNSS Beyond the SSV, including the Deep Space Gateway

Multi-GNSS Space User Initiatives in the USA

Space Uses of Global Navigation Satellite Systems (GNSS)

- **<u>Real-time On-Board Navigation</u>**: Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **<u>Earth Sciences</u>**: Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements
- **<u>Launch Vehicle Range Ops</u>**: Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use
- **<u>Attitude Determination</u>**: Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements
- **<u>Time Synchronization</u>**: Support precise time-tagging of science observations and synchronization of on-board clocks



The capabilities of individual GNSS constellations to support space users will be further improved by pursuing multi-GNSS compatibility and interoperability

Use of GNSS for Navigation in Space is Now Routine

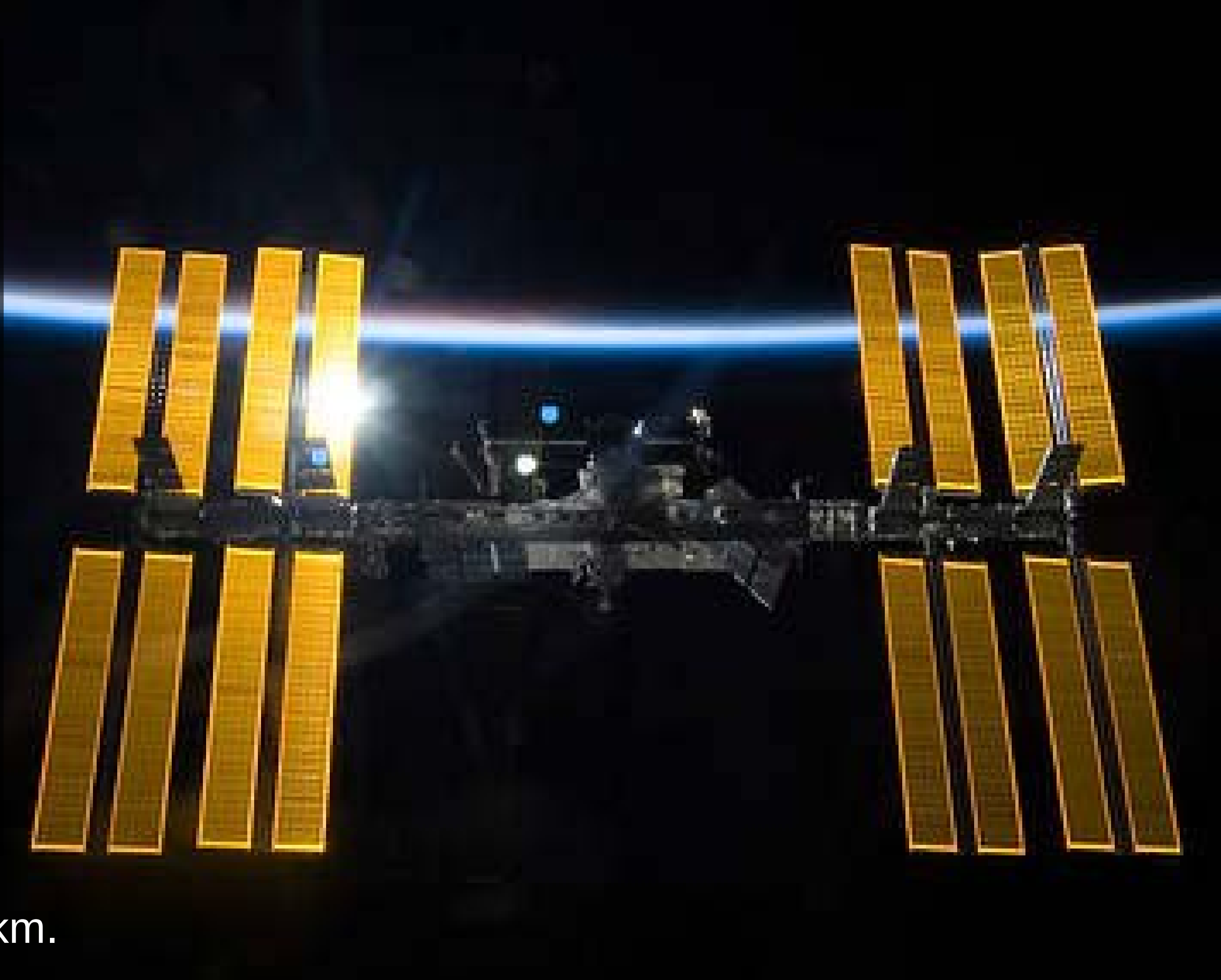
The latest data from the Interagency Operations Advisory Group shows **102** current or upcoming civil missions utilizing GNSS, representing **7** international space agencies.

This data does **not** include:

- Commercial users (e.g. communication satellites)
- Many other government space agencies
- Non-civil users
- Educational applications, etc.

Therefore, it is likely that **hundreds** of satellites have used GNSS in space since the initial experiments in the 1980s, and that number is only increasing.

Of these, a small fraction are considered **high-altitude users**, orbiting at altitudes above approximately 3,000 km.



Civil Space's New Frontier: Expanding GNSS use in and beyond the SSV—from 3,000 km to lunar orbit

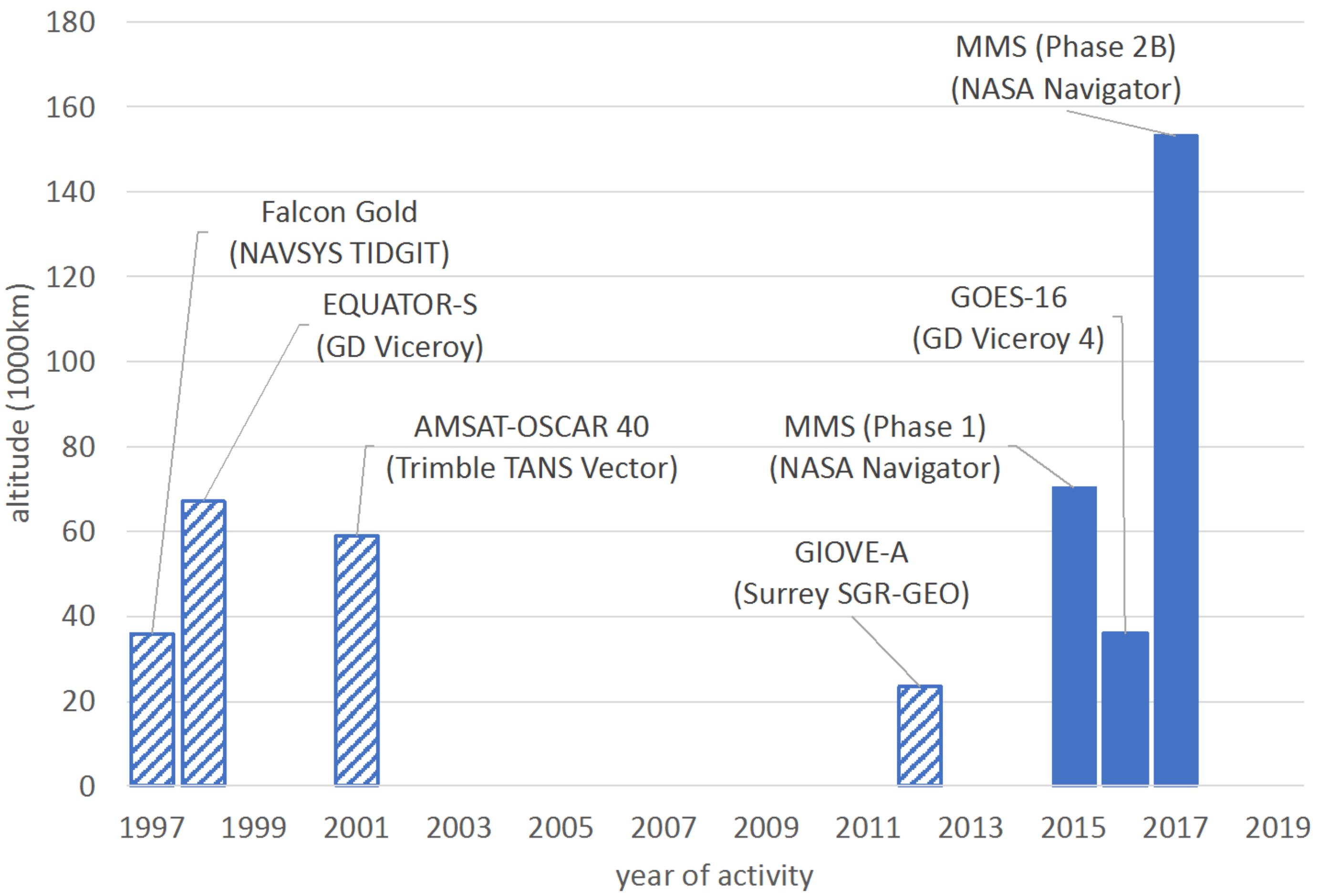
Image: International Space Station (NASA)

A History of High-Altitude GNSS

Transition from experimentation to operational use:

- 1990s: Early flight experiments demonstrated basic feasibility – **Equator-S**, **Falcon Gold**
- 2000: Reliable GPS orbit determination demonstrated at GEO employing a bent pipe architecture and ground-based receiver (Kronman 2000)
- 2001: **AMSAT OSCAR-40** mapped GPS main and sidelobe signals (Davis et al. 2001)
- 2015: **MMS** employed GPS operationally at 76,000 km and recently 150,000 km
- 2016–2017: **GOES-16/17** employed GPS operationally at GEO

	Altitude [km]	Altitude [R_E]
GPS	20,200	3
GEO	36,000	5.6
MMS 1	76,000	12
MMS 2	153,000	24
Moon	378,000	60



U.S. Initiatives & Contributions to Develop & Grow an Interoperable High Altitude GNSS Capability for Space Users

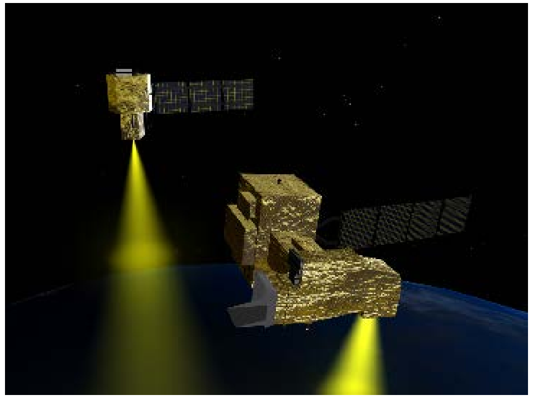
SSV Policy, Specifications & Data

- SSV definition (GPS IIF)
- SSV specification (GPS III)
- ICG Multi-GNSS SSV Initiative
- Measure & publish antenna gain patterns

Operational Guarantees Through Definition & Specification

Space Flight Experiments

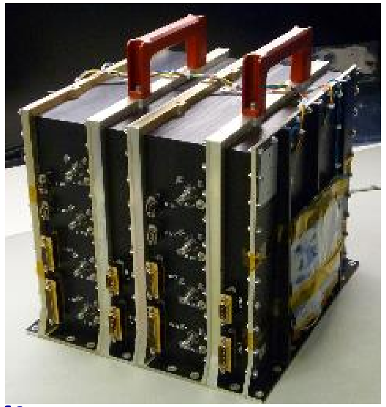
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)



Breakthroughs in Understanding; Supports Policy Changes; Enables Operational Missions

SSV Receivers, Software & Algorithms

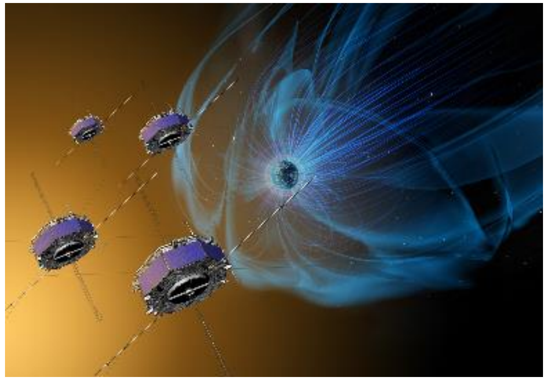
- GEONS (SW)
- GSFC Navigator
- General Dynamics
- Navigator commercial variants (Moog, Honeywell)



Develop & Nurture Robust GNSS Pipeline

Operational Users

- MMS
- GOES-R, S, T, U
- EM-1 (Lunar enroute)
- Satellite Servicing



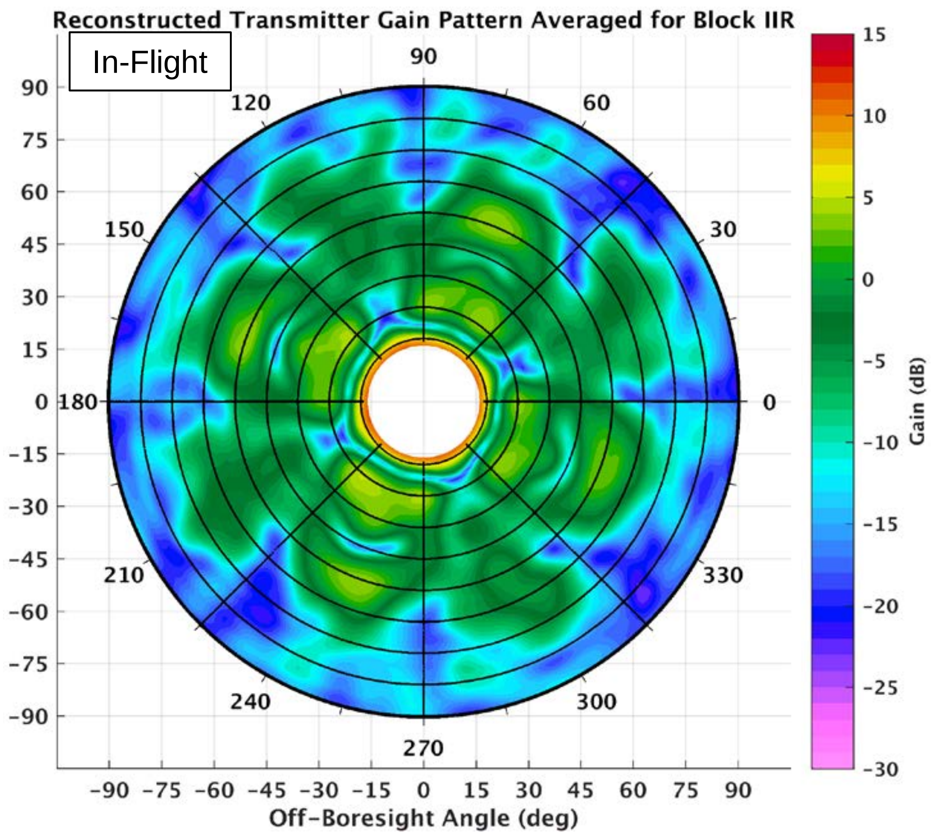
Operational Use Demonstrates Future Need

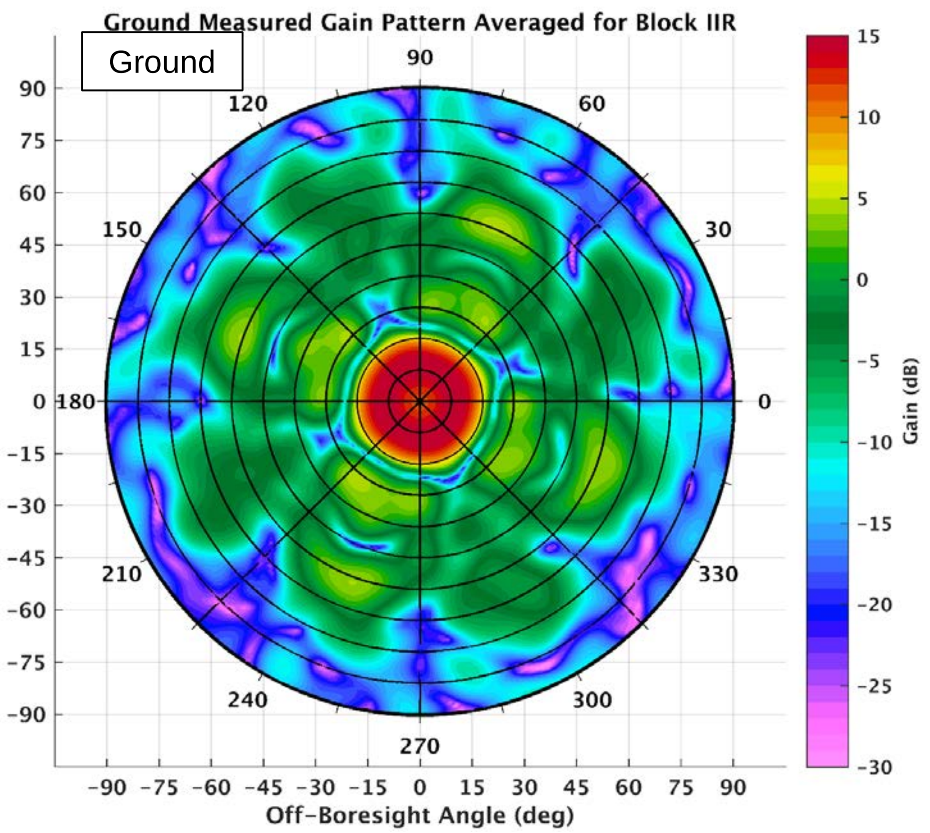
From 1990's to Today, U.S. Provides Leadership & Guidance Enabling Breakthrough, Game-changing Missions through use of High Altitude GNSS

GPS Antenna Characterization Experiment (ACE)* Results
Average Transmit Gain – Block IIR

*J. Donaldson, J. Parker, M. Moreau, P. Martzen, D. Highsmith

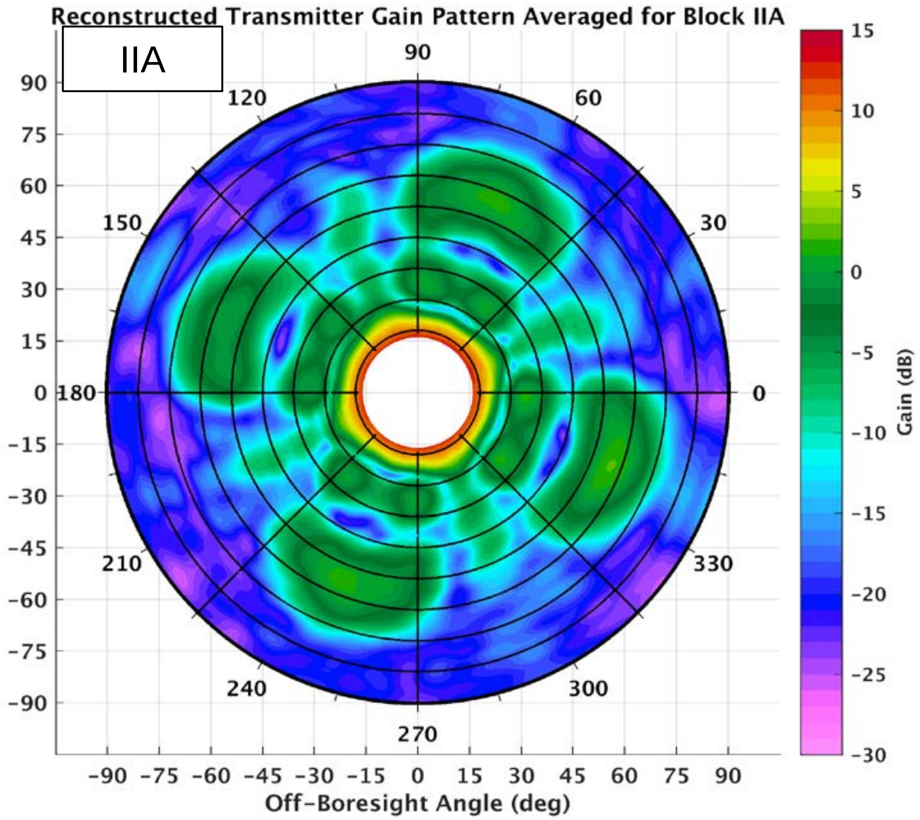
- In-flight averaged over all SVNs in block in 1 deg x 1 deg bins
- Remarkable similarity between average flight and ground measurements
  - Note matching patterns in nulls around outer edge

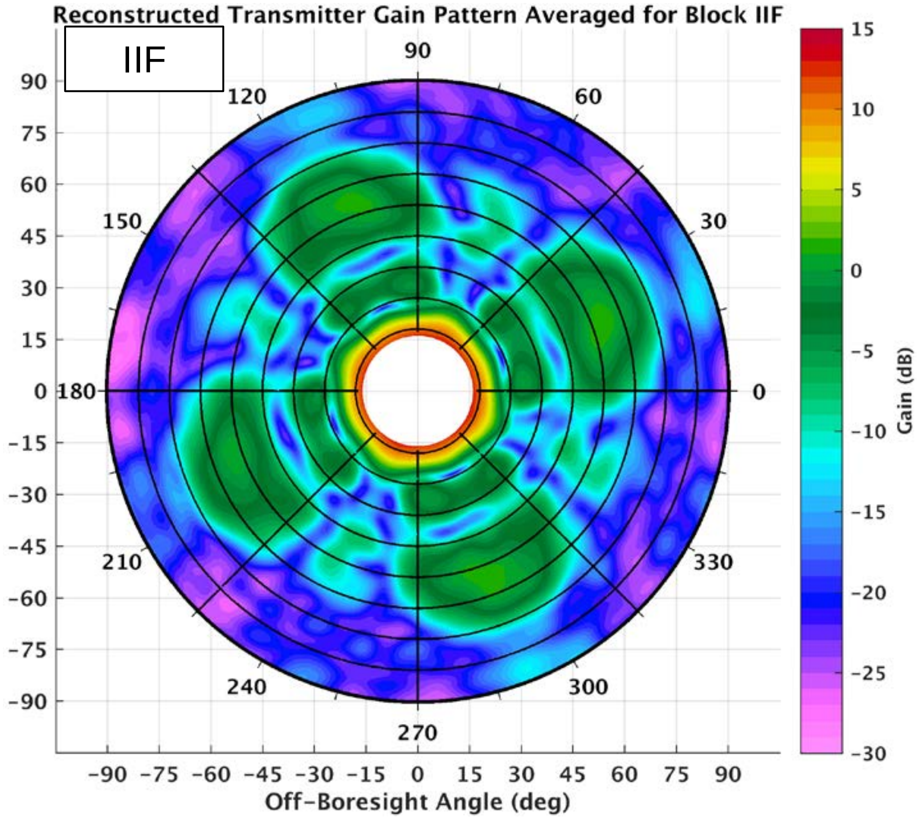




GPS Antenna Characterization Experiment (ACE)* Results Average Transmit Gain – Block IIA/IIF

- 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



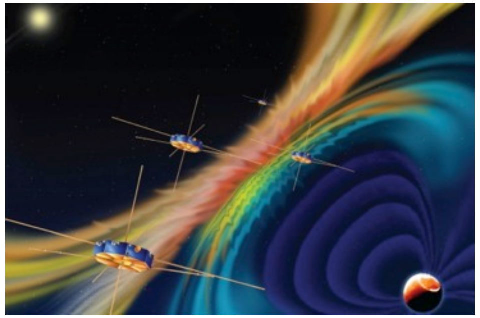


The Promise of using GNSS for Real-Time Navigation within the SSV

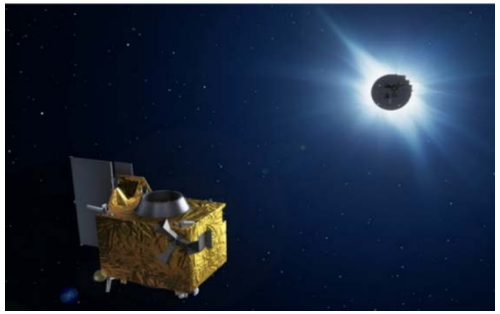
Benefits of GNSS use within the SSV:

- 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

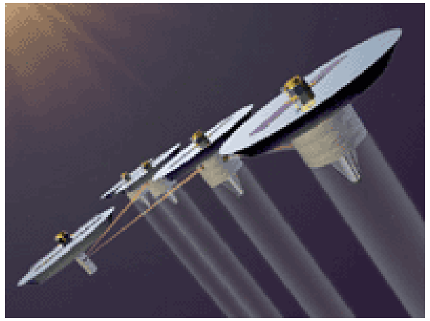


Space Weather Observations



Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



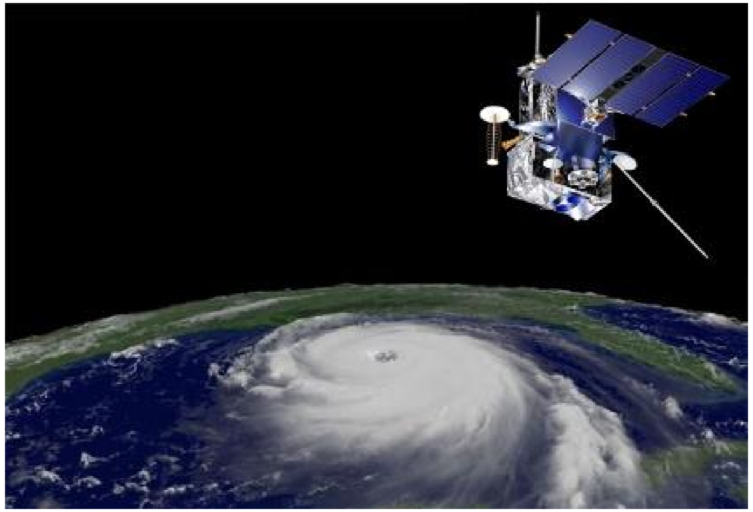
Formation Flying, Space Situational Awareness, Proximity Ops

Precise GEO Co-location

Operational U.S. Missions using GNSS in the High Altitude New Frontier

GOES-R Weather Satellite Series:

- Next-generation U.S. operational GEO weather satellite series
- Series is first to use GPS for primary navigation
- GPS provides quicker maneuver recovery, enabling continual science operations with <2 hour outage per year
- Introduction of GPS and new imaging instrument are **game-changers to humanity, delivering data products to substantially improve public and property safety**



GOES GPS Visibility*:

- Minimum SVs visible: 7
- DOP: 5–15

GOES Nav. Performance* (3σ):

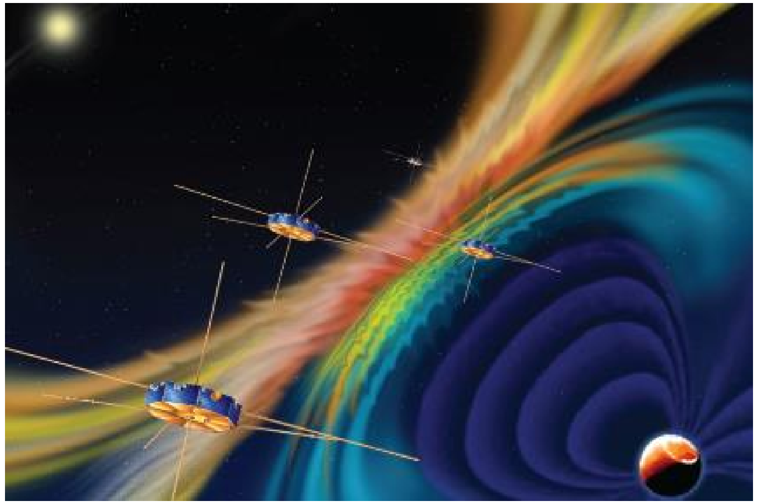
- Radial: 14.1 m
- In-track: 7.4 m
- Cross-track: 5.1 m

- Compare to requirement: (100, 75, 75) m

*Winkler, S., et.al. "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, Salzburg, Austria.

Magnetospheric Multi-Scale (MMS):

- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- Highest-ever use of GPS; Phase I: 12 Earth Radii (RE) apogee (76,000 km); Phase 2B: 25 RE apogee (~150,000 km) ***(40% of way to the moon)***
- Additional apogee raising to 29.34 RE (50% of way to moon) completed in February 2019
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping



MMS Nav. Performance (1σ)

Description	Phase 1	Phase 2B
Semi-major axis est. under 3 R_E (99%)	2 m	5 m
Orbit position estimation (99%)	12 m	55 m

Lunar Trajectory Multi-GNSS Results: ICG Booklet

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."*

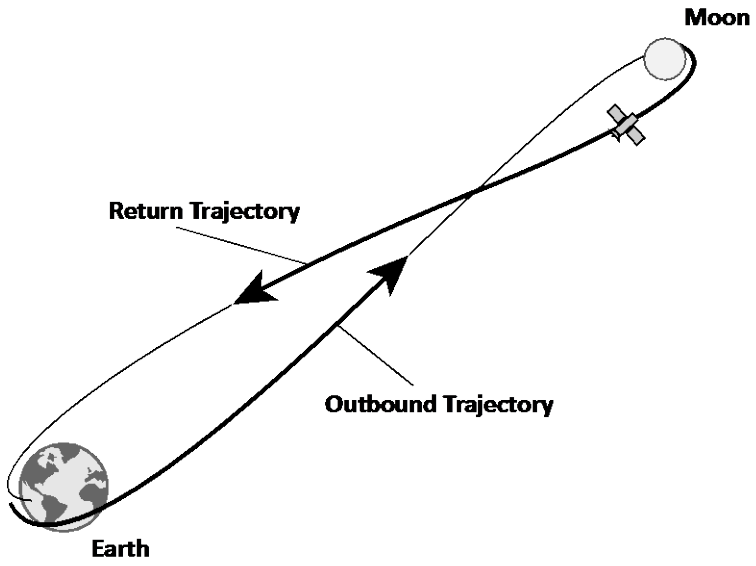
This is being accomplished via several initiatives:

Initiative	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—**Lunar Mission Results Presented Here**	Completed 2017
• **Multi-GNSS SSV Booklet**: Development of a formal UN publication defining the Multi-GNSS SSV, its characteristics, benefits, and applications.	Completed 2018
• **Beyond SSV studies**: Lunar vicinity GNSS performance and augmentation architecture studies—**USA Initiatives Presented Here**	Ongoing
• **SSV Capabilities Outreach**: Coordinating a joint international outreach activity to raise awareness of the final policy.	Ongoing

ICG Performance Analysis of GNSS Signal Availability for Lunar Missions

Goal: Assess technical benefit of combined multi-GNSS SSV, in terms of signal availability performance.

Analysis was performed jointly over multiple years and confirmed by all GNSS providers. Full methods and results are documented in SSV Booklet.



Inputs:

- GNSS constellation configurations (constellation size, orbital configuration)
- Constellation-specific SSV parameters

Performance was estimated:

- Globally
- **With example mission-specific trajectories**

Mission-specific analysis:

- Three mission types:
  - Geostationary
  - Highly-elliptical
  - **Lunar (Apollo-8-type trajectory shown here)**

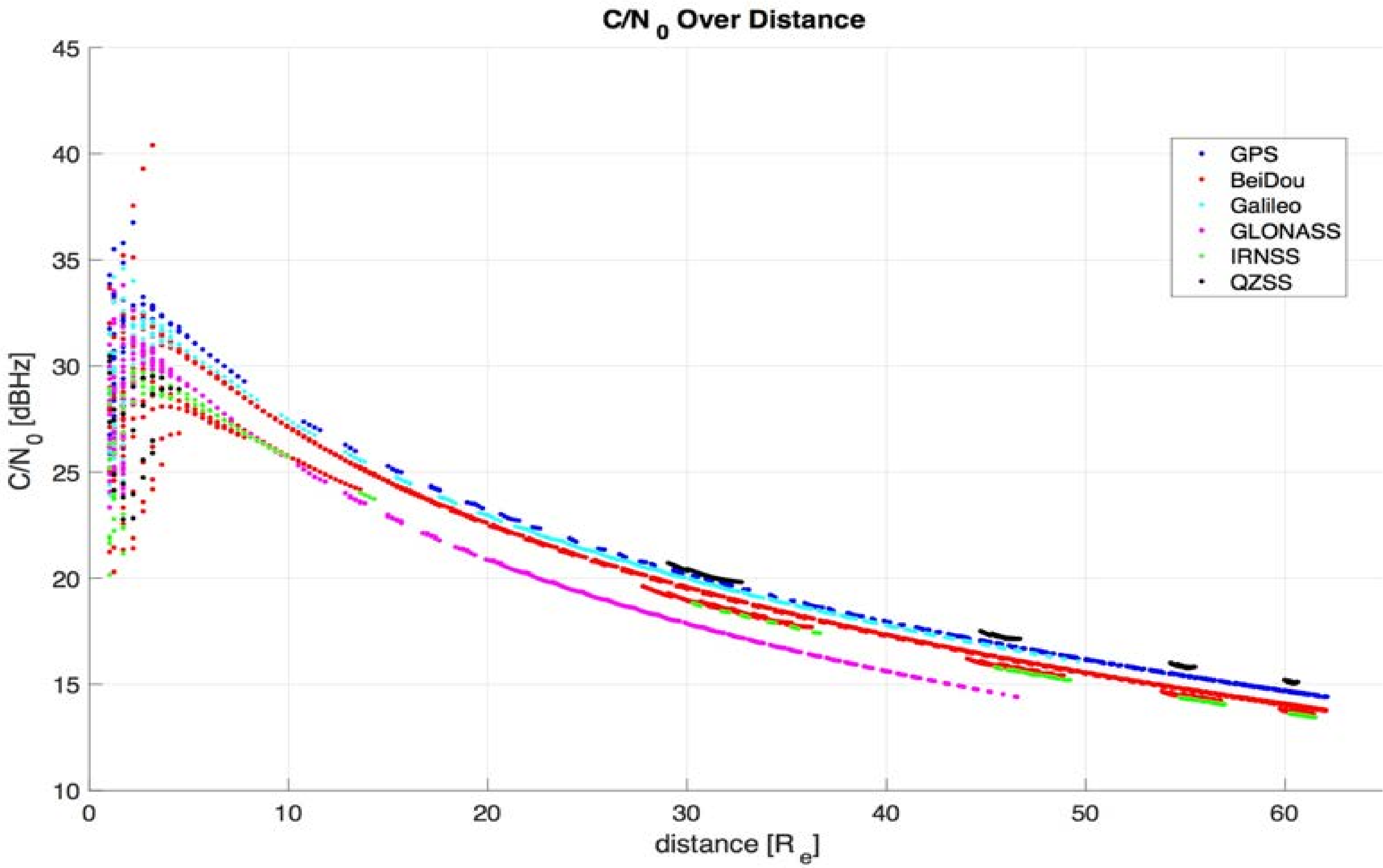
Antennas: zenith-pointing (4.5 dBi peak gain)
nadir-pointing (9 dBi peak gain)

- Single C/N0 threshold value of 20 dB-Hz

ICG Booklet: Simulated C/N_0 for Entire Lunar Trajectory

Results

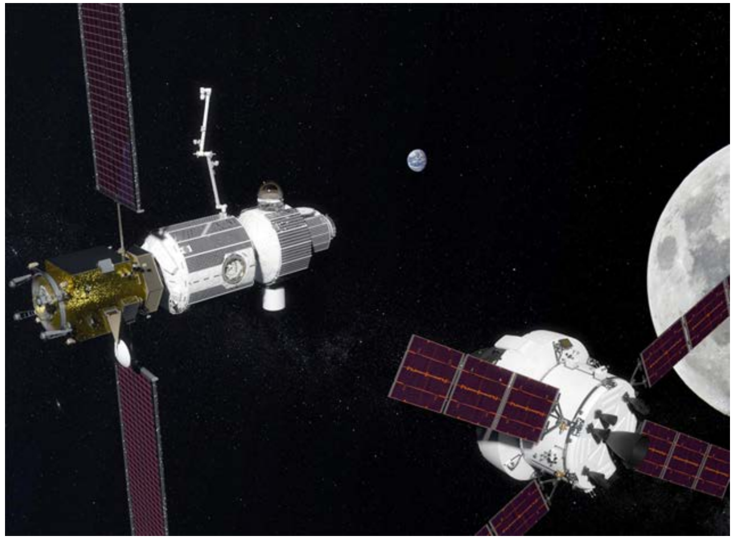
- Booklet simulations show that for assumed receiver threshold (20 dB-Hz) and antenna gain (9.5 dB), GNSS signals drop off at half lunar distance (30 Re)
- Moderately more sensitive receivers or higher gained antennae will enable GNSS reception at lunar distances (60 Re)
- Increasing antenna gain from 9.5 dB to 14 dB with current technology SSV receivers will support GNSS navigation & time sensing in the lunar vicinity



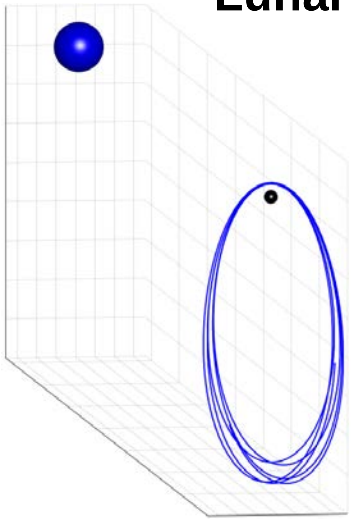
Lunar Trajectory Multi-GNSS Results: USA Follow-on Efforts

Potential Future GNSS 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
- Gateway represents a potential application for on-board GNSS navigation
- NASA performing Gateway GNSS architecture studies and is providing updates to ICG team as they evolve
- The orbit studied for the Gateway: L2 Southern Near Rectilinear Halo Orbit (NRHO) with average periapsis altitude ~1800 km, apoapsis altitude of 68,000 km, 6.5 day period, in 9:2 resonance with the Moon's orbit



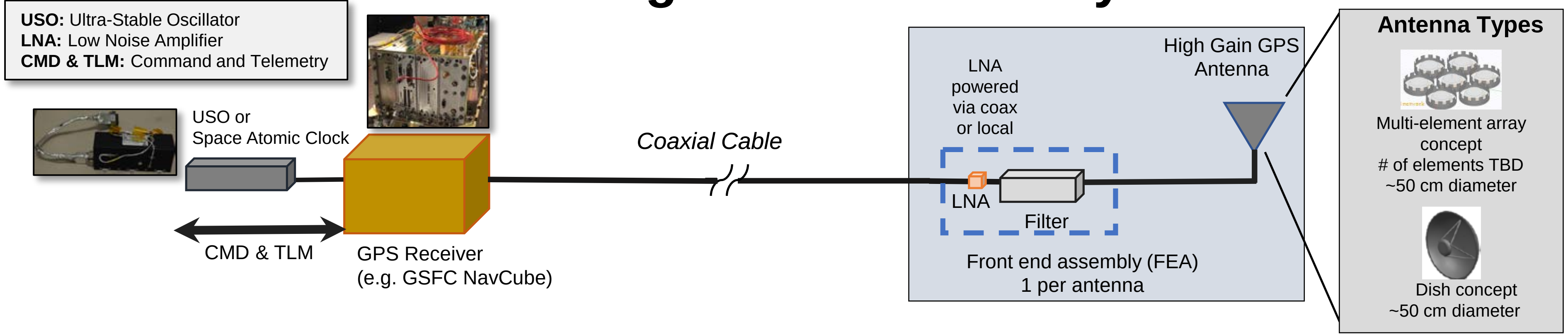
Lunar Gateway



Gateway Near Rectilinear Halo Orbit (NRHO)

GPS Based Autonomous Navigation Study for the Lunar Gateway*

NASA study predicts that an MMS-like GPS navigation system, with an Earth pointed high-gain antenna (~14dBi) would provide strong onboard navigation for Gateway



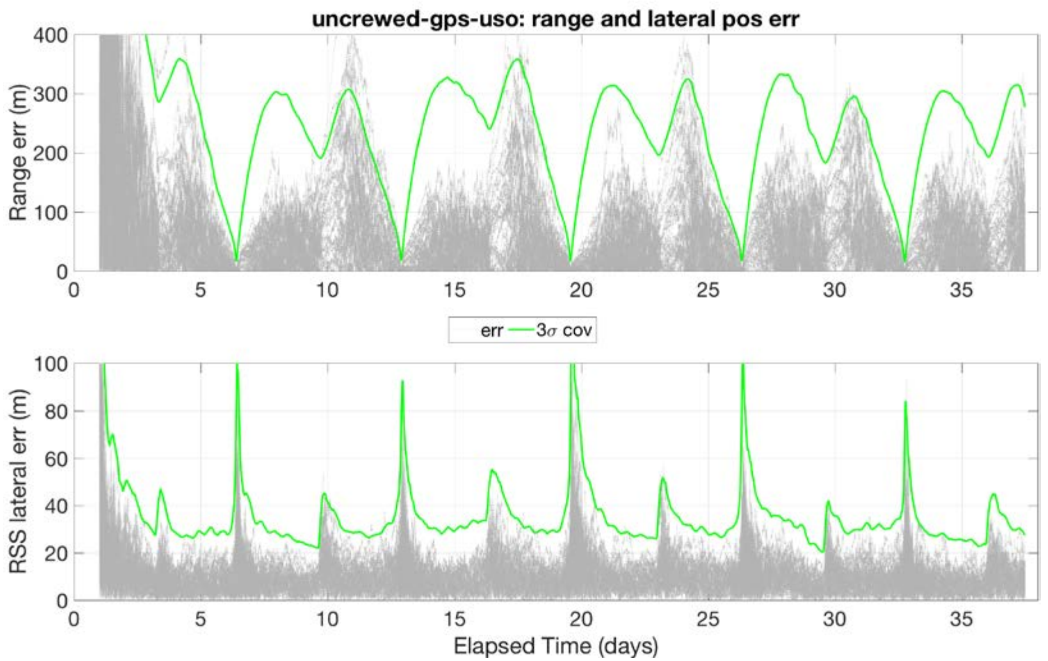
- **Main electronics**
  - GSFC NavCube – Next Gen MMS Navigator GPS:
    - Reprogrammable Software Defined Receiver (SDR)
      - Upgradable to multi-GNSS, etc.
    - Updated MMS GPS baseband processor logic
    - GEONS navigation filter software tuned for NRHO
- **External oscillator**
  - MMS USO or
  - Space-rated atomic clock (Could significantly enhance performance)

- **Antenna and Front End Assembly (FEA)**
  - 1 FEA with cables per antenna
  - 1 High gain GPS Antenna ~14dBi
    - *a small dish or multi-element array*
    - *Earth pointed, gimbal*

*Winternitz et. al, AAS GNC Conference Breckenridge, CO Feb 2019

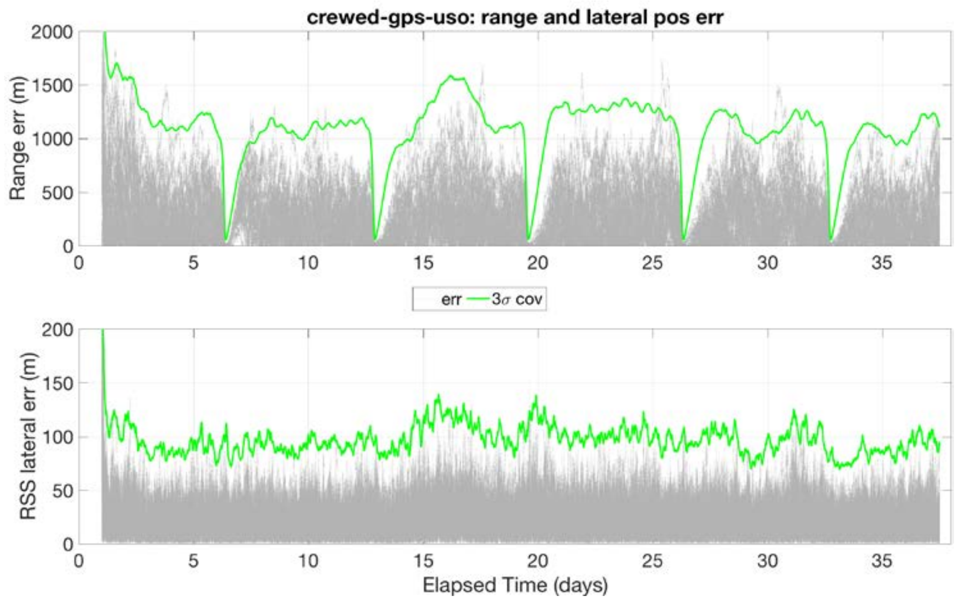
Lunar Gateway Position Performance: with no Crew and with Crew On-Board

No Crew



No Crew Scenario GPS Mean of 3-rms value over last orbit				
	Position (m)		Velocity (mm/sec)	
	Range	RSS Lateral	Range	RSS Lateral
USO	202.9	31.3	1.9	1.4
Atomic Clock	8.5	30.5	0.2	1.2

With Crew

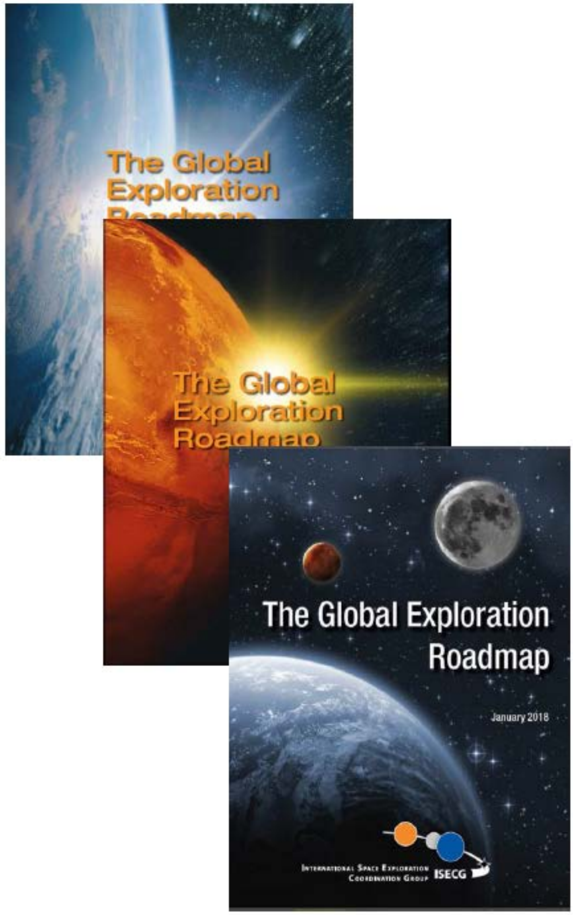


Gateway Crew Scenario GPS Mean of 3-rms value over last orbit				
	Position (m)		Velocity (mm/sec)	
	Range	RSS Lateral	Range	RSS Lateral
USO	909.7	79	18.9	12.3
Atomic Clock	21.4	76.9	3.5	11.9

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

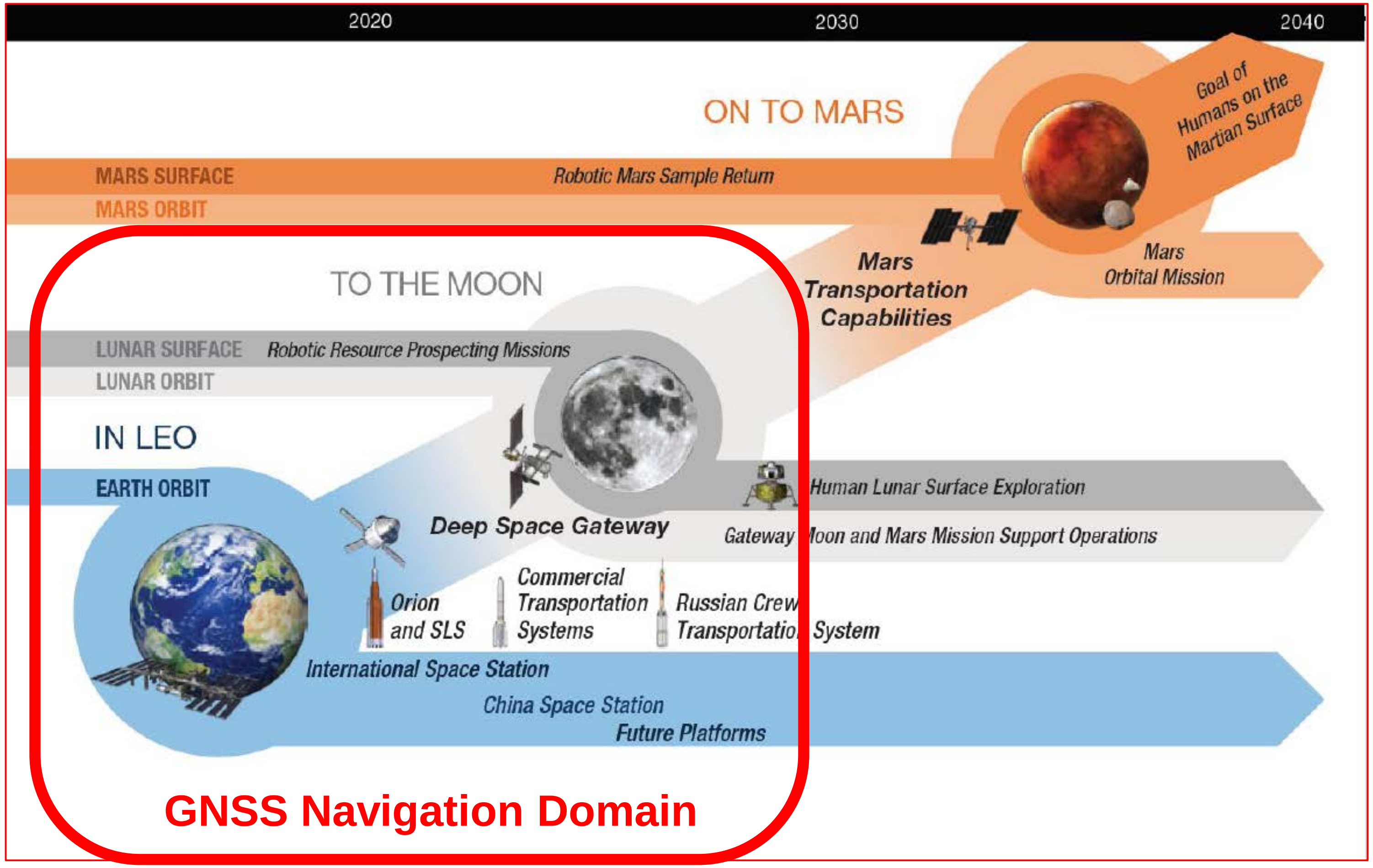


www.globalspaceexploration.org
www.nasa.gov/isecg

Renewed Interest in Lunar Exploration

- There is significant global interest in sustained lunar exploration; dozens of missions in planning
- US human lunar exploration will start with EM-1 and EM-2 in the early 2020s
- NASA and international partners plan to establish a Gateway, a permanent way-station in the vicinity of the moon
- GNSS on lunar missions would:
  - enable *autonomous* navigation
  - reduce tracking and operations costs
  - provide a backup/redundant navigation for human safety
  - provide timing source for hosted payloads
  - reduce risk for commercial development

Global Exploration Roadmap



Lunar Missions Represent a Ripe New Frontier for High Altitude GNSS

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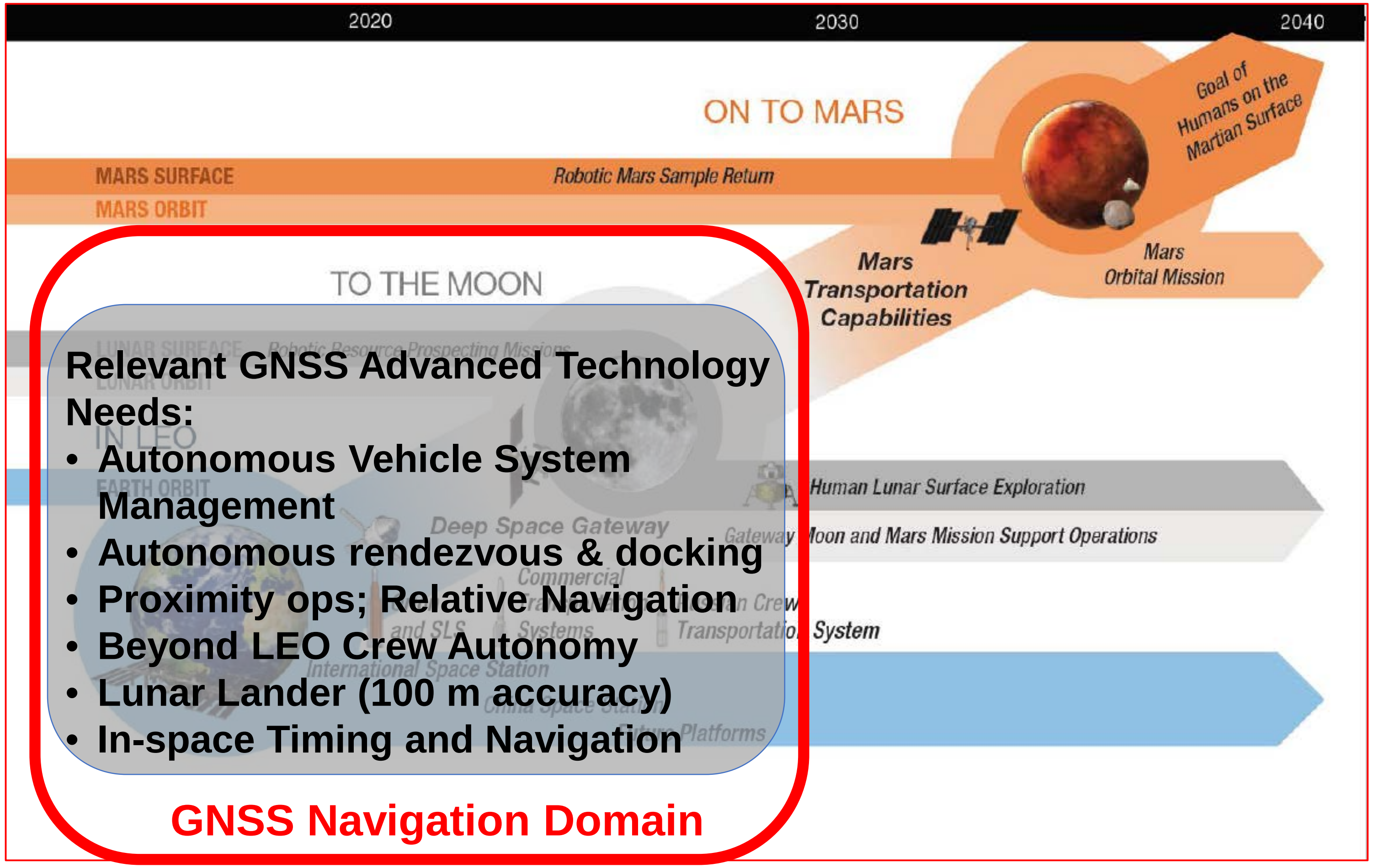
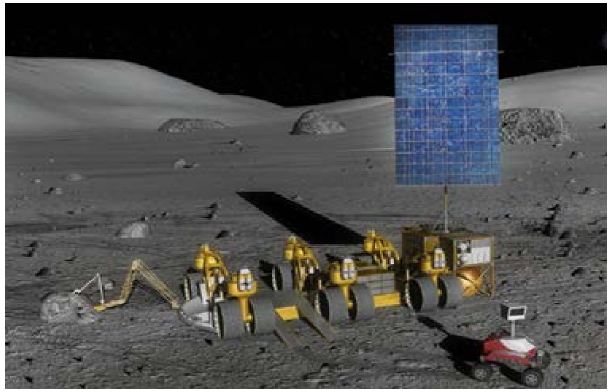
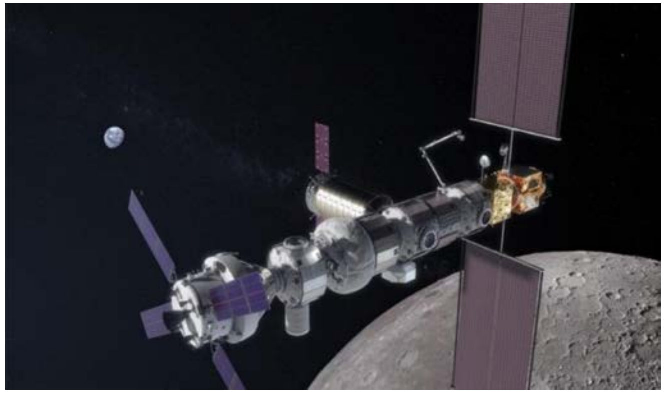


Lunar Missions Represent a Ripe New Frontier for High Altitude GNSS

Lunar Exploration Mission Types
Enabled via GNSS Navigation & Timing



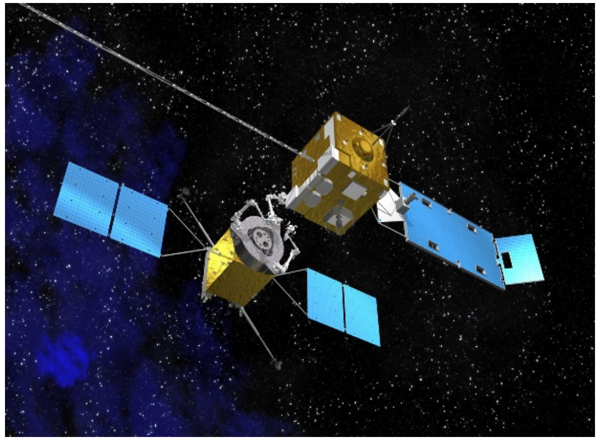
Lunar Surface Operations
Robotic Prospecting & Human Exploration



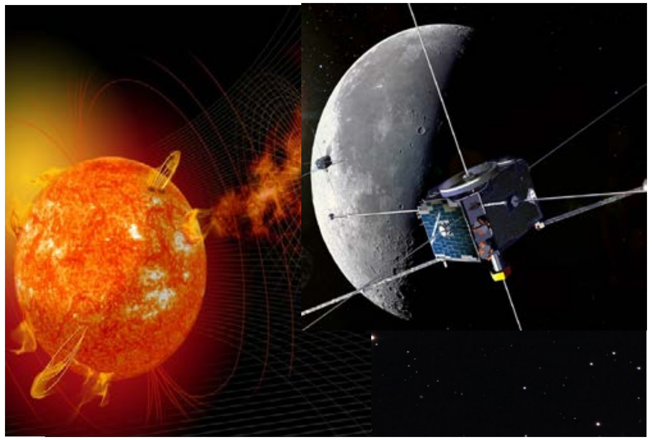
Human-tended Lunar Vicinity
Lunar Orbiting Platform-Gateway

Robotic Lunar Orbiters
Resource & Science Sentinels

Earth & Astrophysics Observations

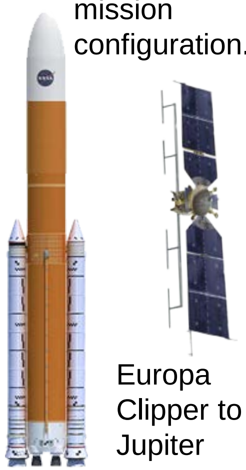
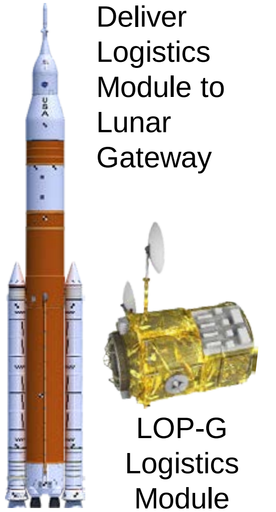
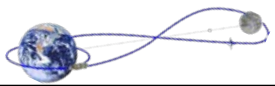
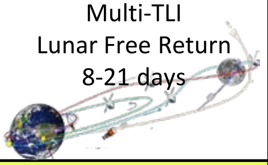


Satellite Servicing



Solar & Space Weather Observations

GNSS Use Aboard Space Launch System

EM-1 Exploration Mission 1	EM-2 Exploration Mission 2	SM-1 Science Mission 1	EM-3 Exploration Mission 3	EM-4 Exploration Mission 4	EM-5 Exploration Mission 5
2021	2022	2023	2024	2025	2026
Block 1: ICPS	Block 1: ICPS	Block 1B Cargo	Block 1B: EUS	Block 1B: EUS	Block 1B: EUS
Cargo	4 Crew	Europa Clipper	4 Crew	4 Crew	4 Crew
Cis-Lunar Space Mission to confirm vehicle performance and operational capability.  13 CubeSat Payloads	First crewed mission, to confirm vehicle performance and operational capability, same profile as EM-1.  Orion Capsule + Crew	First cargo mission configuration.  Europa Clipper to Jupiter	First Orion Docking to extract Habitat Module from EUS, deliver to Lunar Orbit Platform - Gateway  LOP-G Habitat Module	Deliver Logistics Module to Lunar Gateway  LOP-G Logistics Module	Deliver Airlock Element to Lunar Gateway  LOP-G Airlock Element
Cis-Lunar Trajectory 11-21 days 	Multi-TLI Lunar Free Return 8-21 days 	Jupiter Direct 2.5 years 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 	Near-Rectilinear Halo Orbit (NRHO) 26-42 days 	Near-Rectilinear Halo Orbit (NRHO) 26-42 days 
Honeywell SIGI with SPS Trimble Force 524D (L1 C/A Code Only) for Orbit Determination, Trans-Lunar Injection Burn and End-of-Mission disposal burn.	SIGI w/SPS Force 524D	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.

SLS Mission Data is based upon SLS-DDD-284, *Space Launch System Mission Configuration Definition*, Draft Version, October 2018.

Conclusions

- **High-altitude space use of GNSS**—within the SSV and **to lunar** distances**—**represents Civil Space's **Newest Frontier**
- Despite significant technical challenges, high-altitude GNSS offers numerous benefits to space users including:
  - Promising new mission types and operations concepts
  - Precise real-time navigation and time sensing
  - Enhanced on-board autonomous operations and reduced ground support
- The international GNSS community have overcome high-altitude GNSS technology & political hurdles through:
  - On-orbit flight experiments and operational mission result sharing to demonstrate that high-altitude GNSS is realizable
  - High-altitude GNSS receiver developments
  - UN ICG initiatives where **all GNSS constellation providers are working together to realize the Multi-GNSS SSV**
- Numerous planned geostationary and lunar exploration missions are poised to reap great benefits from this new technological capability
- NASA and the U.S. Government are **proud to wor**k 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

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 the SSV	36,000-360,000+	Even weaker signals & worse signal geometry	Use higher gain, small footprint antenna; accept geometric performance degradation or augment with signals of opportunity to improve	Operational to 150,000 km (MMS), Orion Lunar perf. experiment

Example: Global Performance Summary

Band	Constellation	At least 1 signal		4 or more signals	
		Avail. (%)[1]	MOD (min)[2]	Avail. (%)[1]	MOD (min)[2]
L1/E1/B1	Global systems	78.5–94	48–111	0.6–7	*
	QZSS	0	*	0	*
	Combined	**99.9**	**33**	**89.8**	**117**

[1]average across all grid locations
[2]at worst-case grid location
*no signal observed for the worst-case grid location for full simulation duration

Observations:

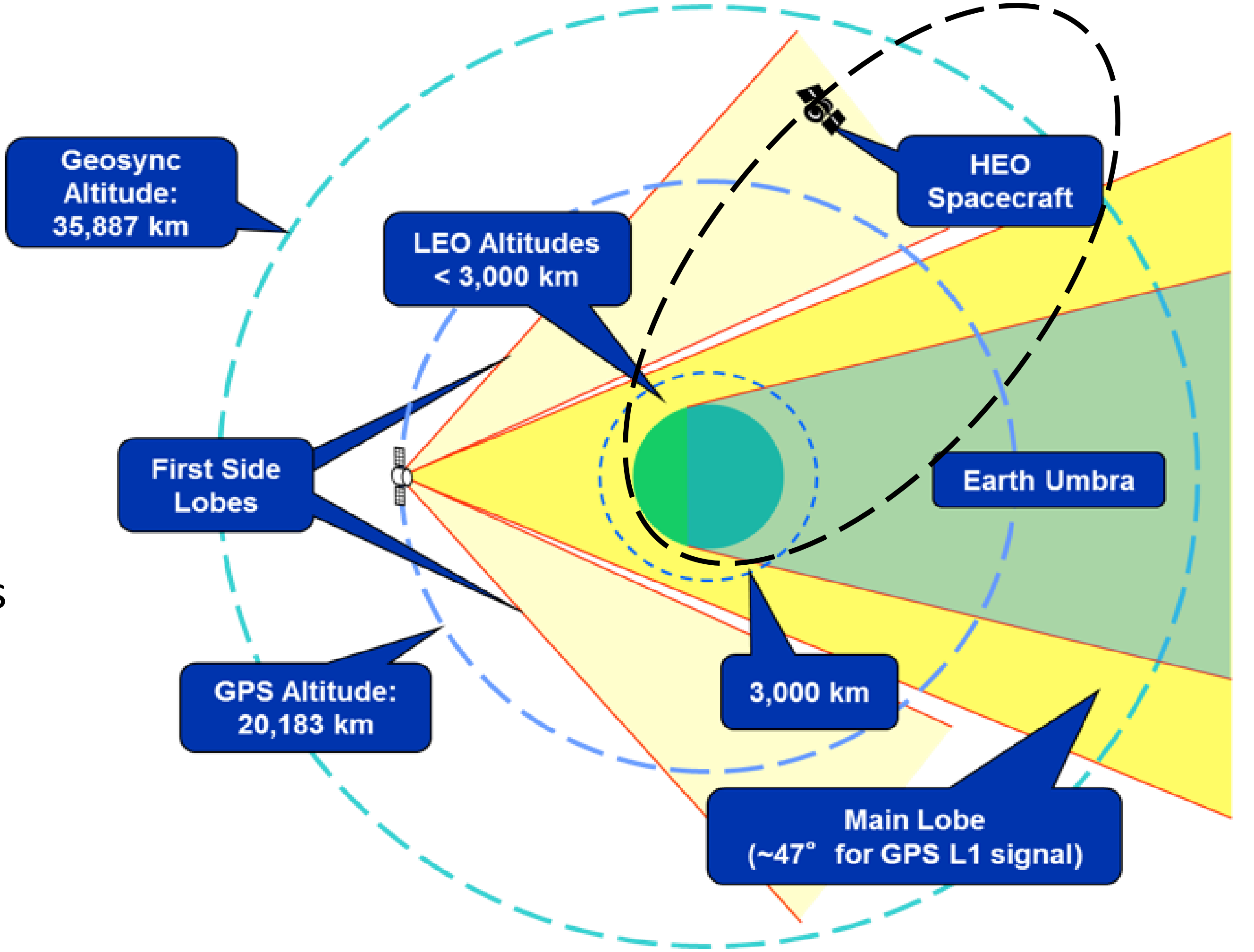
- Using all constellations provides nearly continuous single-signal coverage (99.9% on average) at GEO.
- Combined, average four-signal availability grows by an order of magnitude over the best-performing individual constellation.
- Performance estimates are conservative, based on constellation baseline main lobe performance estimates shown previously.

Summary data condenses individual constellation results for:

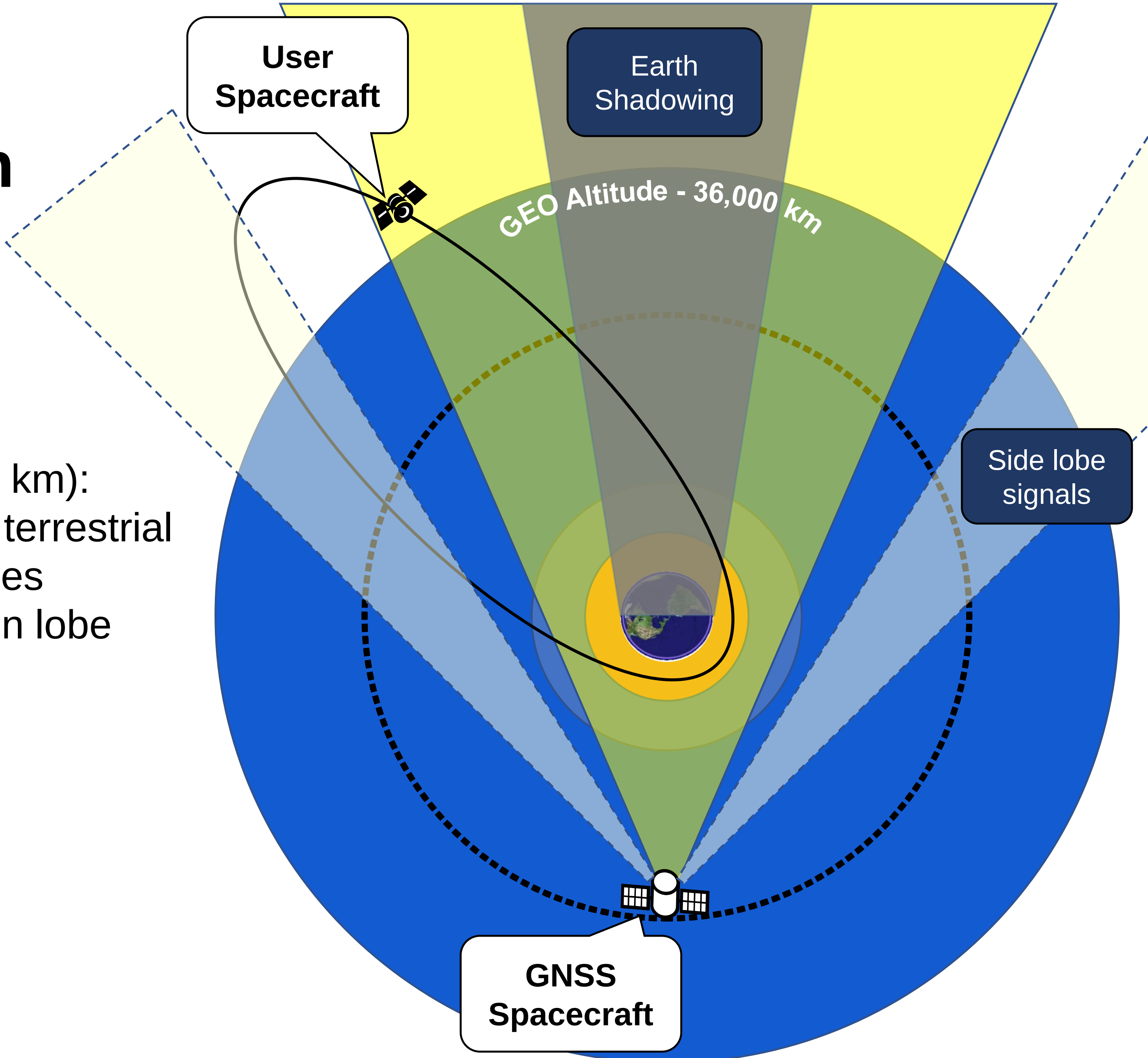
- L1 band
- Upper SSV
- 20 dB-Hz receiver threshold

GPS 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 GPS in the SSV increasing despite geometry, Earth occultation, and weak signal strength challenges
- Spacecraft use of GPS in TSV & SSV enables:
    - reduced post-maneuver recovery time
    - improved operations cadence
    - increased satellite autonomy
    - more precise real-time navigation and timing performance



High-altitude GNSS reception comes with many challenges



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

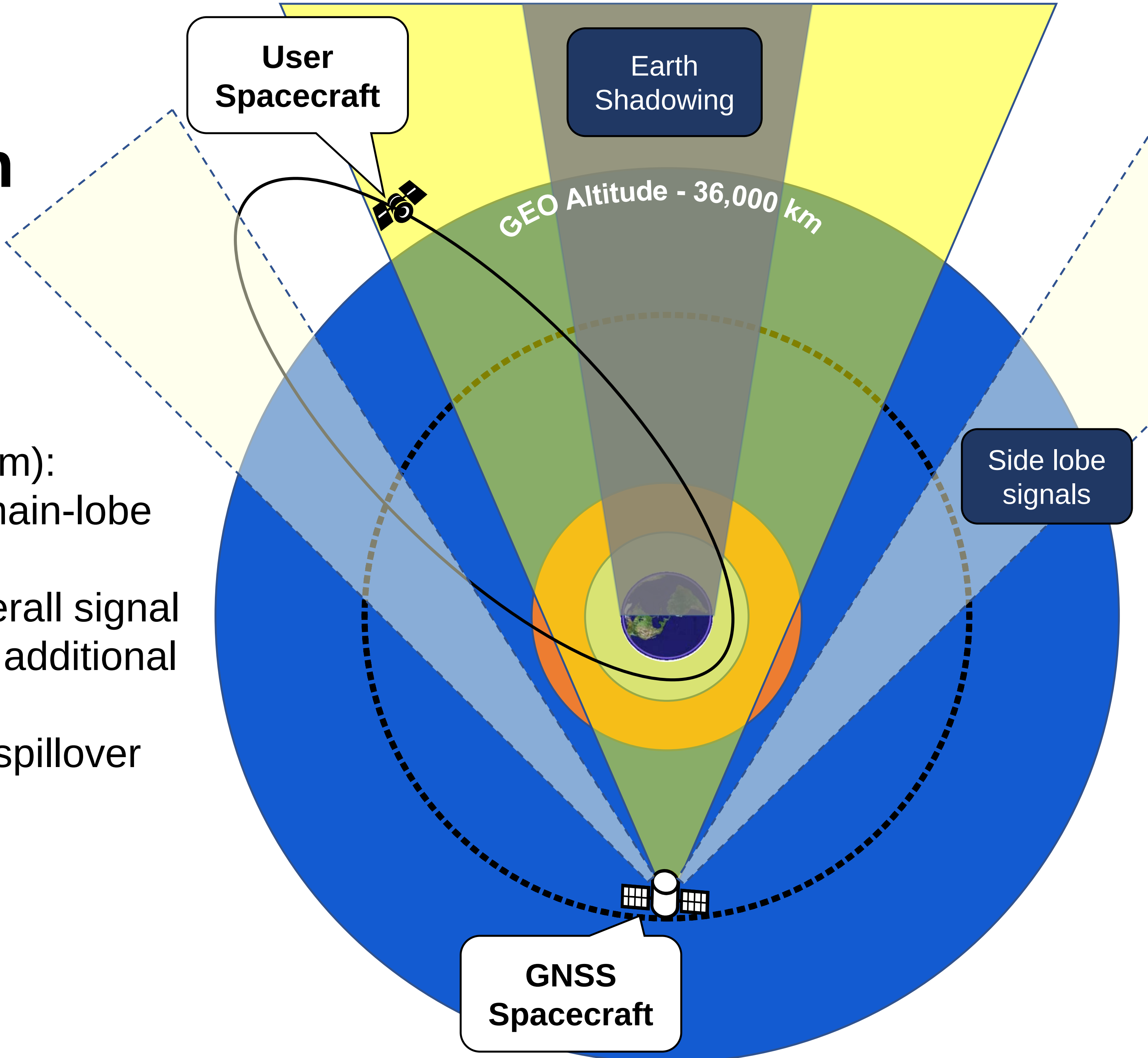
GNSS usage is **widespread**.

High-altitude GNSS reception comes with many challenges

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**.

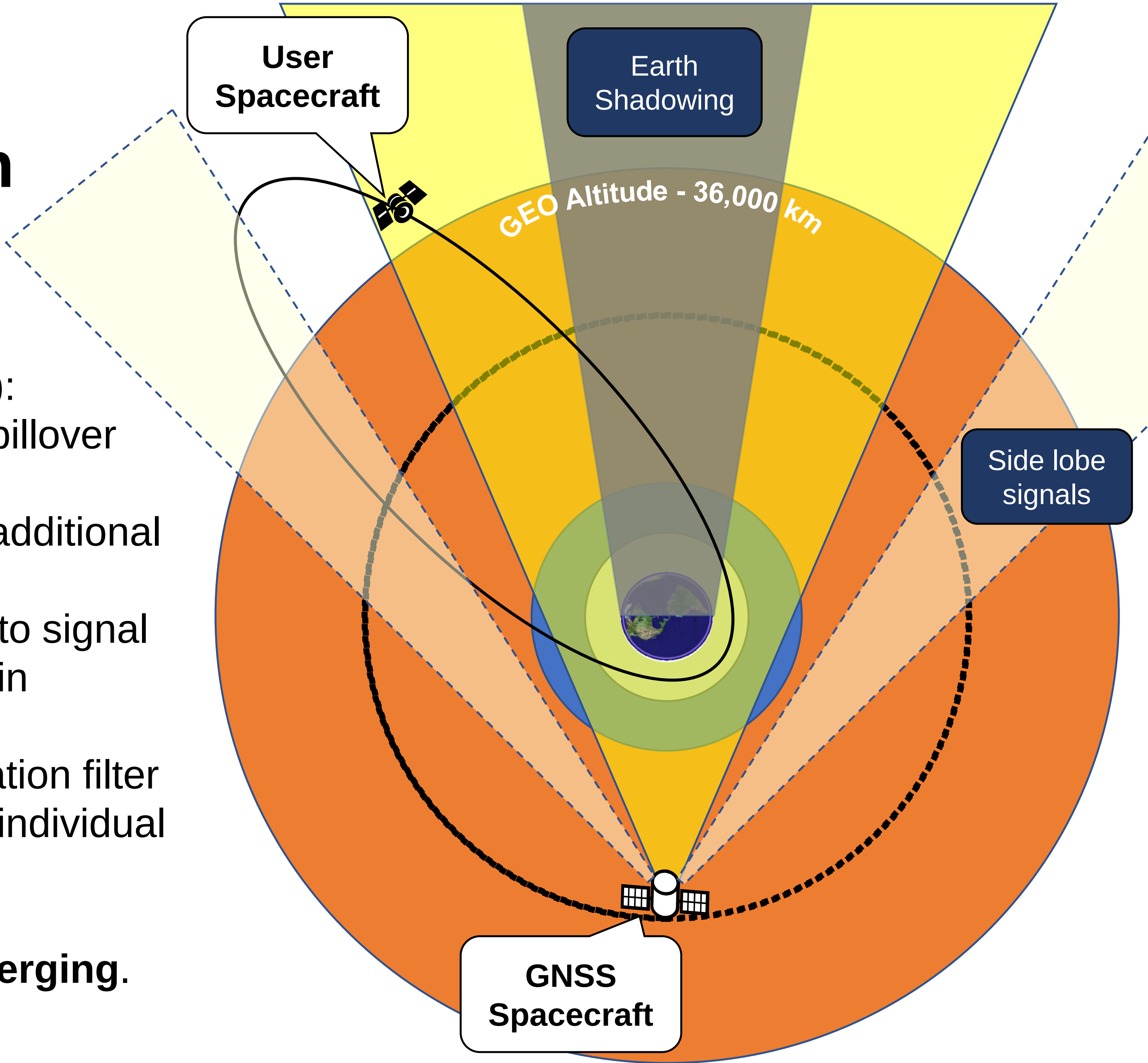


High-altitude GNSS reception comes with many challenges

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**.

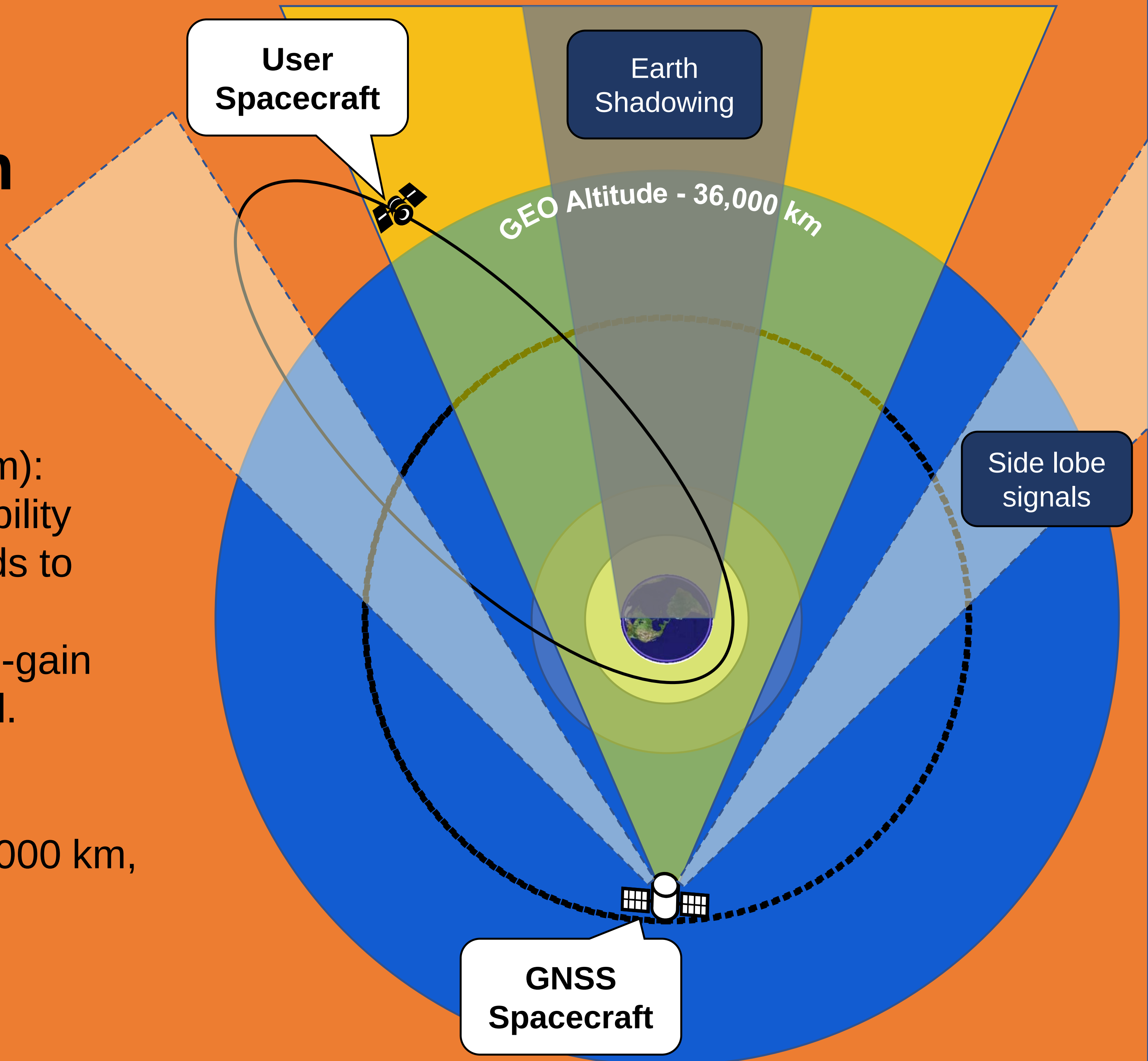


High-altitude GNSS reception comes with many challenges

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.



International Coordination of High Altitude GNSS via the UN ICG

The **United Nations International Committee on GNSS (ICG)** brings together all six GNSS providers and other voluntary participants to:

- *Promote the use of GNSS and its integration into infrastructures, particularly in developing countries*
- *Encourage compatibility and interoperability among global and regional systems*

International Committee on Global Navigation Satellite Systems

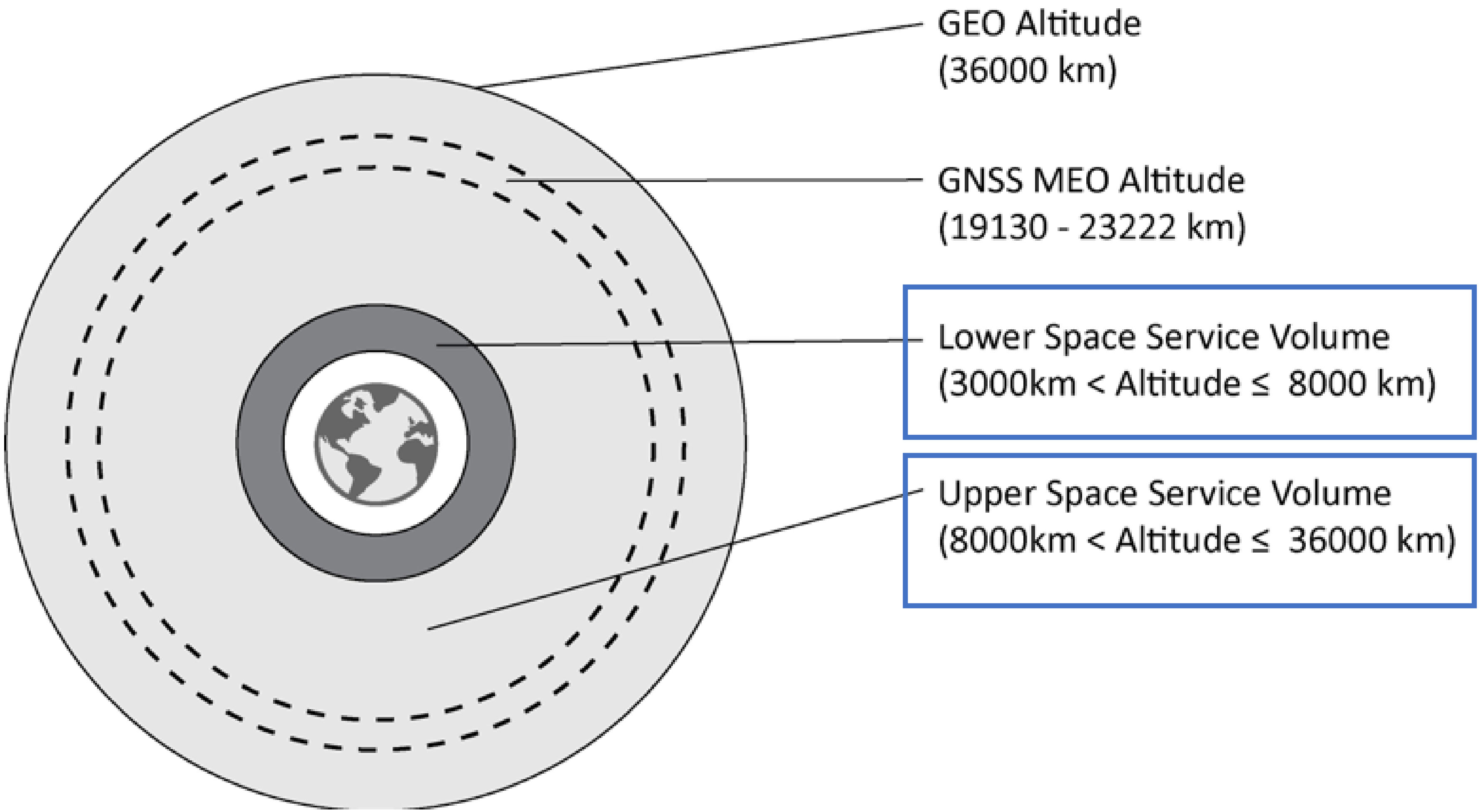
The ICG consists of four working groups. Of these two have primary roles related to high-altitude users:

WG-S: Systems, Signals and Services—Ensures underlying compatibility and interoperability of signals

WG-B: Enhancement of GNSS Performance, New Services and Capabilities—Leads development of the Multi-GNSS Space Service Volume concept and related activities

What is the Multi-GNSS Space Service Volume (SSV)?

The internationally-adopted definition of the Multi-GNSS Space Service Volume.



Two altitude regions:

- **Lower SSV**
- **Upper SSV**

Three performance metrics:

- **Pseudorange accuracy**
- **Received signal power**
- **Signal availability**

  Specified as:
  - Percent availability
  - Maximum outage duration

Every GNSS Constellation Provider has Published 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

Multi-GNSS activities in the ICG WG-B

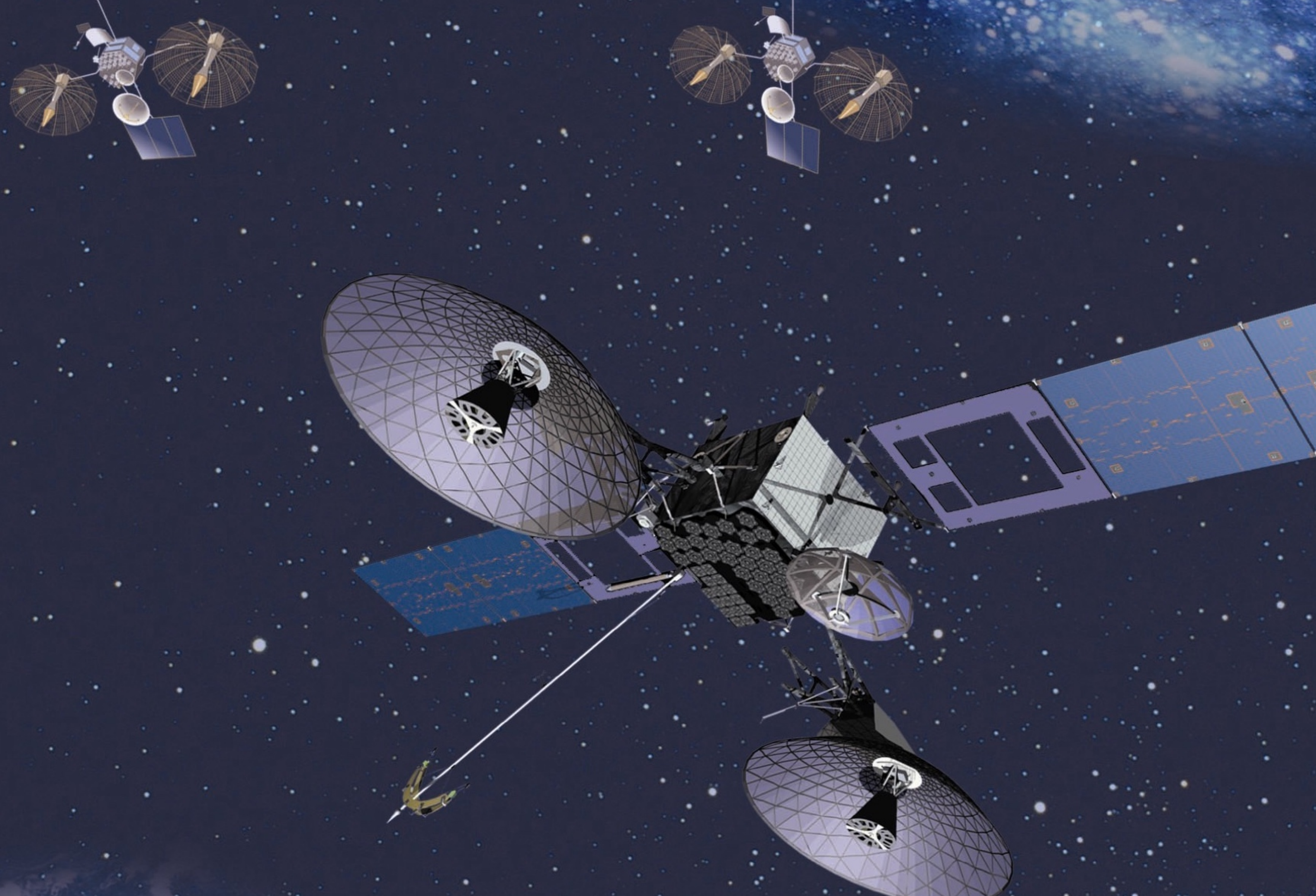
As amended in 2015, the ICG WG-B work plan directs it to:

> *“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:

Initiative	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. Add booklet URL	Completed 2018
Beyond SSV studies: Lunar vicinity GNSS performance and augmentation architecture studies	Ongoing
SSV Capabilities Outreach: Coordinating a joint international outreach activity to raise awareness of the final policy.	Ongoing

User Application: GEO Colocation



Needs:

- **GNSS signal availability, improved geometric diversity, and few outages, enabling reduced spacing between satellites, responsive maneuvering, and autonomous operations.**

Examples:

- **GEO communications satellites**

Image: TDRS-H, I, J illustration (NASA)

Development And Utilization of High Altitude GNSS Offers Numerous Benefits To Users

- **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.

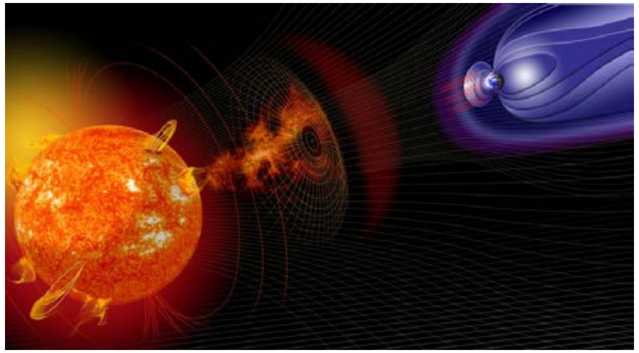
Image: Southeastern USA at night, from ISS (NASA)

The Promise of using GNSS for Real-Time Navigation at High Altitudes & Beyond the Space Service Volume

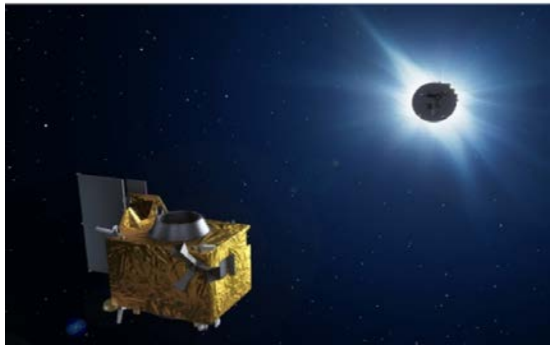
Benefits of High Altitude GNSS use:

- **Supports real-time navigation/timing 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 **mission scenarios,** including:

Earth Observations

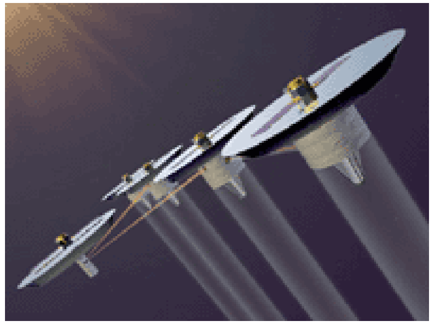


Space Weather Observations

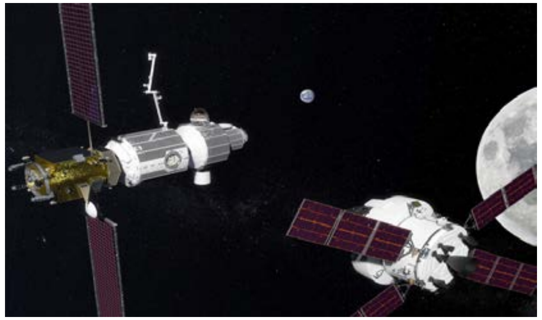


Precise Relative Positioning

Launch Vehicle Upper Stages & Cislunar applications



Formation Flying, Space Situational Awareness, Proximity Ops



Lunar Orbiting Platform-Gateway Human & Robotic Space Applications

User Application: Earth Weather Observations

Needs:

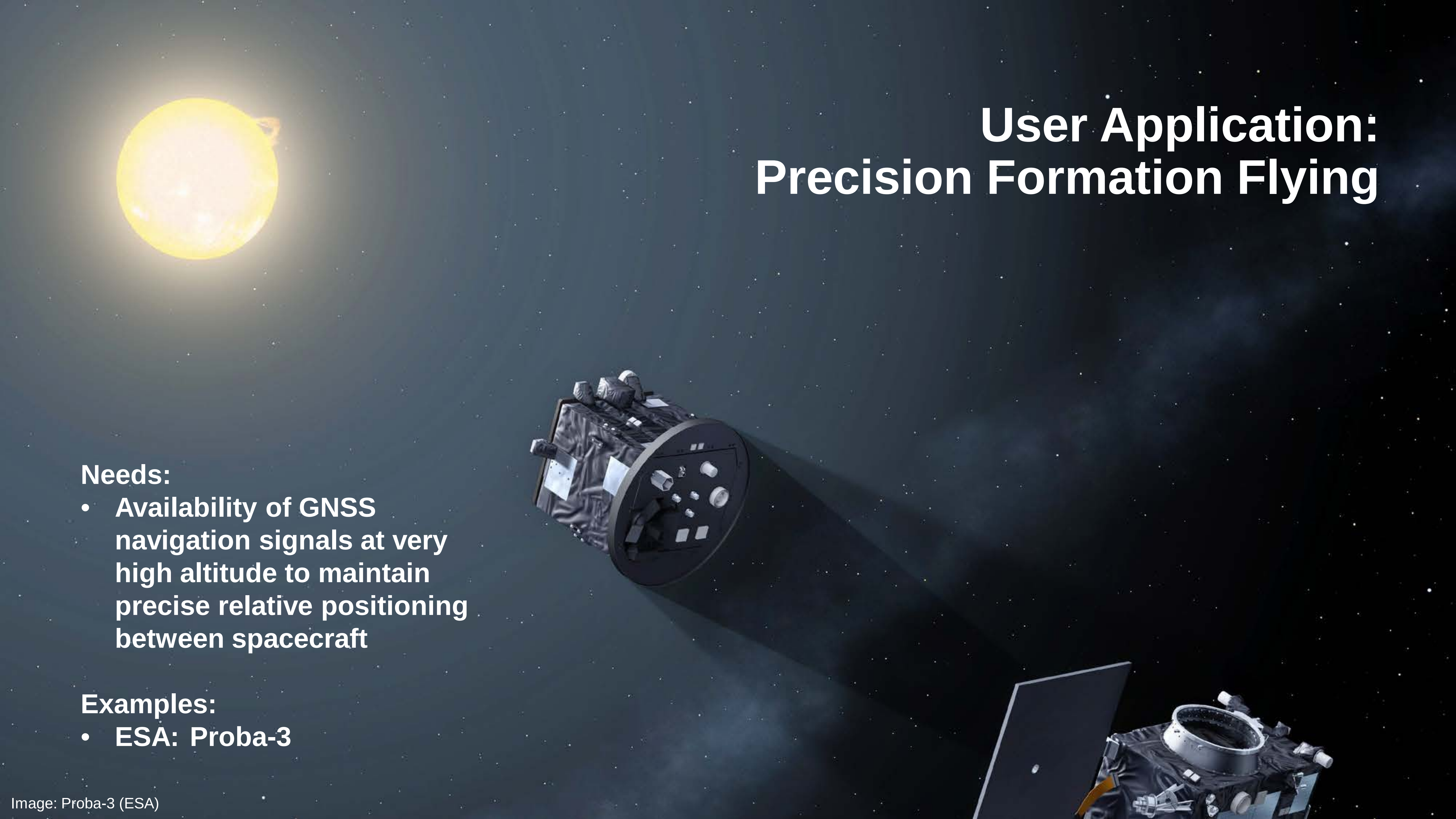
- **Near-continuous availability of GNSS signals at GEO to maintain platform stability without service outages**

Examples:

- **US:** **Geostationary Operational Environmental Satellite (GOES) R-series**
- **Russia:** **Elektra-L**

Image: Hurricane Lane (2018) from the ISS (NASA)

User Application: Precision Formation Flying



Needs:

- **Availability of GNSS navigation signals at very high altitude to maintain precise relative positioning between spacecraft**

Examples:

- **ESA: Proba-3**

Image: Proba-3 (ESA)

User Application: Cislunar Trajectories

Needs:

- **GNSS signal availability at extremely high altitude, such as to lunar distance, to perform on-board navigation of exploration vehicles**
- **Few signal outages around critical return events, to ensure precise navigation solution for Earth reentry**

Examples:

- **Lunar exploration vehicles**
- **Launch vehicle upper stages**

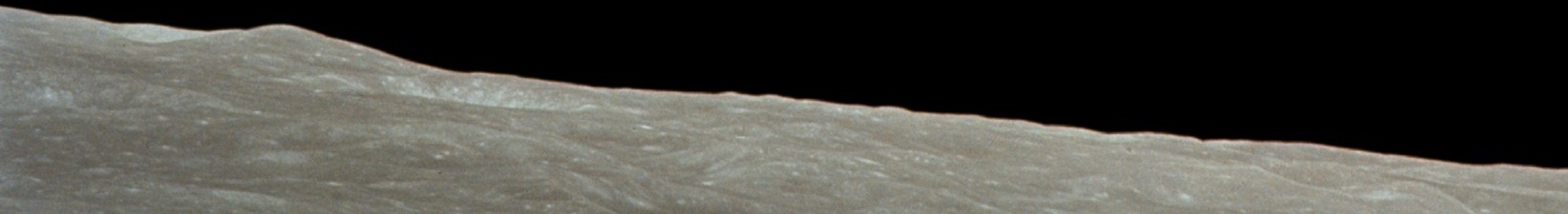


Image: Earthrise from Apollo 8 (NASA)

User Application: Satellite Servicing

Needs:
- **Continuously-available GNSS signals at GEO, to support precise relative positioning, spacecraft agility, and on-board autonomy**

Examples:
- **Proposed GEO automated servicing vehicles**

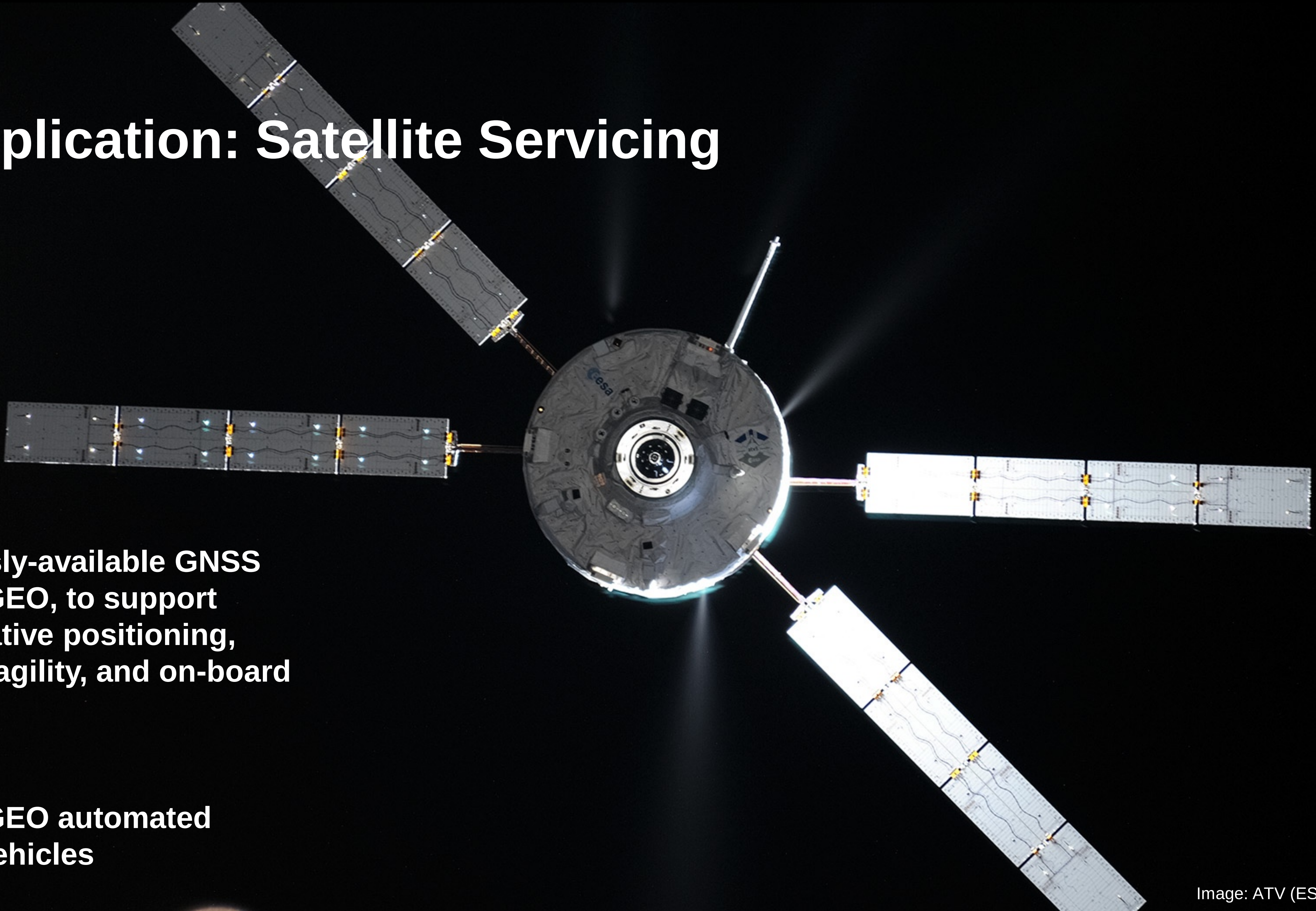


Image: ATV (ESA)