The Expanding Civil Space User Segment: Reaching for New Frontiers

Mr. Joel J. K. Parker
U.S. National Aeronautics and Space Administration
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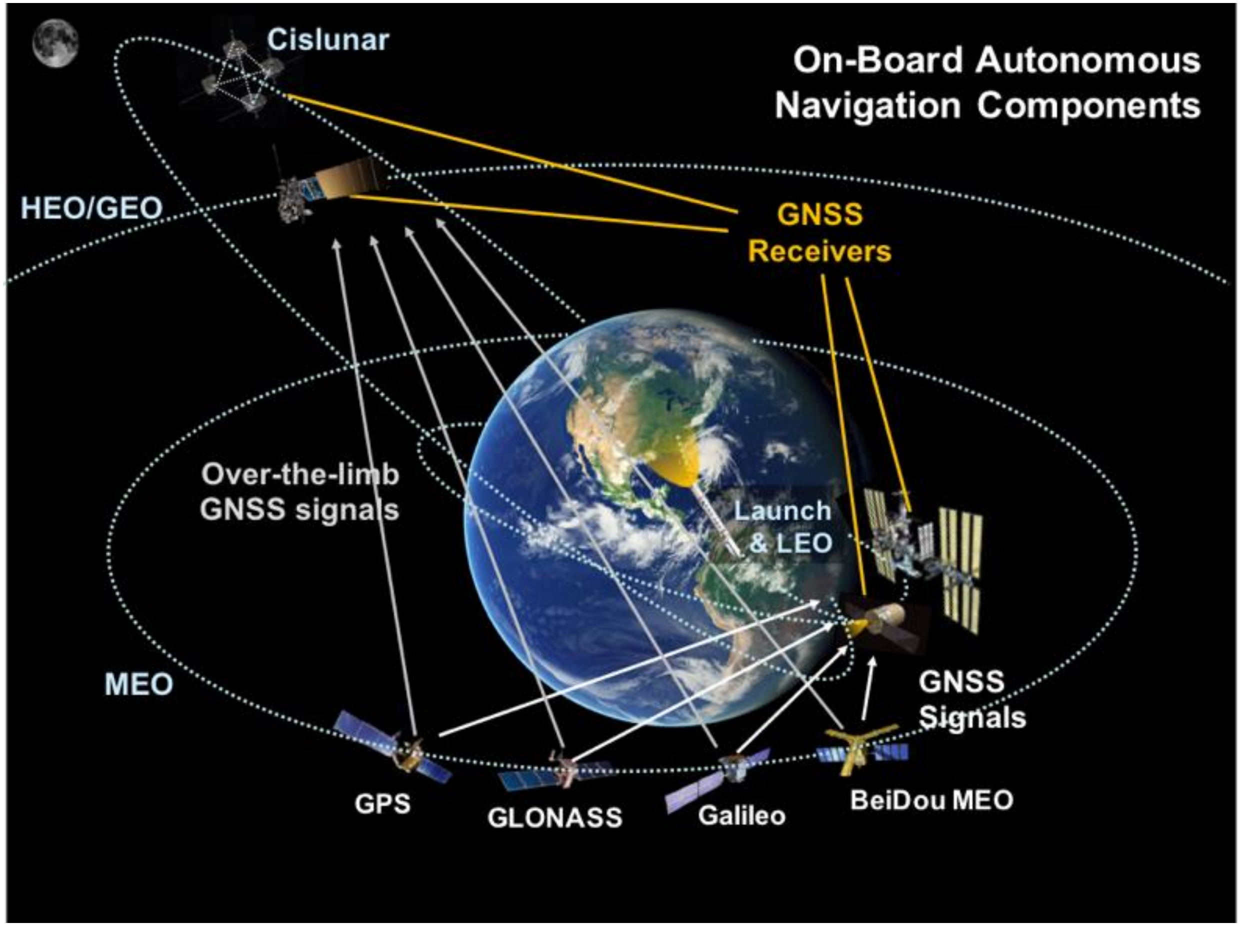
The Lunar Orbital Platform—Gateway, a potential application of international collaboration on GNSS beyond the SSV

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



Space applications of GNSS are widespread and expanding rapidly. Commitments to support the space user segment will encourage future capability growth for societal benefit.

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.

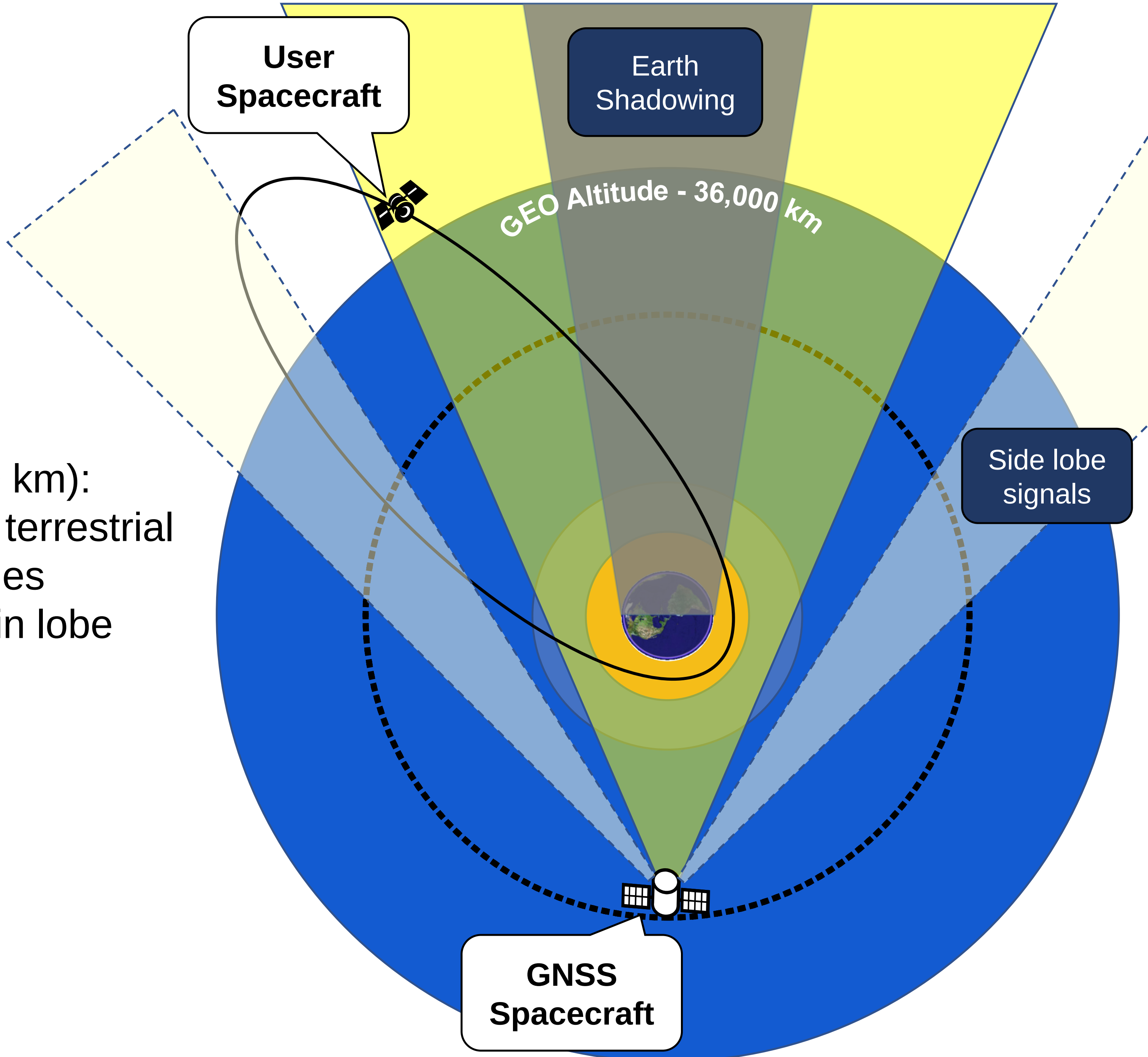
Civil Space's New Frontier: Realizing the benefits of GNSS from 3,000 km to lunar orbit

Image: International Space Station (NASA)

High-altitude use of GNSS 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**.

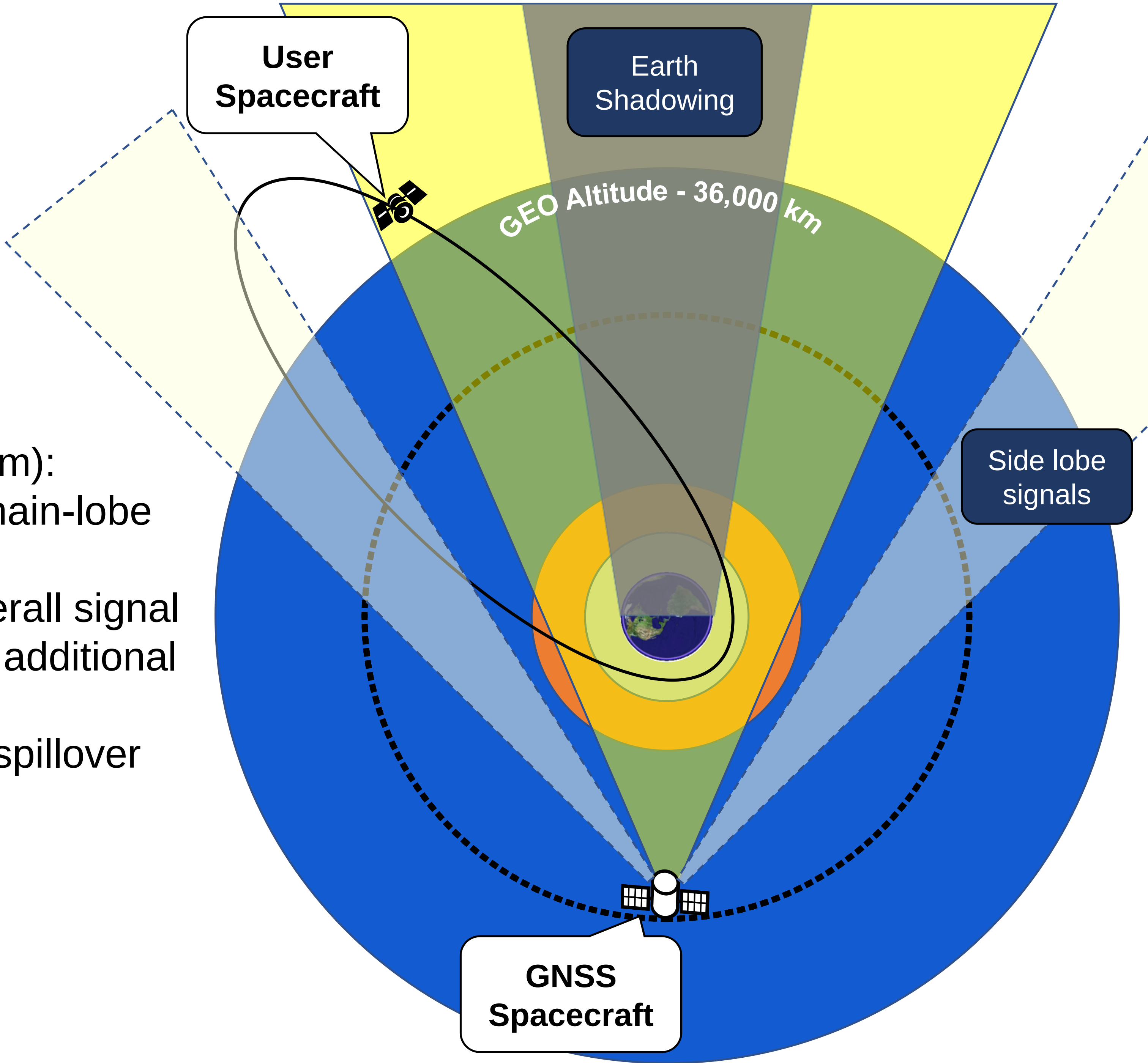


High-altitude use of GNSS comes with many challenges

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**.

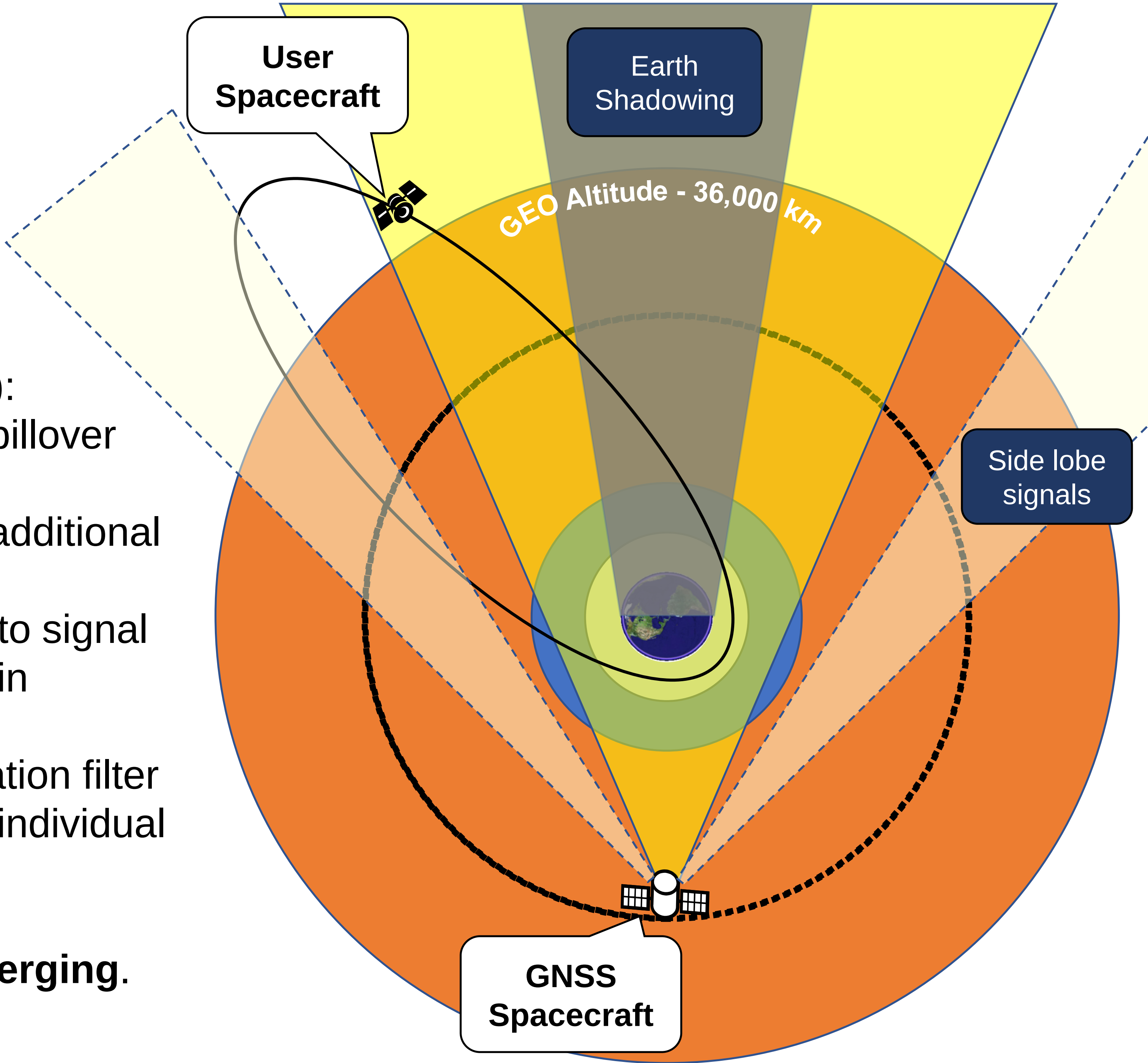


High-altitude use of GNSS comes with many challenges

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.

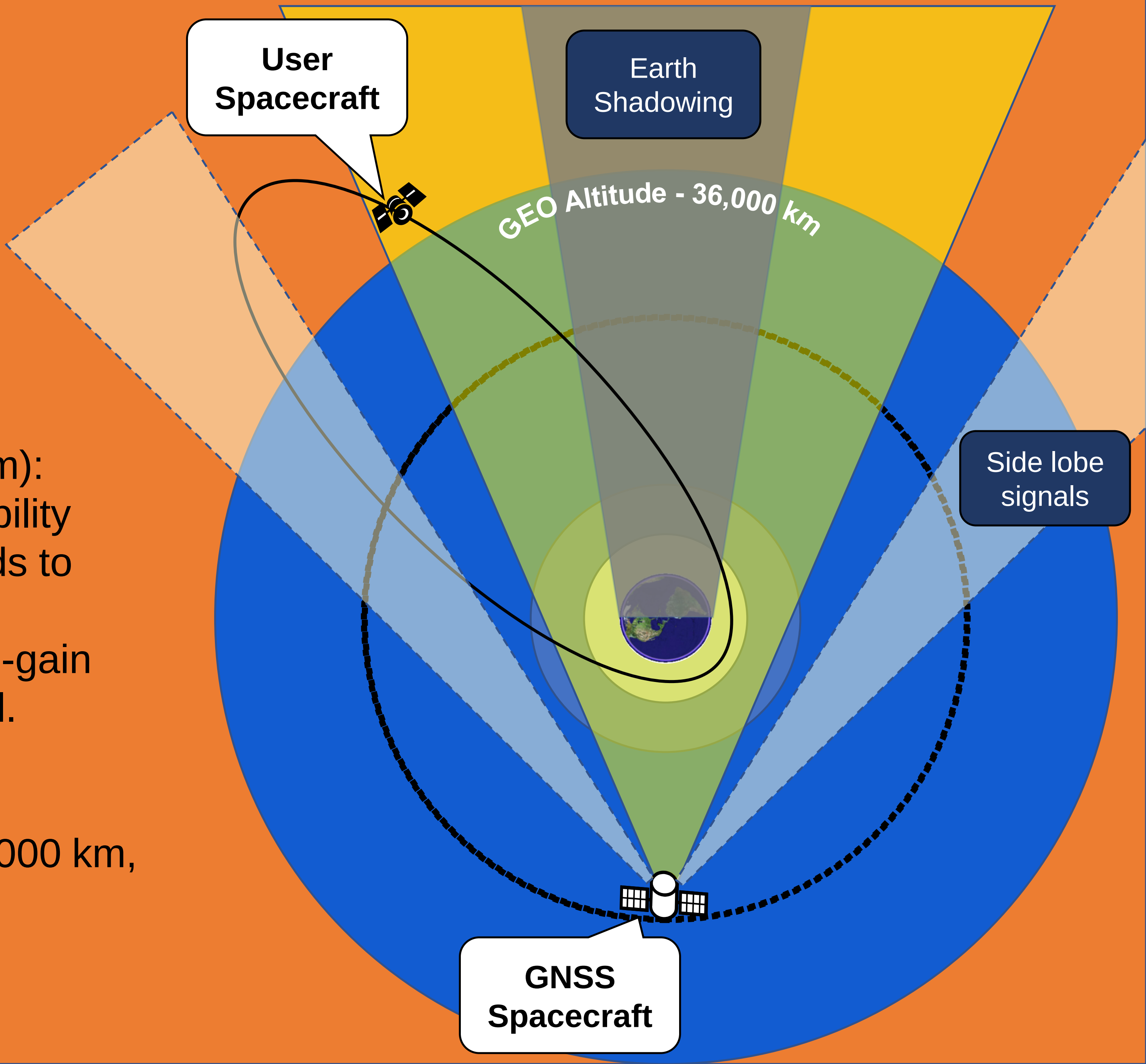
GNSS usage is **operational** but **emerging**.



High-altitude use of GNSS 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.

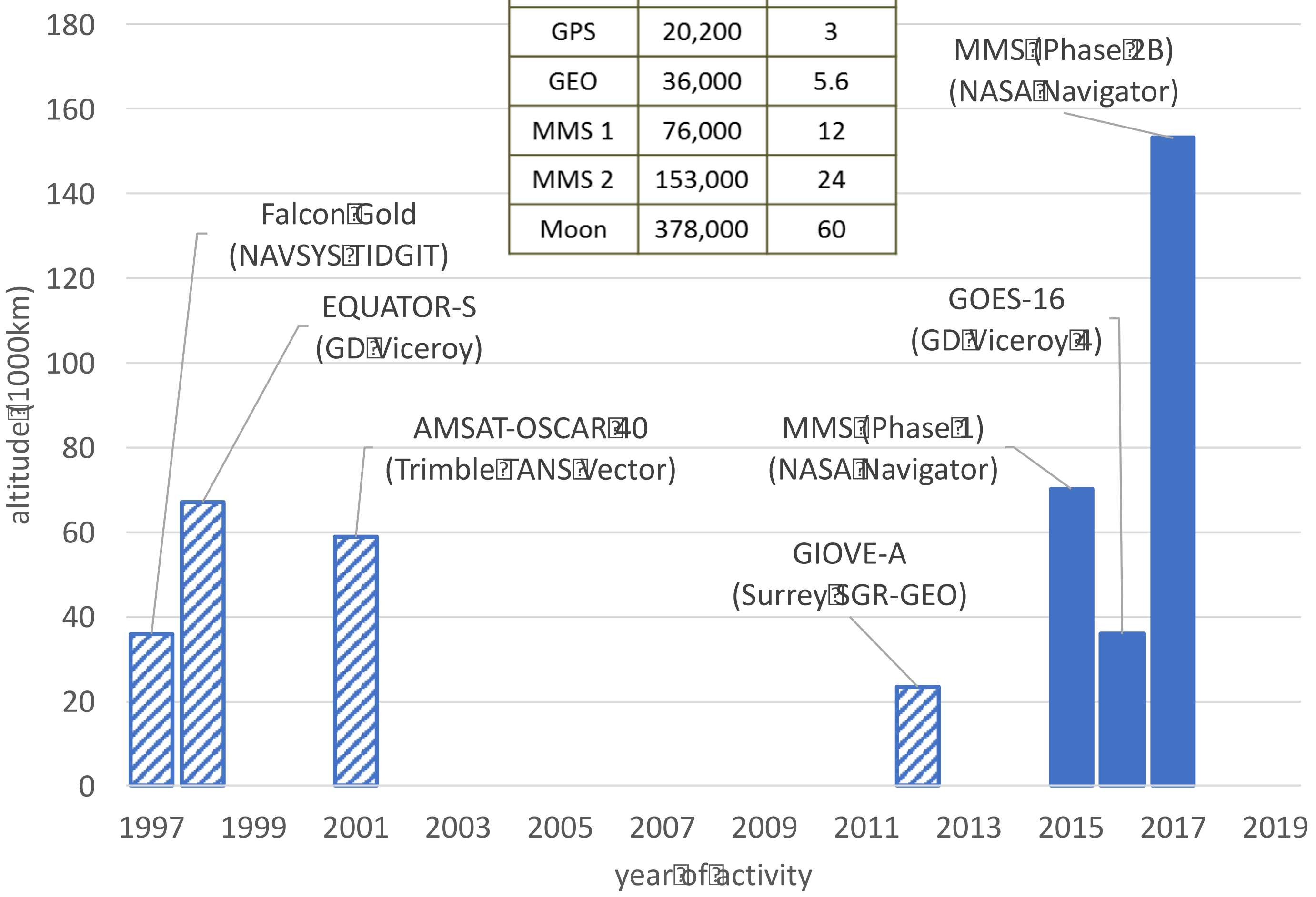


The Past and Future of High-Altitude GNSS

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 (recently increased to 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



The Past and Future of High-Altitude GNSS

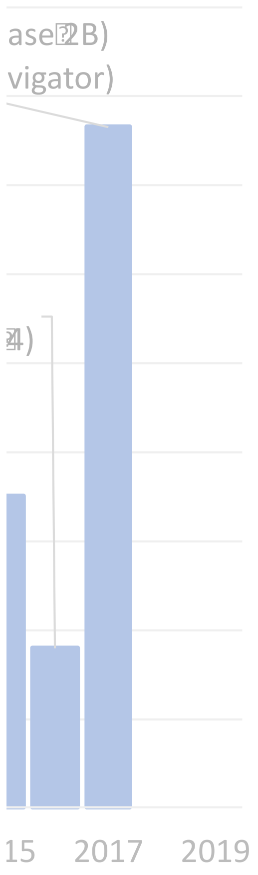
Transition from experimentation to operational use:

- 1990s: Ea feasibility
- 2000: Rel demonstra architectu 2000)
- 2001: AM sidelobe s
- 2015: MM km (recer
- 2016–201 operationa

	Altitude [km]	Altitude [R_E]

The new frontier will be enabled by:

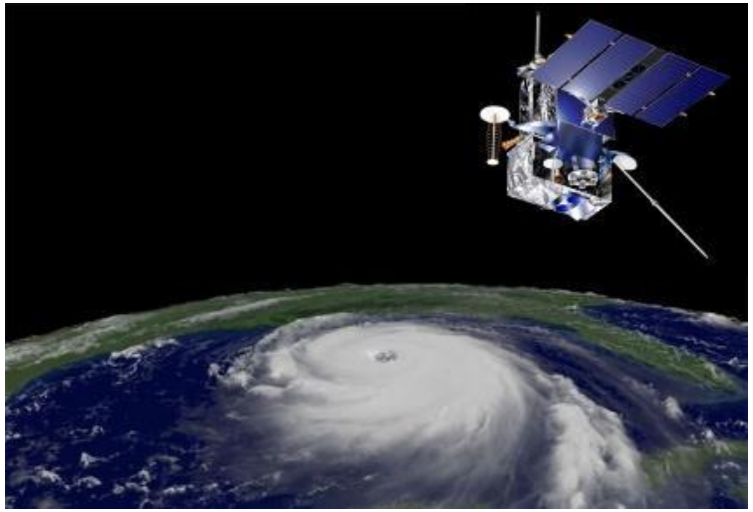
- **Operationalizing**: Transitioning from experiment to operations
- **Enabling**: Documentation, data, and service commitments
- **Extending**: Seeking the true boundaries of GNSS service through technology, experiments, and collaboration
- **Diversifying**: Achieving robust PNT through combined navigation sources



Operationalizing: 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
- First series to use GPS for primary navigation
- GPS provides rapid maneuver recovery, enabling continual observation 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-16 GPS Visibility:

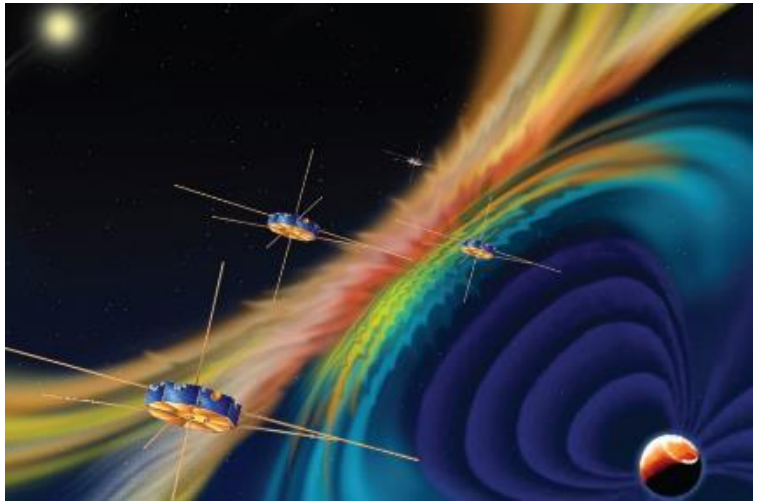
- Minimum SVs visible: 7
- DOP: 5–15

GOES-16 Nav Performance (3σ):

- Radial: 14.1 m
- In-track: 7.4 m
- Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m

Magnetospheric Multi-Scale (MMS) Mission:

- 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% lunar distance)**
  - Additional apogee raising beyond 29 RE **(50% lunar distance)** completed in February 2019
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping

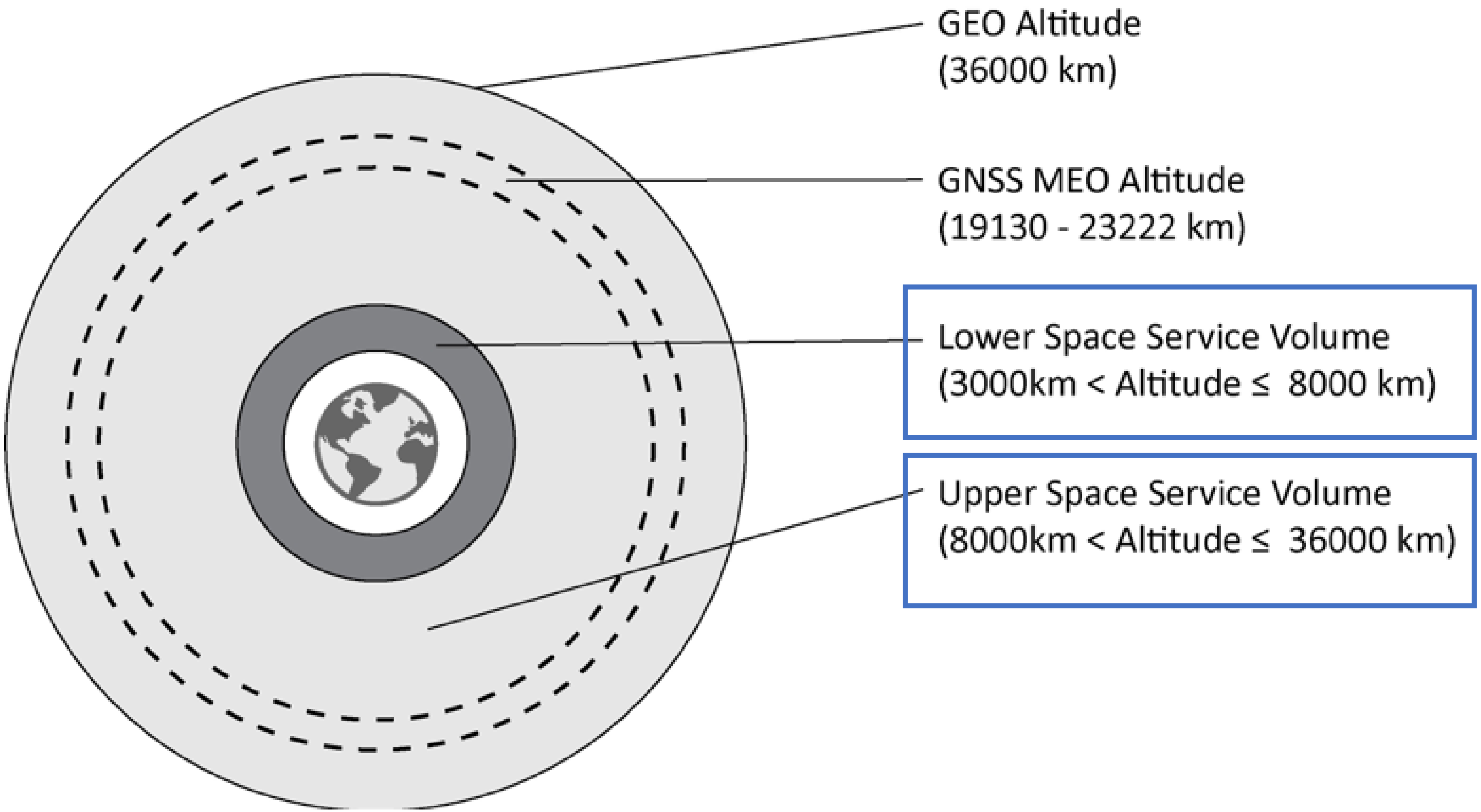


MMS Nav Performance (1σ)

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

Enabling: Defining 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

Enabling: International Multi-GNSS SSV activities in the ICG WG-B

The **United Nations International Committee on GNSS (ICG) Working Group B (WG-B) on Enhancement of GNSS Performance, New Services and Capabilities**
leads development of the Multi-GNSS Space Service Volume concept and related activities.

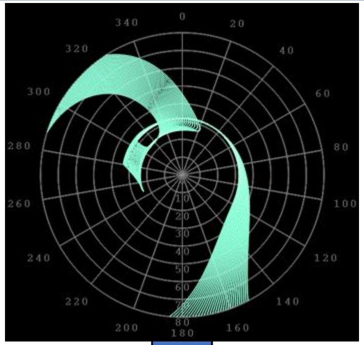
This is being accomplished via several initiatives:	**Status**
• **SSV Definition/Assumption Maturation**: Adopting the formal definition of the Multi-GNSS SSV	Completed 2017
• **Constellation-Specific SSV Performance Data**: Publishing high-altitude performance characteristics for each GNSS constellation	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 (ST/SPACE/75) 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

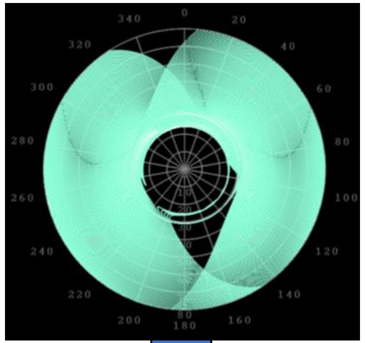
Enabling: The GPS Antenna Characterization Experiment

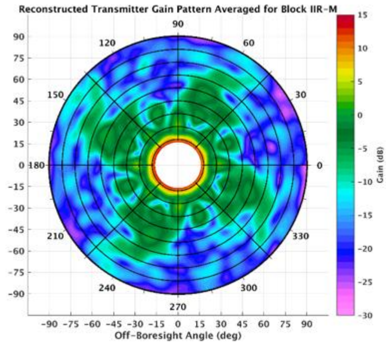
Objective: Complete first ever mapping of the GPS L1 sidelobes for all GPS satellites to determine signal availability for future missions in the Space Service Volume.

- **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



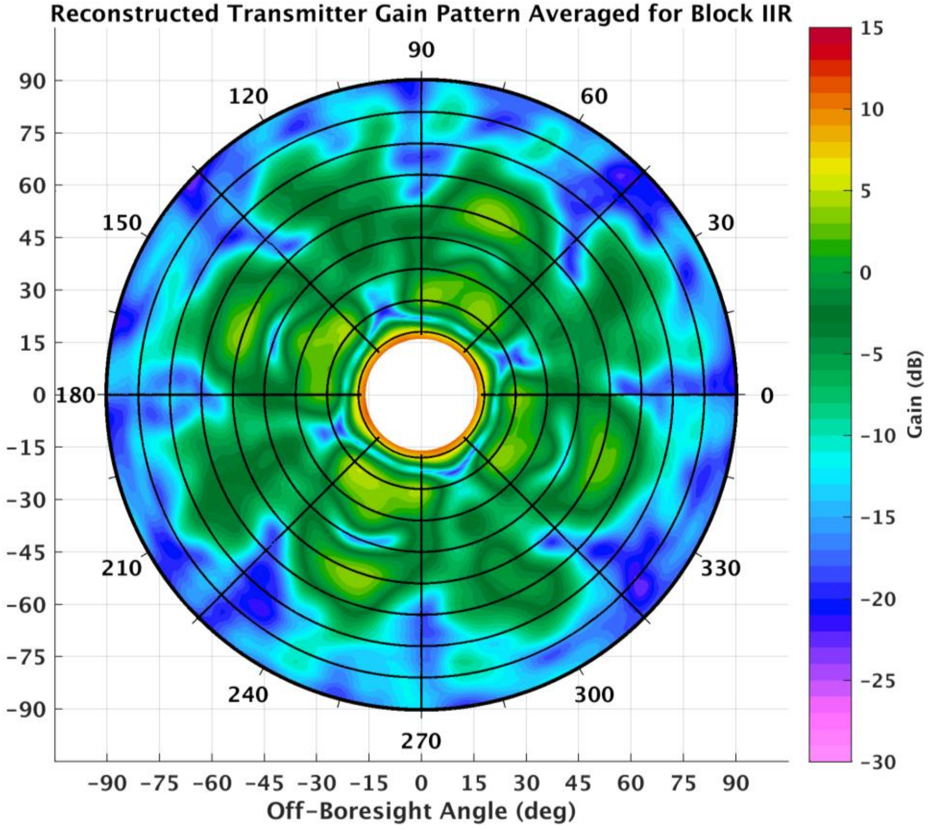




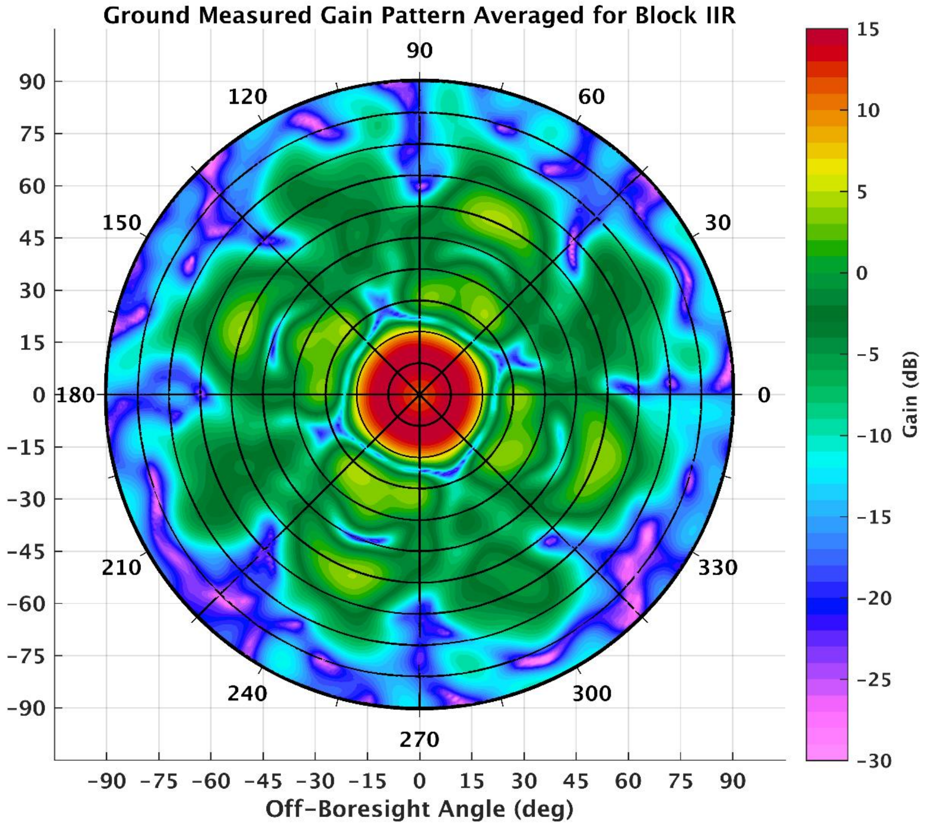
Enabling: Example ACE Results: Average Transmit Gain – Block IIR

- 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

IIR In-Flight Measurements



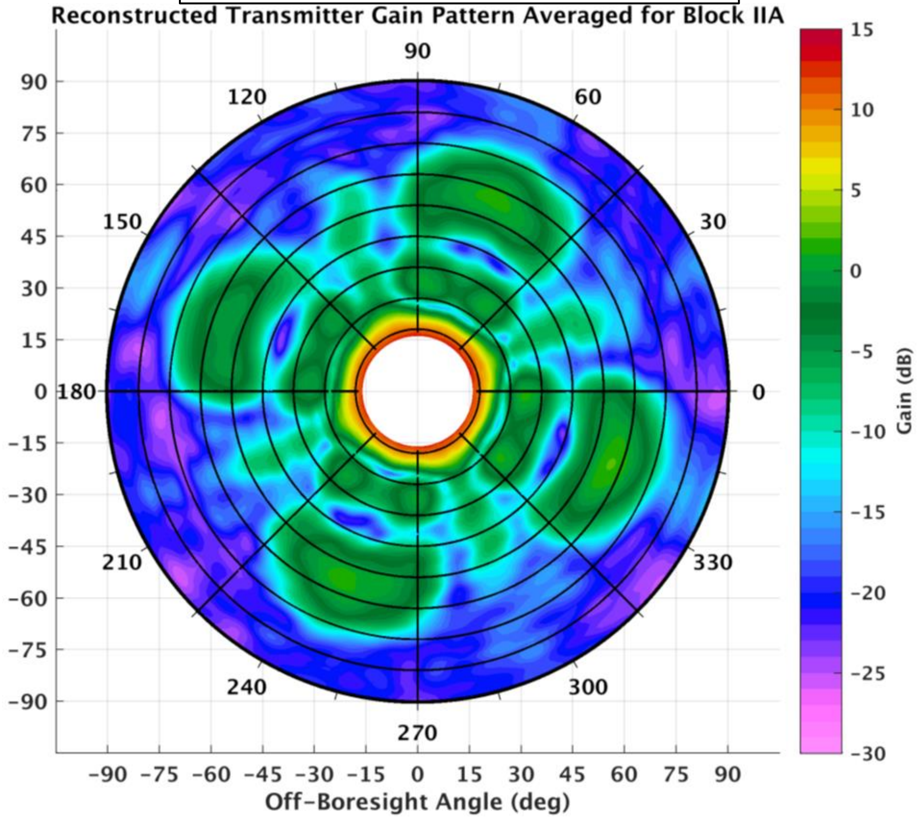
IIR Ground Measurements



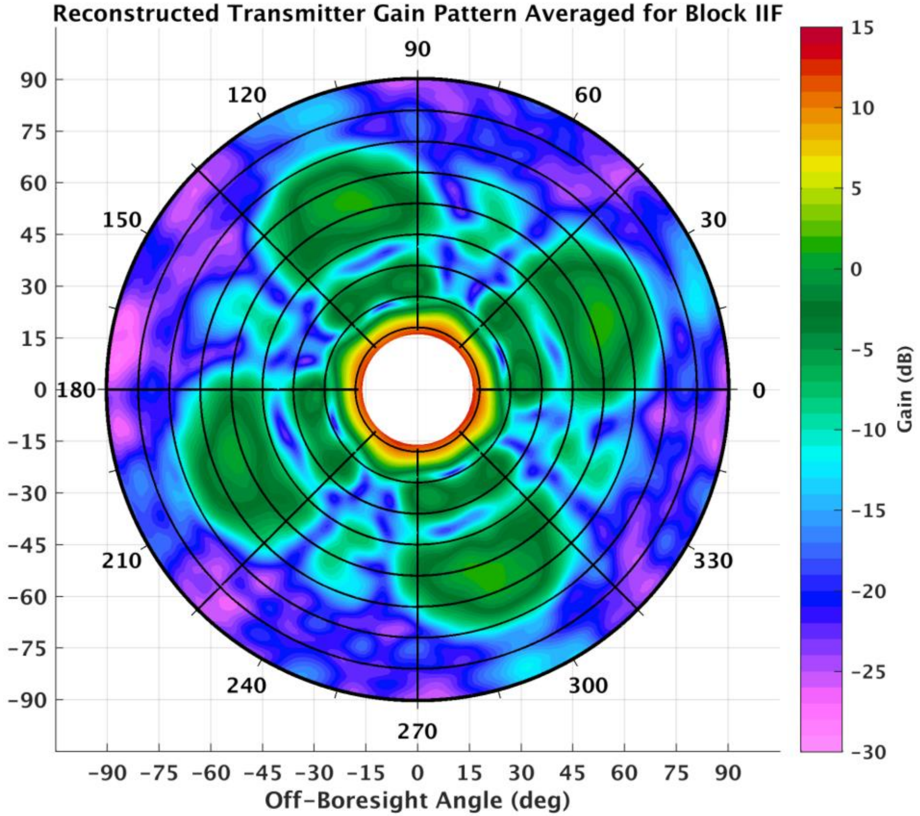
Enabling: Example ACE Results: Average Transmit Gain – Block IIA/IIF

- First full-pattern characterization of blocks 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

IIA In-Flight Measurements



IIF In-Flight Measurements



Enabling: NASA-USAF SSV Collaboration

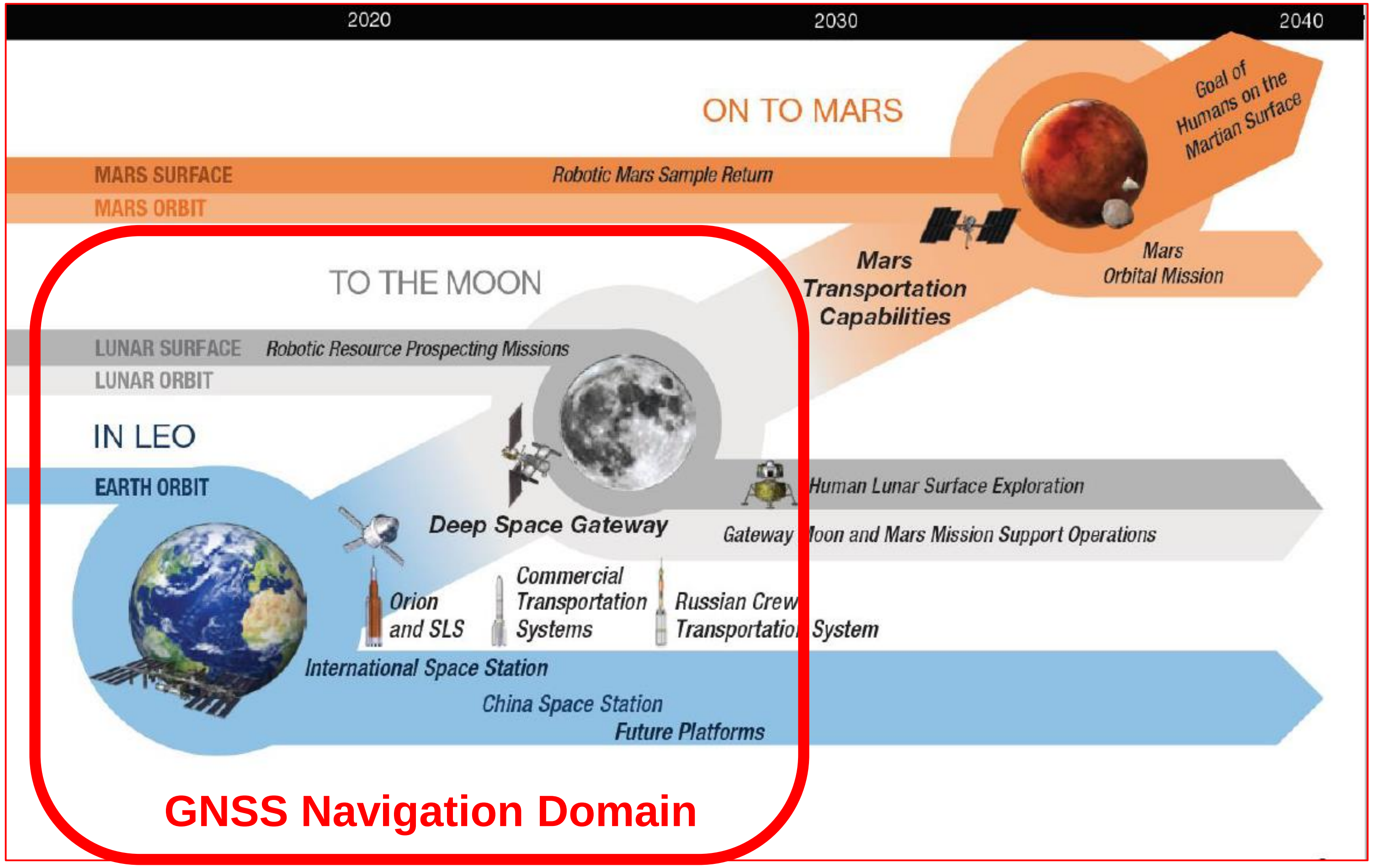
- **Oct 13 2017: Joint NASA-USAF Memorandum of Understanding (MOU)** signed
  - MOU addresses civil Space Service Volume (SSV) requirements
  - Scope relevant to GPS IIIF acquisition process
    - Civil space early insight into Block IIIF design relevant to SSV performance
    - Access to Block IIF, 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

Extending: Renewed Interest in Lunar Exploration

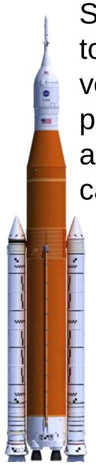
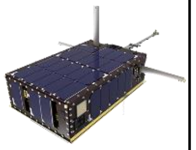
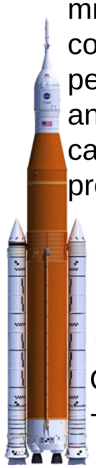
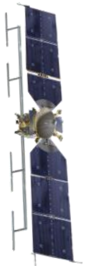
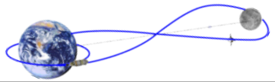
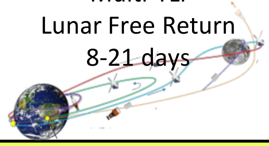
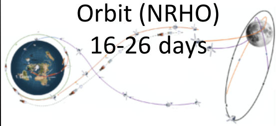
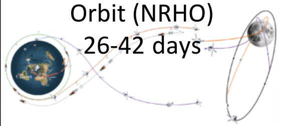
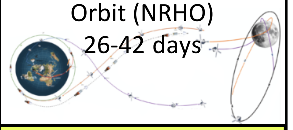
- There is significant global interest in **sustained lunar exploration**; dozens of missions in planning
- US human lunar exploration will continue with **EM-1 and EM-2 in the early 2020s**
- NASA and international partners plan to establish a **Gateway**, a permanent way-station in the vicinity of 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



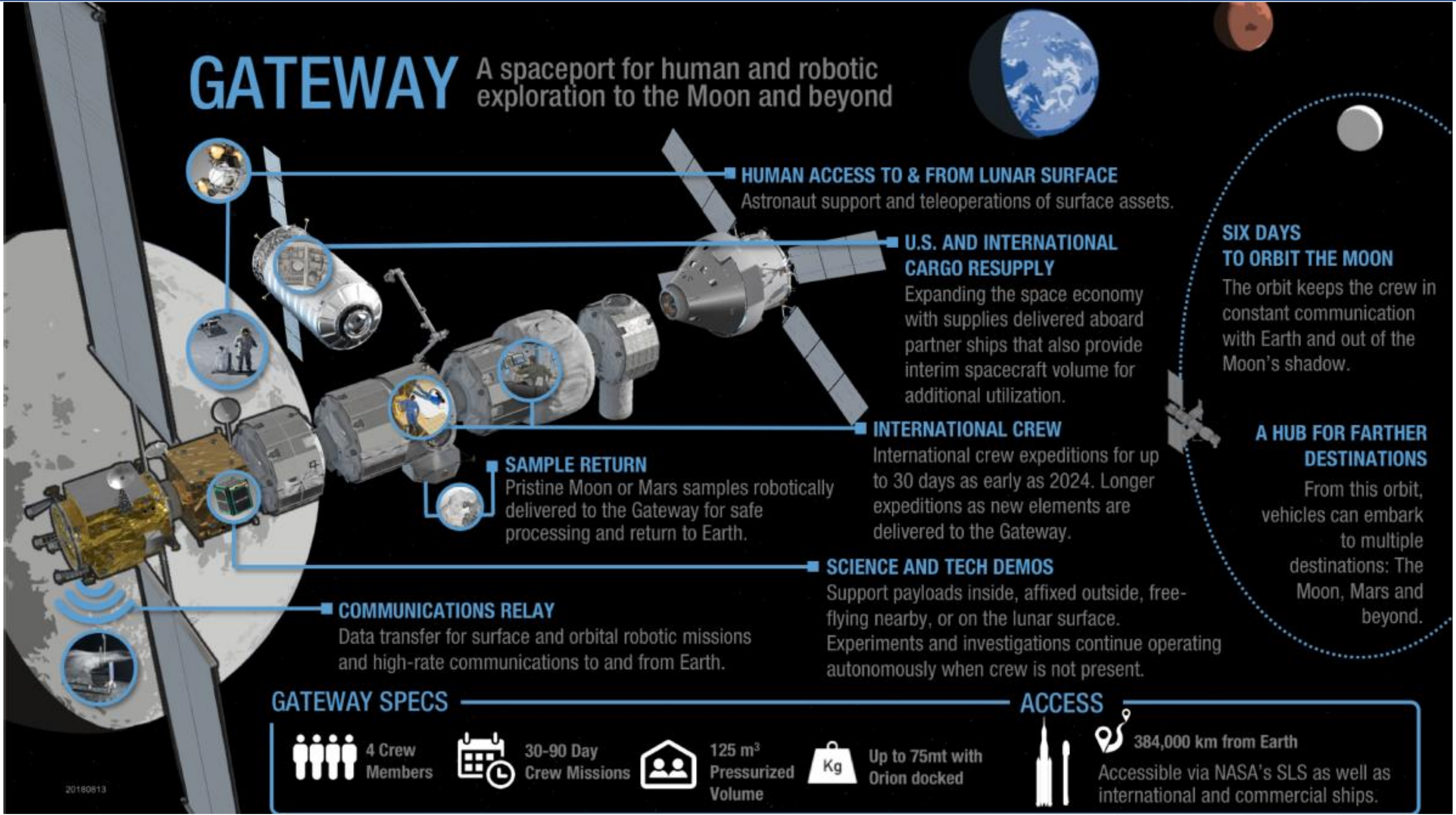
Lunar Missions Represent a Ripe New Frontier for High Altitude GNSS

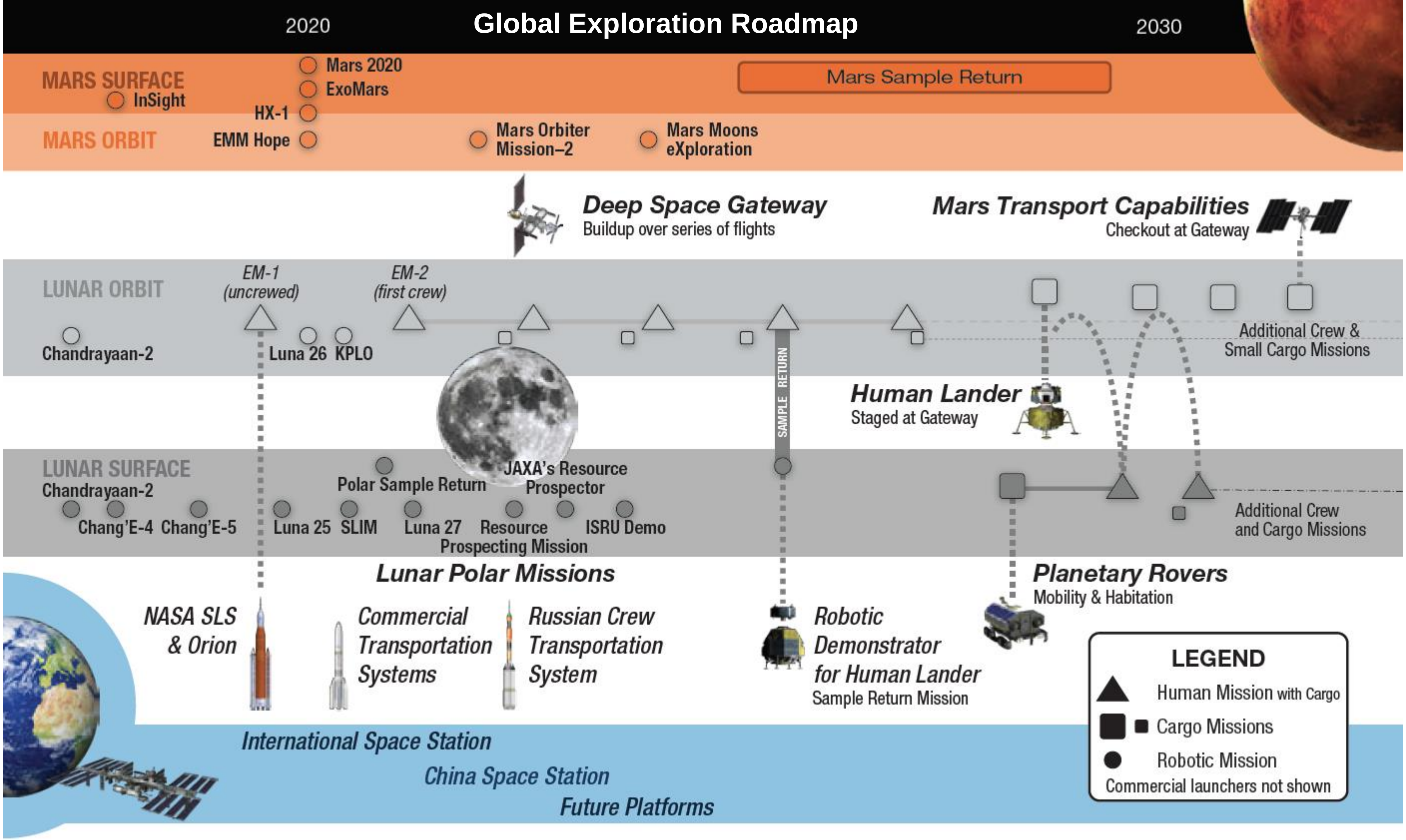
Extending: GPS use aboard Space Launch System

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.

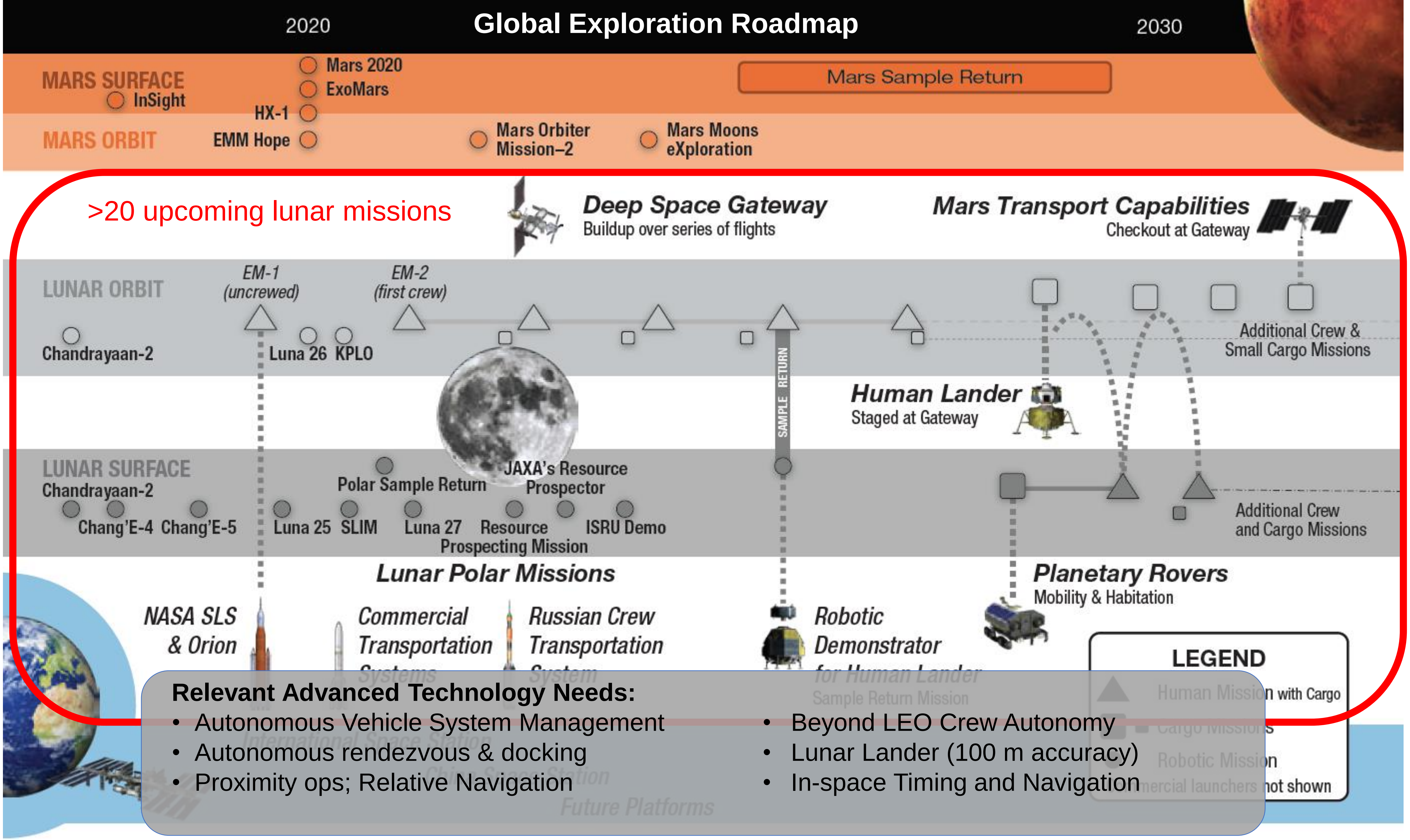
SLS Mission Data is based upon SLS-DDD-284, *Space Launch System Mission Configuration Definition*, Draft Version, October 2018.

Extending: Potential Application: Lunar Orbital Platform—Gateway





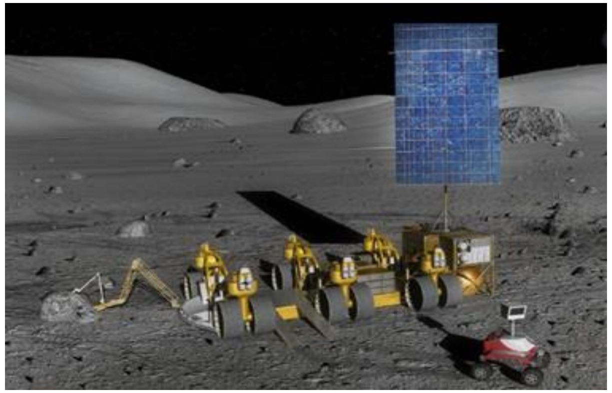
Global Exploration Roadmap
2020
2030
MARS SURFACE
InSight
Mars 2020
ExoMars
HX-1
Mars Sample Return
MARS ORBIT
EMM Hope
Mars Orbiter Mission–2
Mars Moons eXploration
Deep Space Gateway
Buildup over series of flights
Mars Transport Capabilities
Checkout at Gateway
LUNAR ORBIT
EM-1 (uncrewed)
EM-2 (first crew)
Chandrayaan-2
Luna 26
KPLO
Additional Crew & Small Cargo Missions
SAMPLE RETURN
Human Lander
Staged at Gateway
LUNAR SURFACE
Chandrayaan-2
Chang'E-4
Chang'E-5
Luna 25
SLIM
Polar Sample Return
Luna 27
Resource Prospecting Mission
JAXA's Resource Prospector
ISRU Demo
Additional Crew and Cargo Missions
Lunar Polar Missions
Planetary Rovers
Mobility & Habitation
NASA SLS & Orion
Commercial Transportation Systems
Russian Crew Transportation System
Robotic Demonstrator for Human Lander
Sample Return Mission
LEGEND
Human Mission with Cargo
Cargo Missions
Robotic Mission
Commercial launchers not shown
International Space Station
China Space Station
Future Platforms

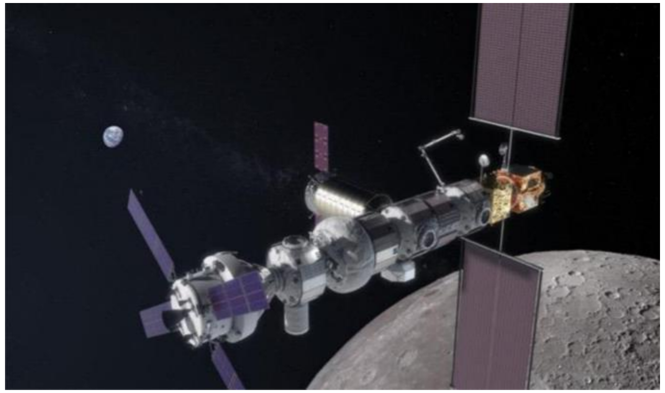


Relevant Advanced Technology Needs:

- 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

Extending: Lunar Exploration Mission Classes Benefited by GNSS Navigation & Timing

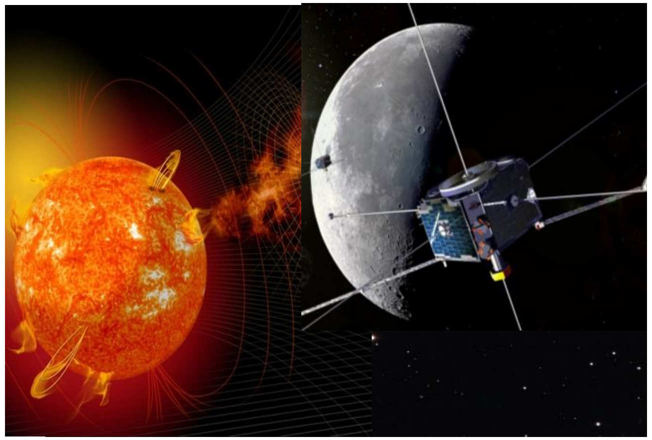


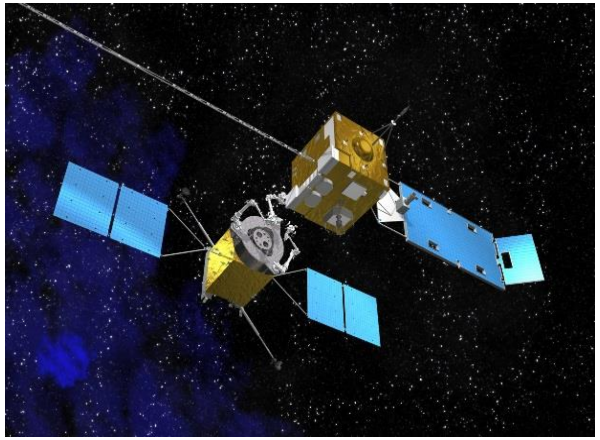


Lunar Surface Operations, Robotic Prospecting, & Human Exploration

Human-tended Lunar Vicinity Vehicles (Lunar Orbital Platform-Gateway)

Robotic Lunar Orbiters, Resource & Science Sentinels





Earth, Astrophysics, & Solar Science Observations

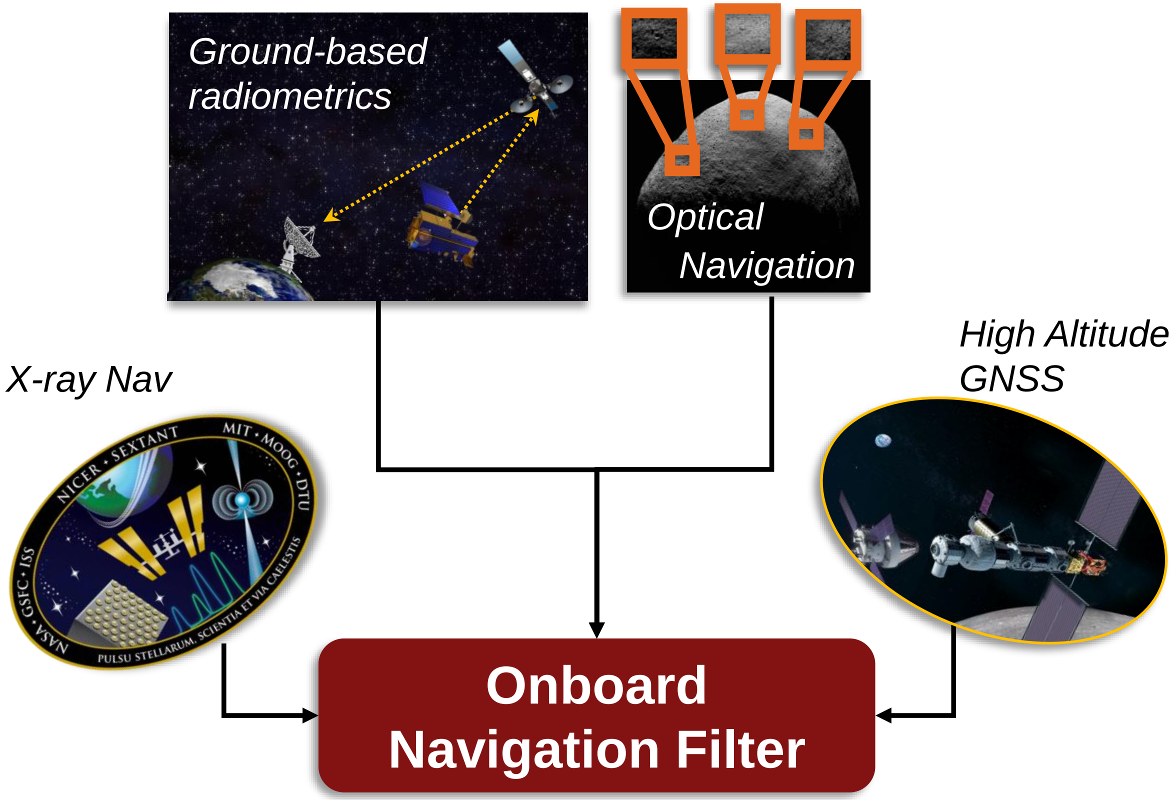
Satellite Servicing

Lunar Exploration Infrastructure

Diversifying: Robust High-Altitude PNT

Robust high-altitude PNT relies on a diversity of navigation sources, each with strengths and weaknesses.

- **GPS + GNSS**
  Work through ICG enables multi-GNSS high-altitude navigation
- **Augmentations**
  Lunar GNSS augmentation architectures and concepts like NASA's Next-Generation Broadcast Services provide dedicated space user augmentation signals
- **Ground-based tracking**
  Periodic ground-based two-way measurements improve overall navigation performance
- **Optical navigation**
  Celestial and terrain-relative optical techniques navigate relative to planetary bodies
- **X-ray pulsar navigation**
  X-ray pulsar navigation acts as "galactic GPS", enabling course navigation anywhere
- **Other sources** (e.g. signals of opportunity, etc.)



Conclusions

- Use of GNSS for navigation & timing in space is now routine at low orbital altitudes
- **High-altitude space use of GNSS,** (i.e. 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 is overcoming high-altitude GNSS technology & political hurdles through:
  - **Operationalizing** high-altitude GNSS in known regimes
  - **Enabling** future development through international collaborations, data availability, and provider support
  - **Extending** the boundaries of GNSS usage in space to lunar vicinity
  - **Diversifying** to enable robust space-based PNT
- The US civil space community looks forward to future collaboration, internally and externally, to make these benefits a reality.

NASA