The Expanding Civil Space User Segment: Reaching for New Frontiers

Joel J.K. Parker

U.S. National Aeronautics and Space Administration

CGSIC

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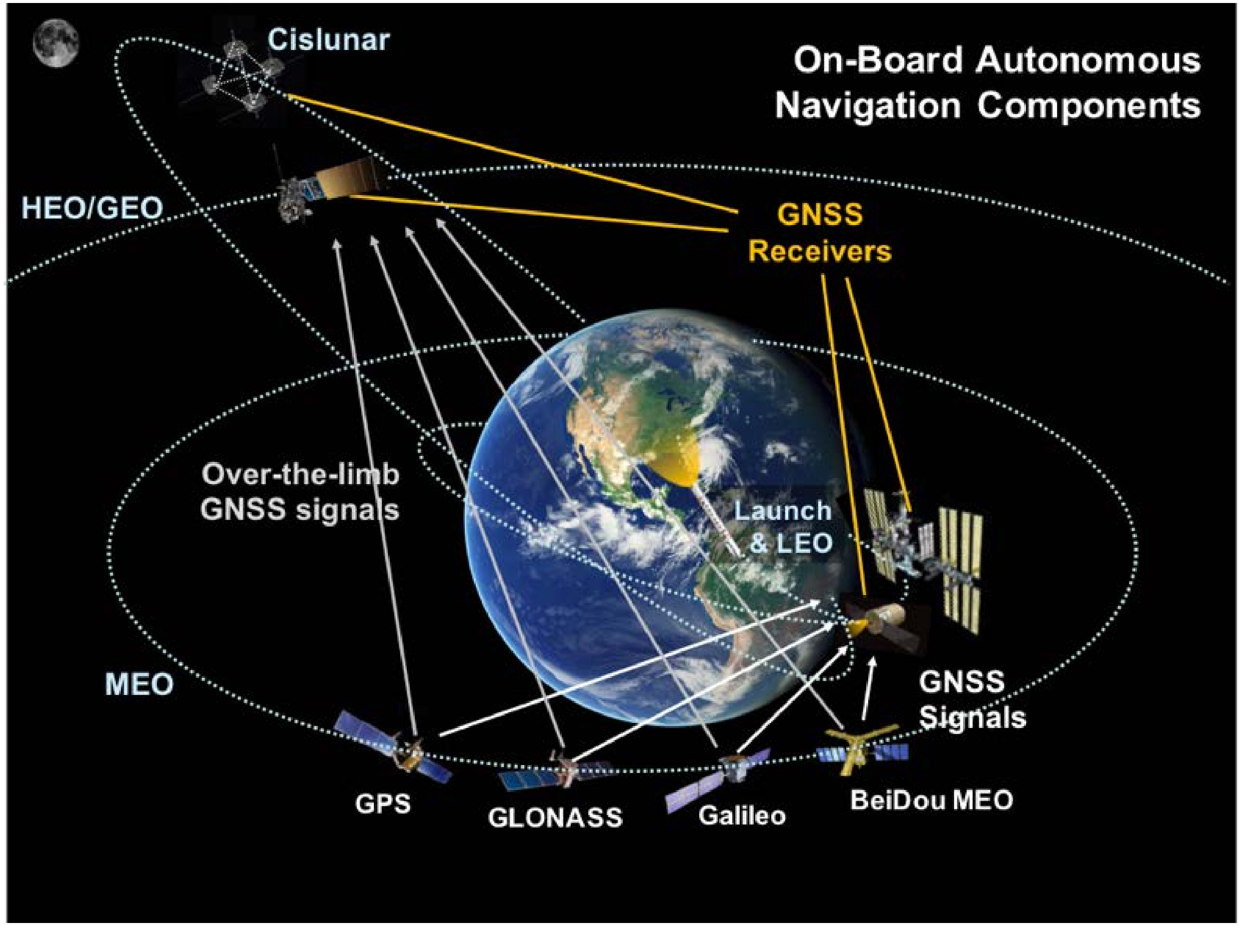
ICG Collaboration on GNSS Beyond the SSV, including the Deep Space Gateway

Space Uses of Global Navigation Satellite Systems (GNSS)

- **Real-time On-Board Navigation**: Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences**: Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements
- **Launch Vehicle Range Ops**: Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use
- **Attitude Determination**: Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements
- **Time Synchronization**: 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 from 3,000 km to lunar orbit

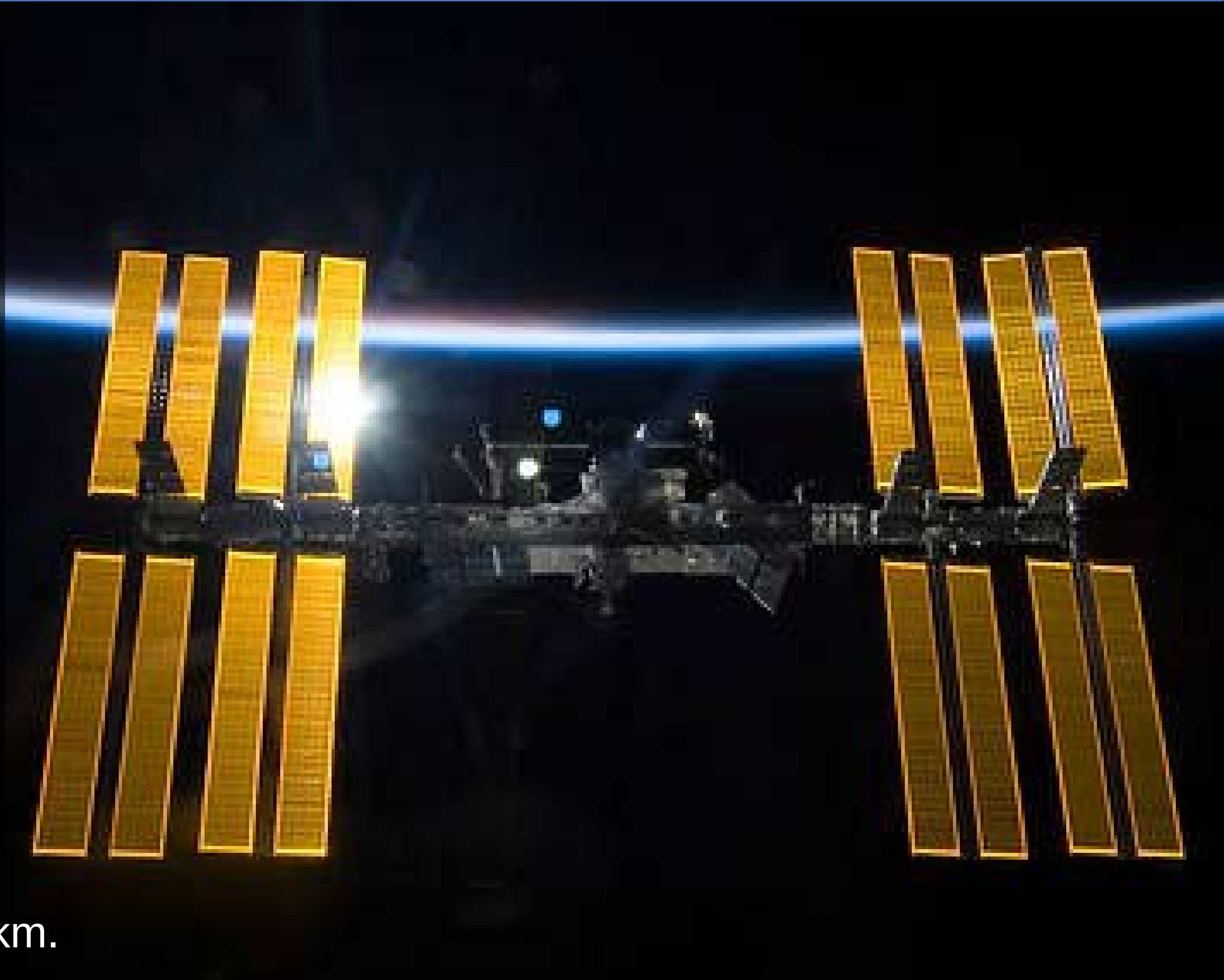
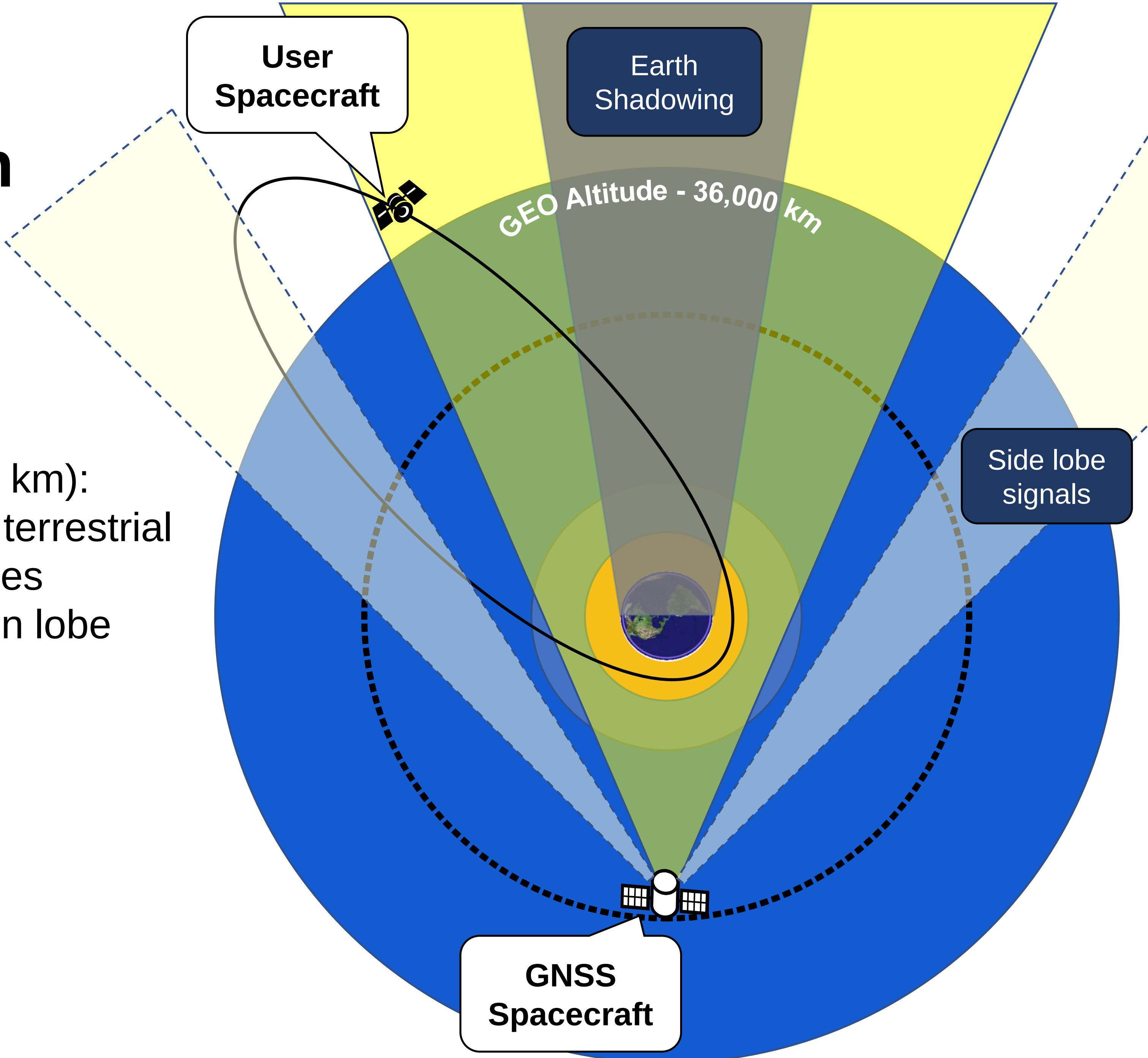


Image: International Space Station (NASA)

High-altitude GNSS reception comes with many challenges

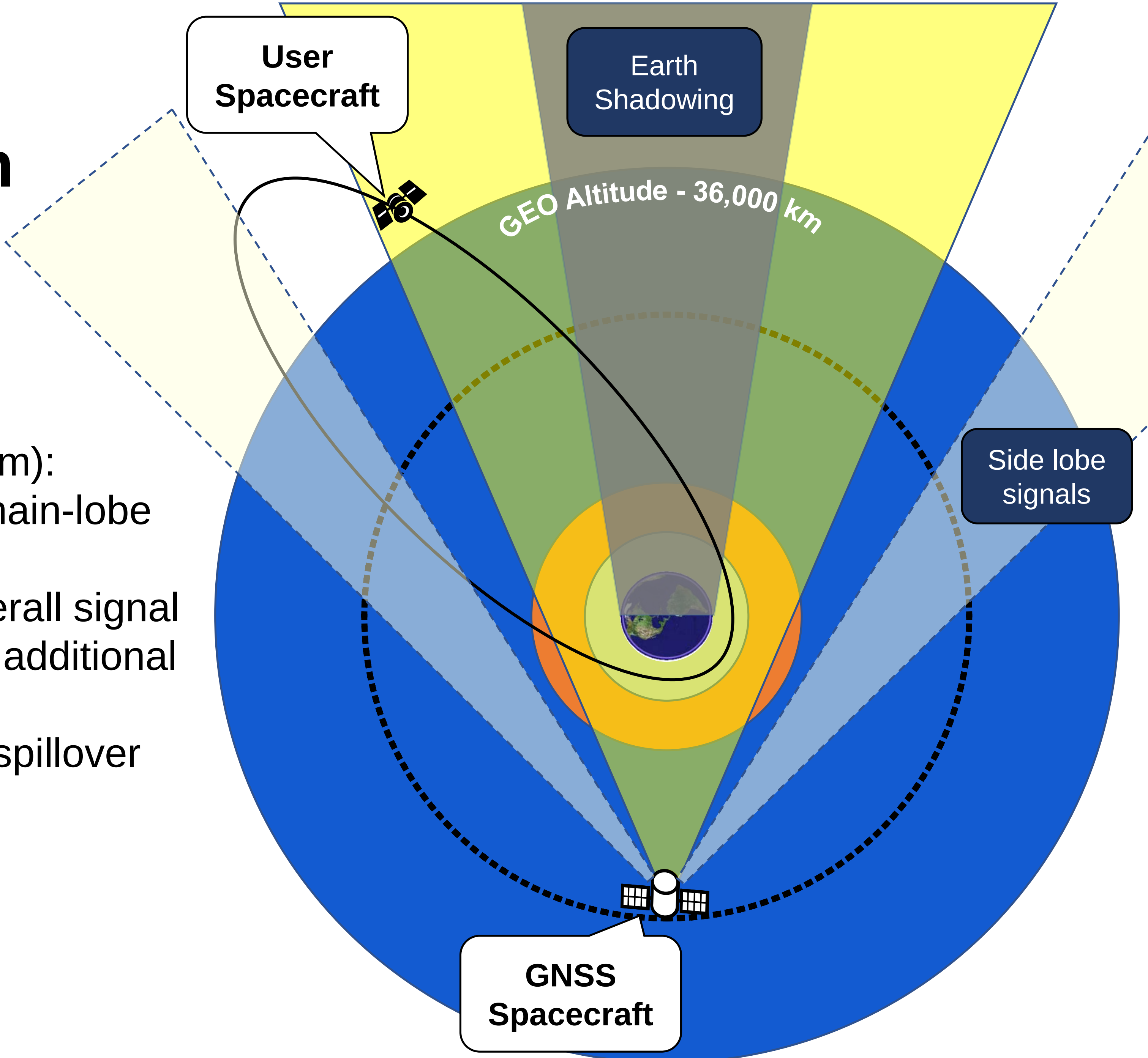


Low altitudes (below approx. 3,000 km):

- 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.

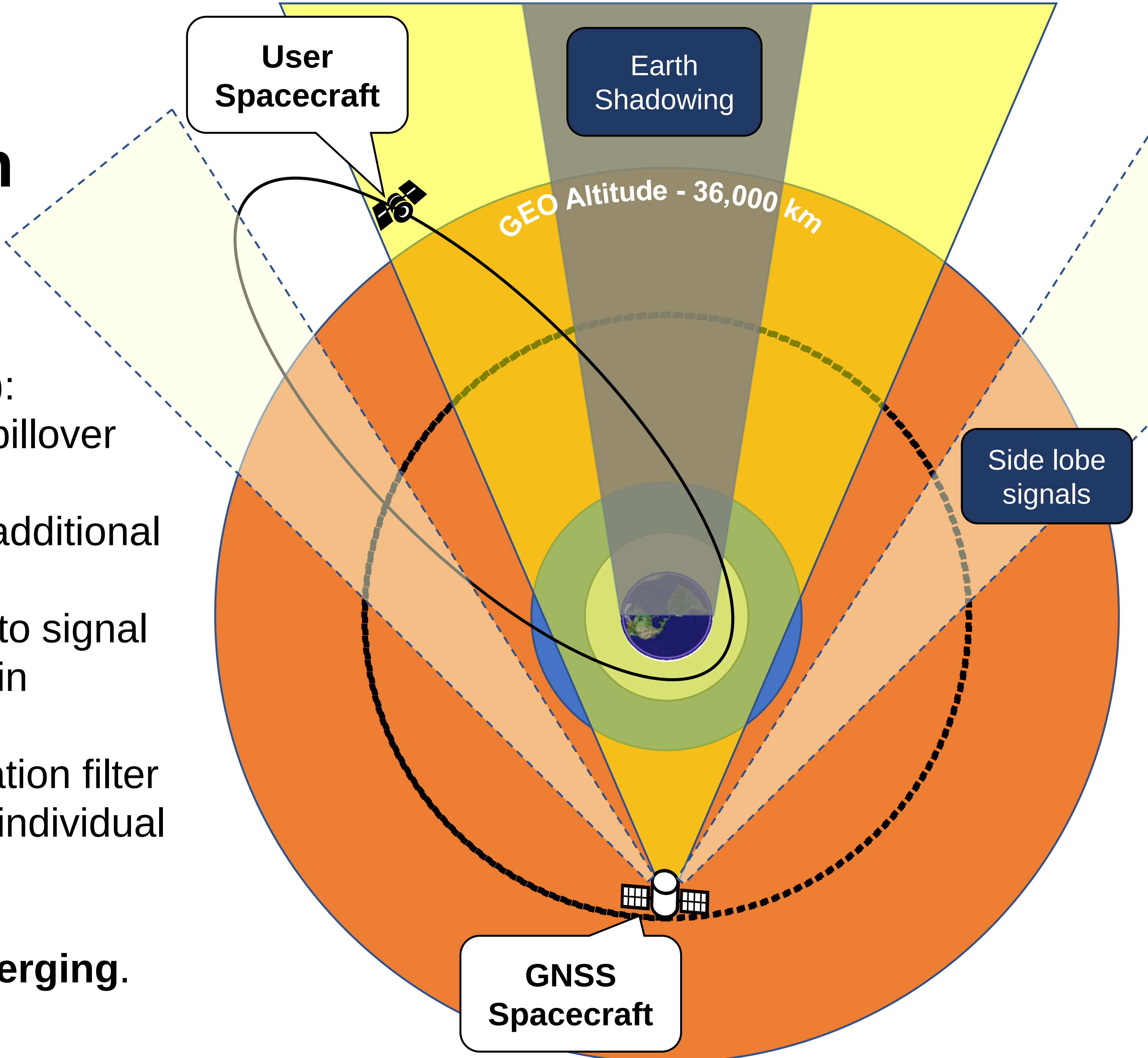
GNSS usage is **operational**.

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**.

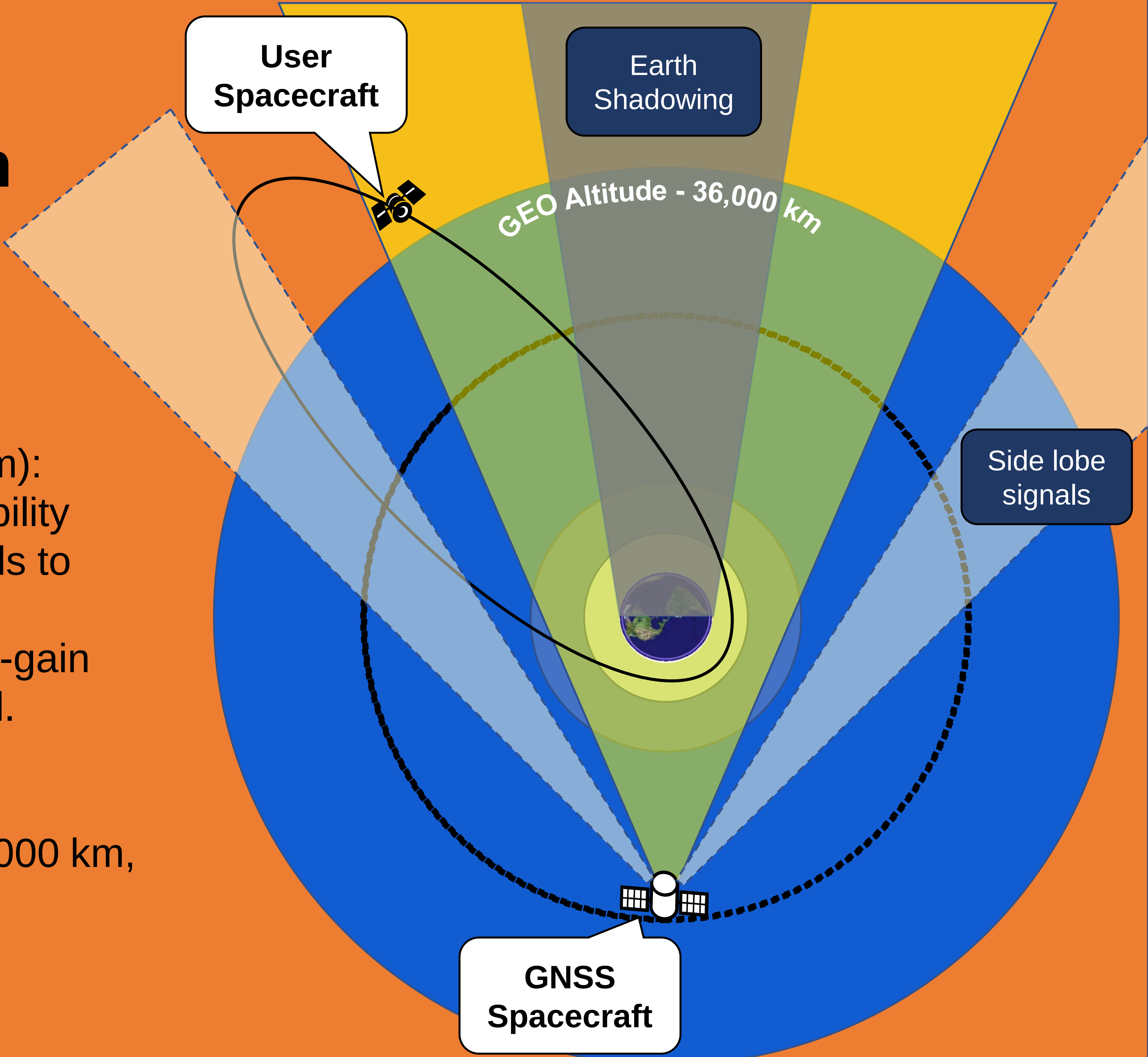


High-altitude GNSS reception comes with many challenges

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.

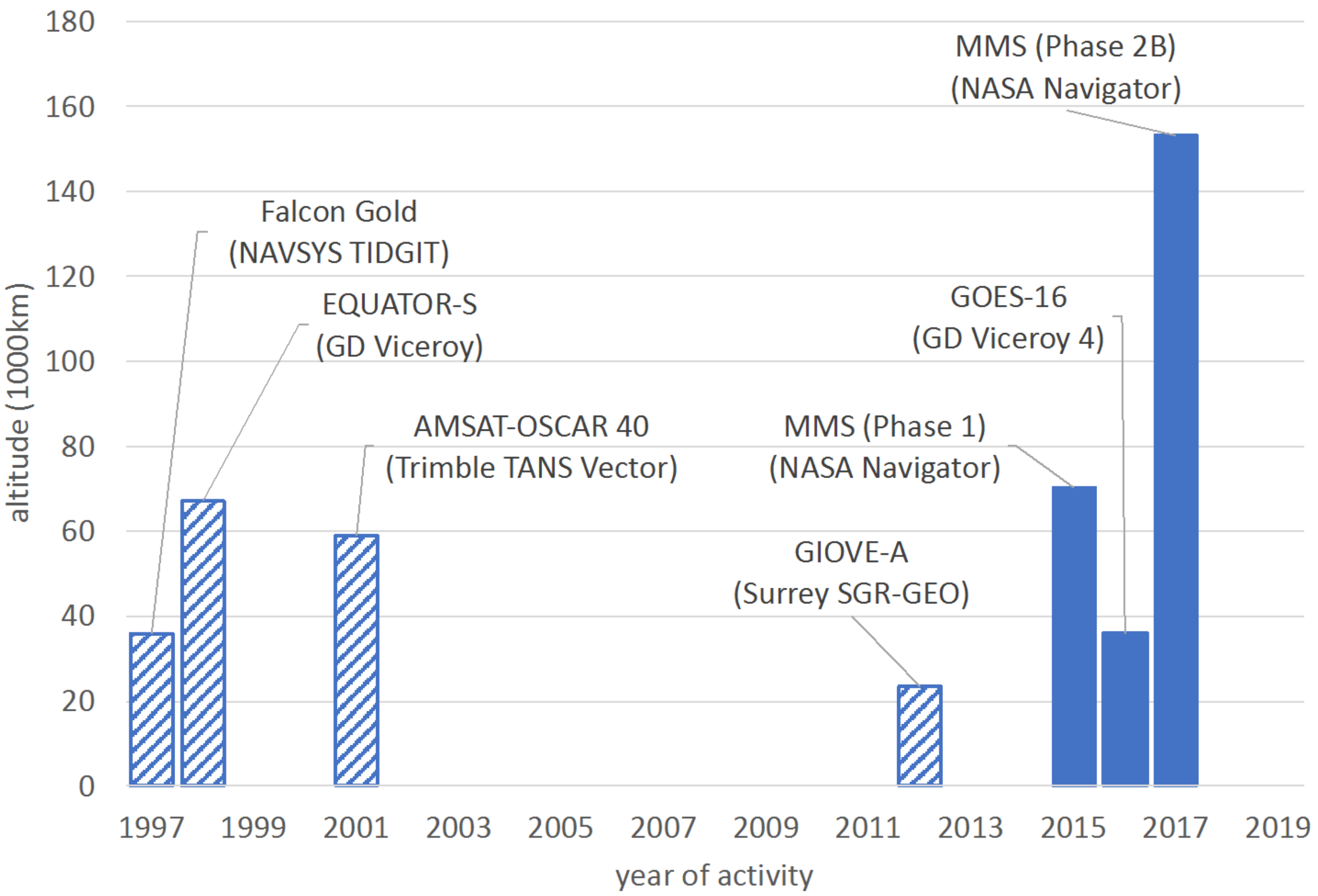


A History of High-Altitude GNSS

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



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*

ICG International Committee on Global Navigation Satellite Systems

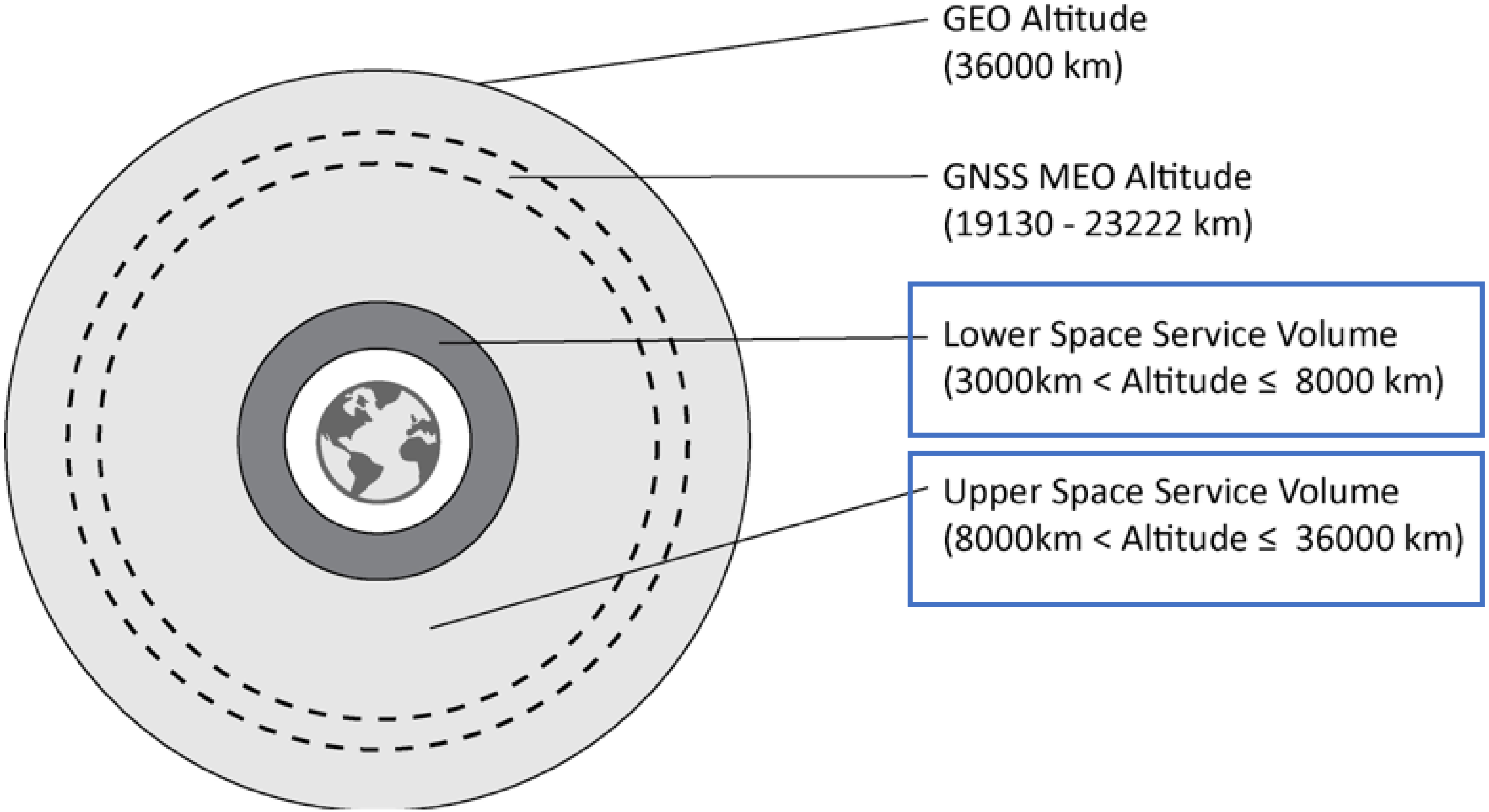
The ICG consists of four working groups. Of these two have primary roles related to high-altitude users:

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.



GEO Altitude
(36000 km)

GNSS MEO Altitude
(19130 - 23222 km)

Lower Space Service Volume
(3000km < Altitude ≤ 8000 km)

Upper Space Service Volume
(8000km < Altitude ≤ 36000 km)

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

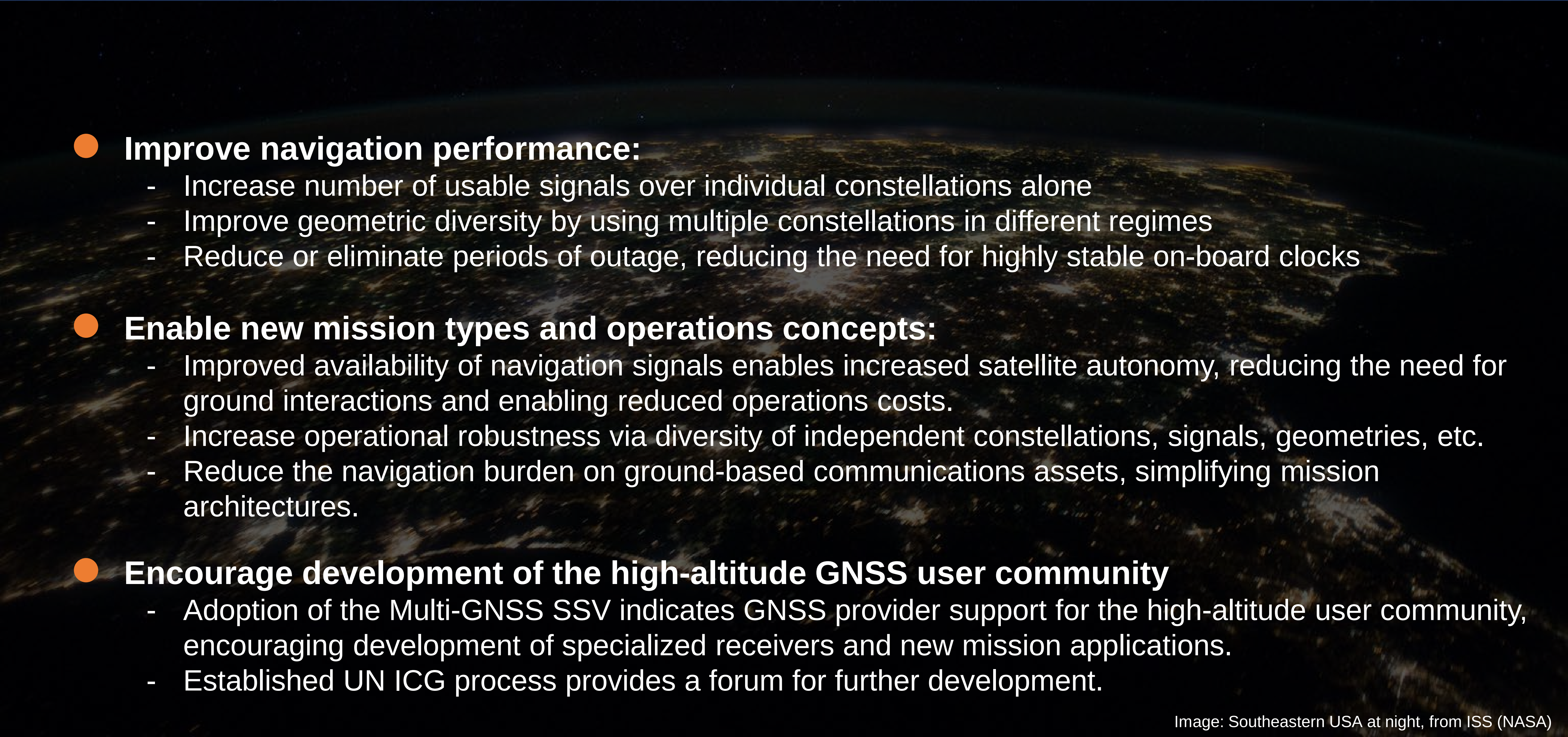
As amended in 2015, the ICG WG-B work plan directs it to:

> *“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:

	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.	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

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.

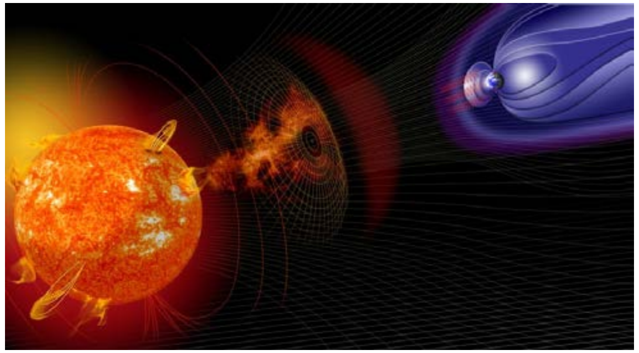
Image: Southeastern USA at night, from ISS (NASA)

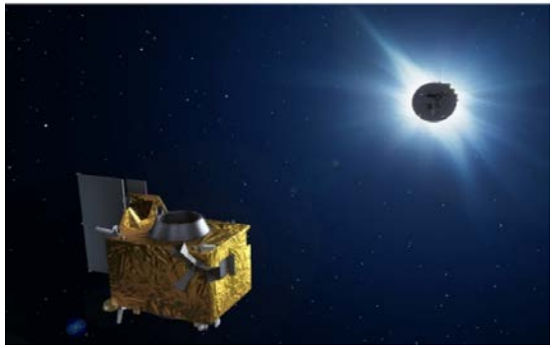
The Promise of using GNSS for Real-Time Navigation at High Altitudes & Beyond the Space Service Volume

Benefits of High Altitude GNSS use:

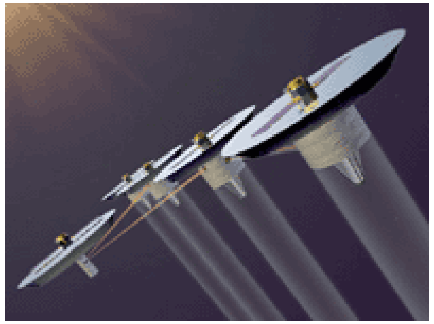
- **Supports real-time navigation/timing performance** (from: *no real time* to: real-time 1 km – 100 m position, µsec timing)
  - Improved performance with (pseudo-) satellite and clock augmentations
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- **Near-continuous 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:

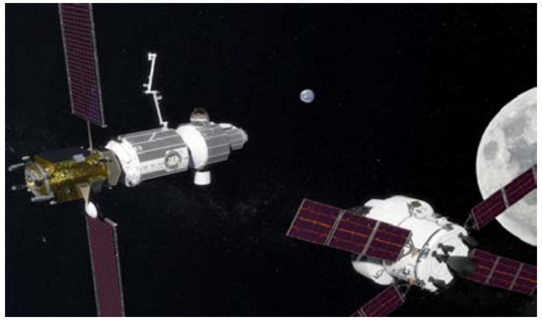

Earth Observations


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:

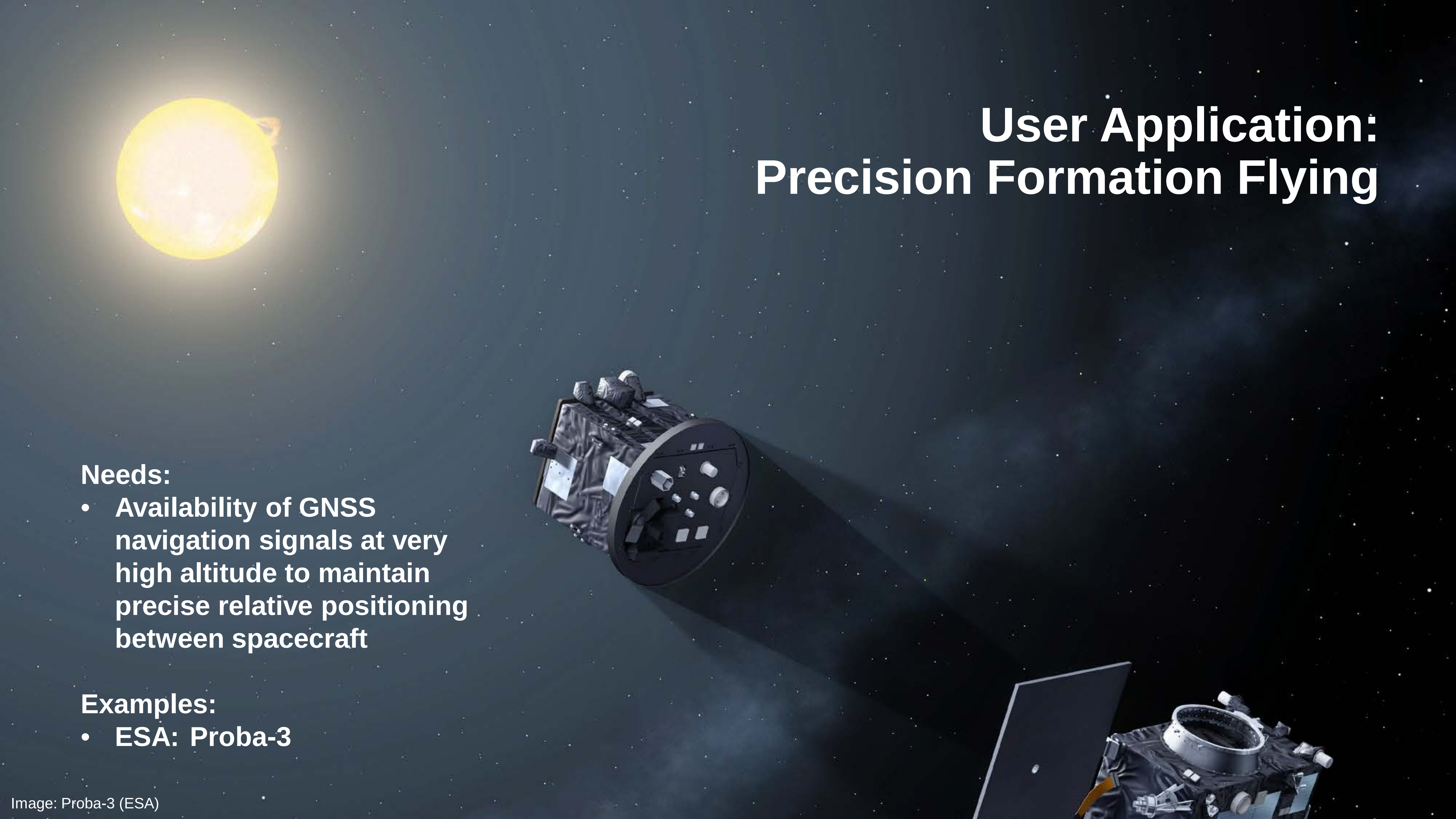
- **Near-continuous availability of GNSS signals at GEO to maintain platform stability without service outages**

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:

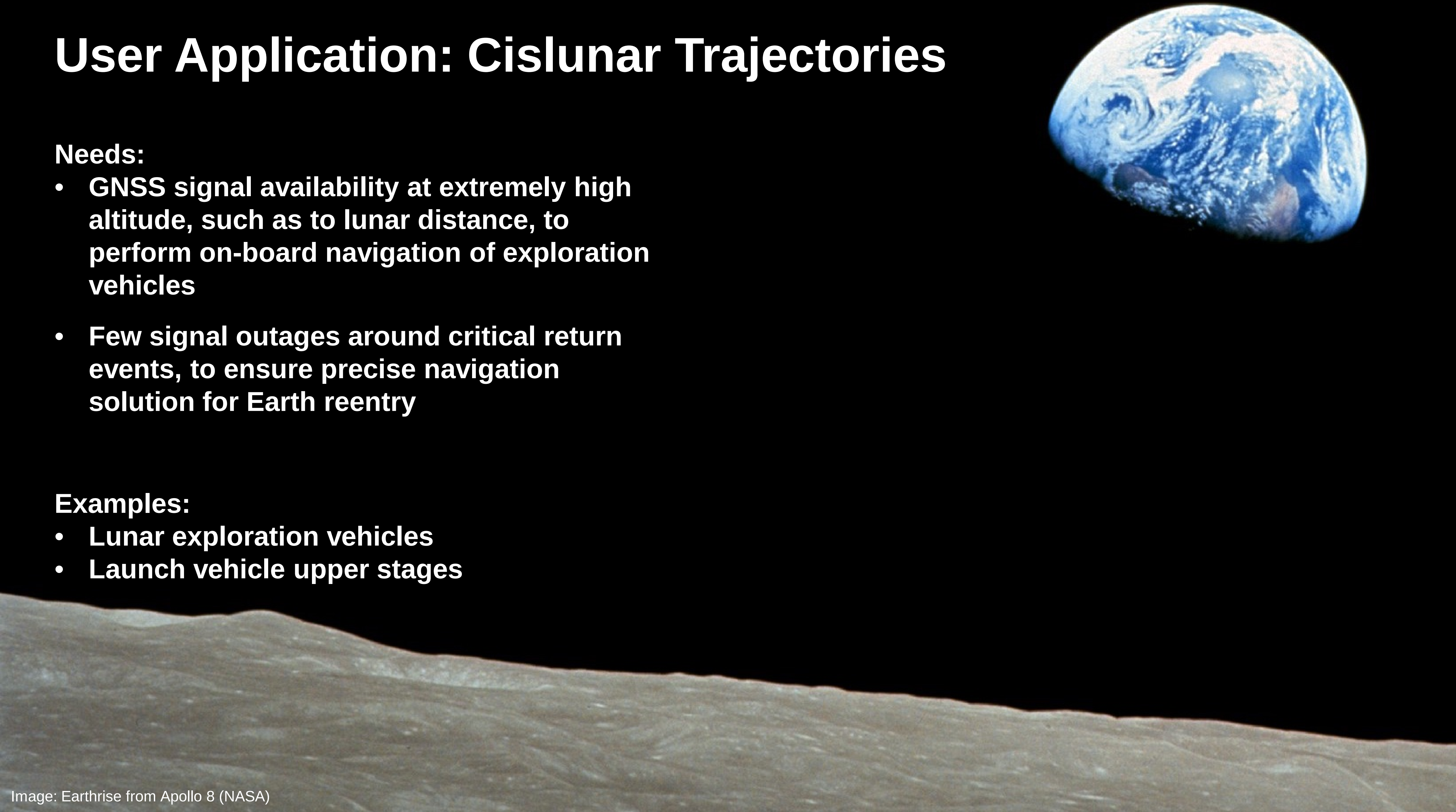
- **Availability of GNSS navigation signals at very high altitude to maintain precise relative positioning between spacecraft**

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

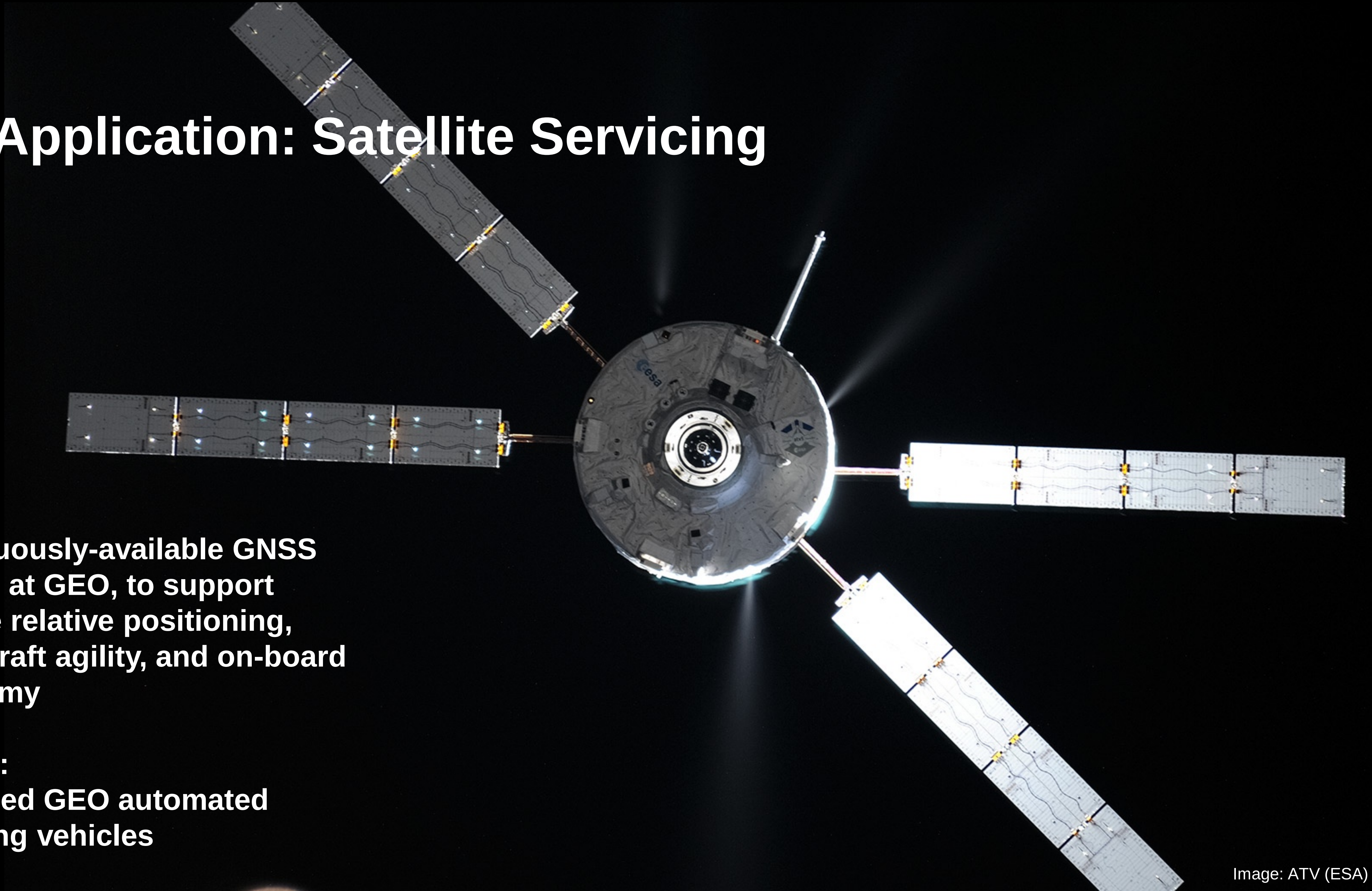


Image: ATV (ESA)

Needs:

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

Examples:

- **Proposed GEO automated servicing vehicles**

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:

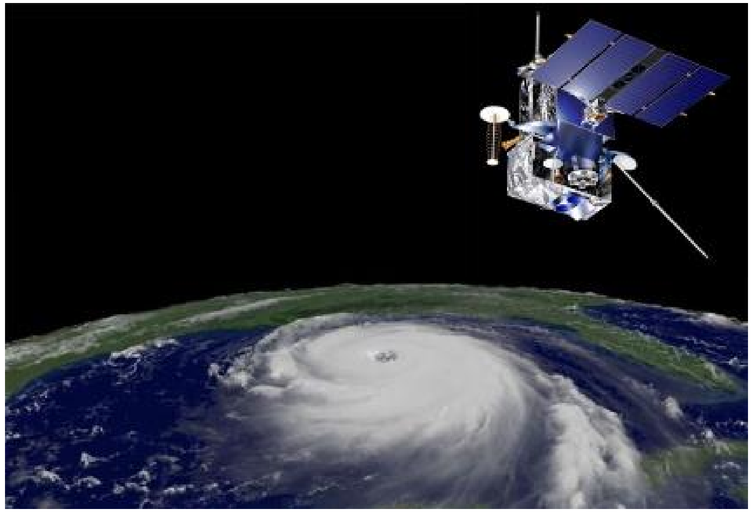
- **GEO communications satellites**

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

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):

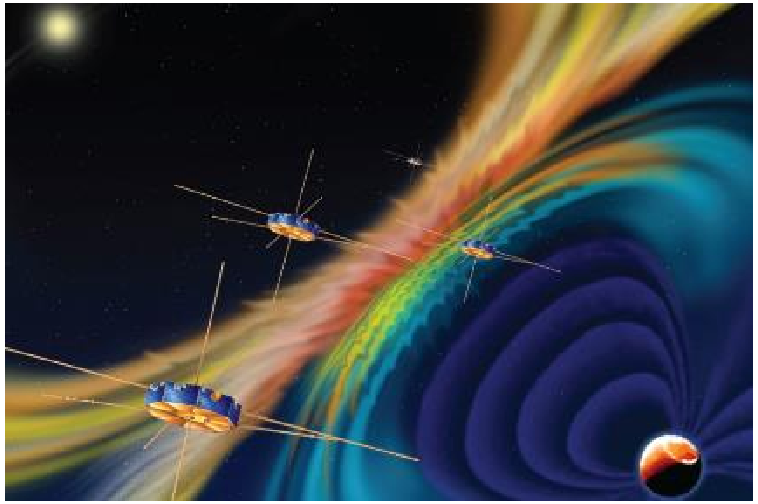
- Radial: 14.1 m
- In-track: 7.4 m
- Cross-track: 5.1 m

- 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



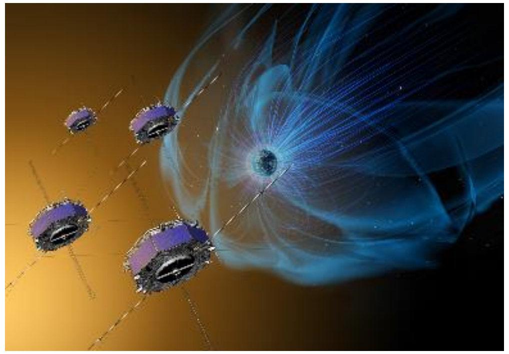
MMS Nav. Performance (1σ)

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

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

Operational Users

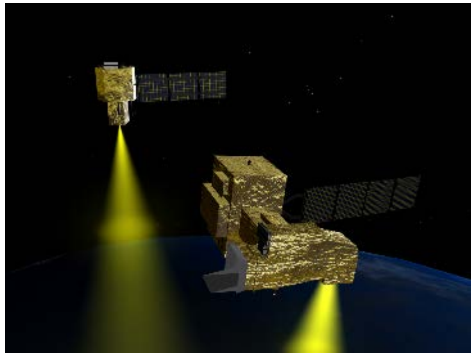
- MMS
- GOES-R, S, T, U
- EM-1 (Lunar enroute)
- Satellite Servicing



Operational Use Demonstrates Future Need

Space Flight Experiments

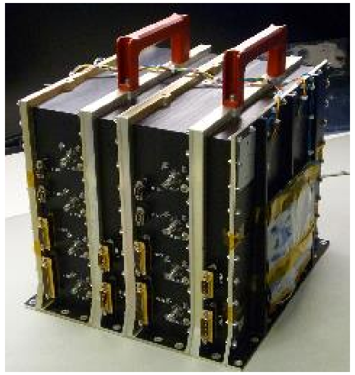
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)



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

SSV Policy & Specifications

- SSV definition (GPS IIF)
- SSV specification (GPS III)
- ICG Multi-GNSS SSV common definitions & analyses

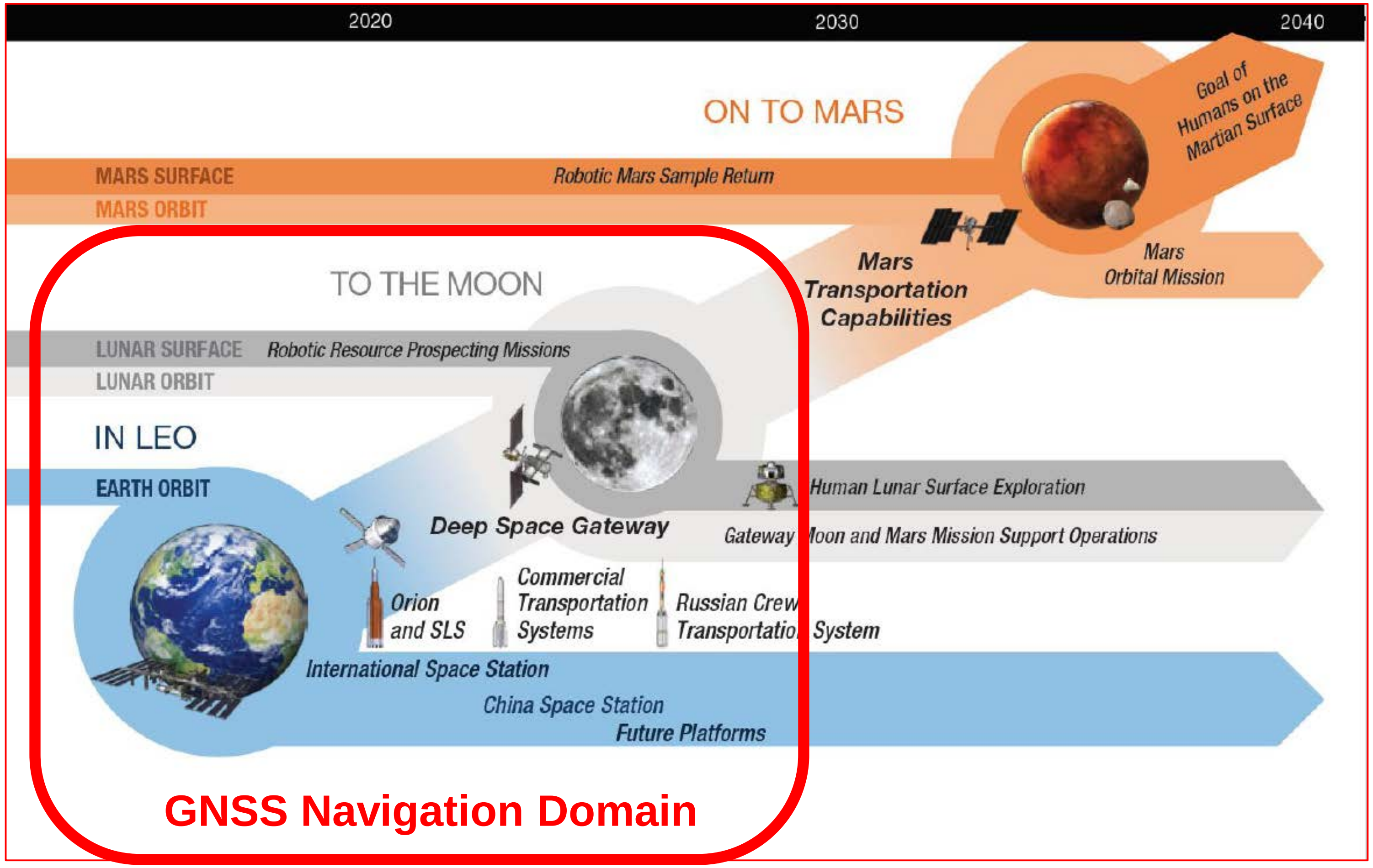
Operational Guarantees Through Definition & Specification

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

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

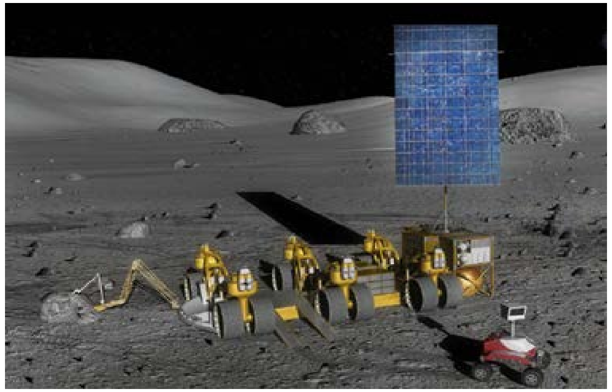
Global Exploration Roadmap



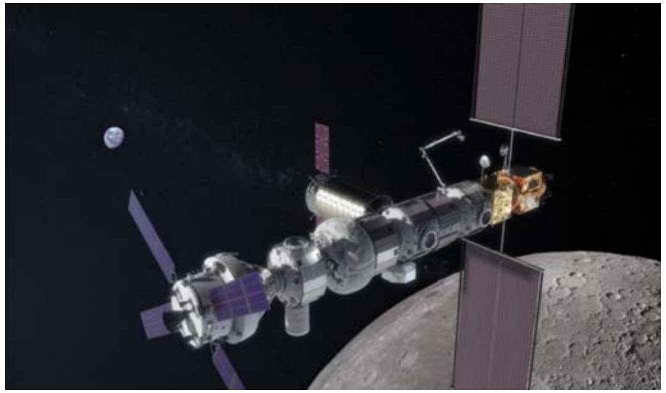
Lunar Missions Represent a Ripe New Frontier for High Altitude GNSS

Lunar Exploration Mission Types

Enabled via GNSS Navigation & Timing



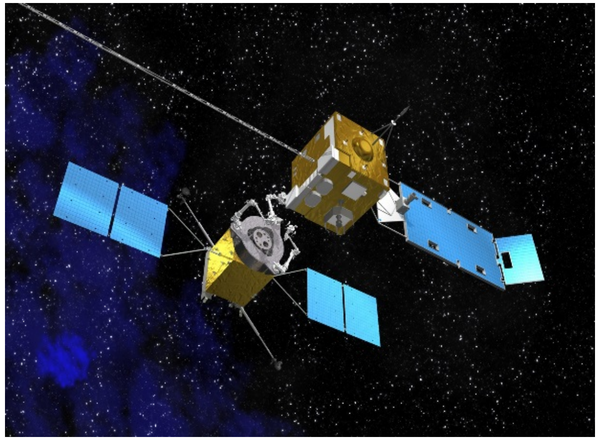
Lunar Surface Operations
Robotic Prospecting & Human Exploration



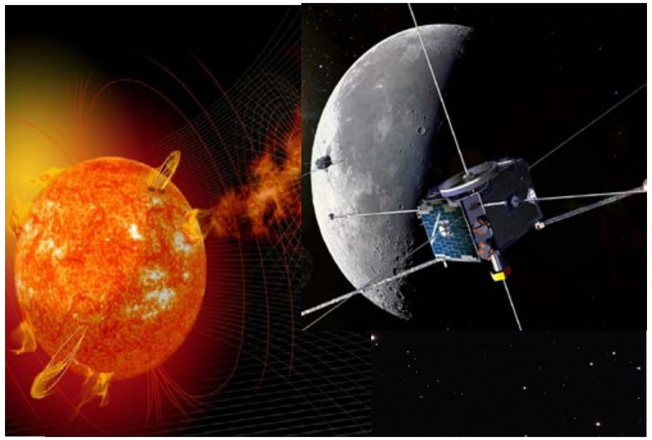
Human-tended Lunar Vicinity
Lunar Orbiting Platform-Gateway

Robotic Lunar Orbiters
Resource & Science Sentinels

Earth & Astrophysics Observations



Satellite Servicing



Solar & Space Weather Observations

Conclusions

- Use of GNSS for navigation & timing in space is now routine at altitudes below 3,000 km
- **High-altitude space use of GNSS,** (i.e. expansion of GNSS use from 3,000 km to lunar orbit), 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 demonstrations
  - High-altitude GNSS receiver developments
  - UN ICG initiatives where **all GNSS constellation providers** have adopted common interoperable definitions, including the Multi-GNSS Space Service Volume, have published performance characteristics, and have performed joint analyses documenting the benefits of utilizing multi-GNSS in this regime
  - Sharing operational mission results, including the GOES and MMS spacecraft, to show high-altitude GNSS is realizable
- Numerous planned geostationary and lunar exploration missions are poised to reap great benefits from this new technological 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