The Expanding Civil Space User Segment: Reaching for New Frontiers

The Lunar Orbital Platform—Gateway, a potential application of international collaboration on GNSS beyond the SSV

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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
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

<table>
<thead>
<tr>
<th>Year of Activity</th>
<th>Altitude [km]</th>
<th>Altitude [R_E]</th>
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<tbody>
<tr>
<td>GPS 1990's</td>
<td>20,200</td>
<td>3</td>
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<tr>
<td>GEO 2000</td>
<td>36,000</td>
<td>5.6</td>
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<tr>
<td>MMS 1 2001</td>
<td>76,000</td>
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<td>MMS 2 2015</td>
<td>153,000</td>
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<tr>
<td>Moon 2015</td>
<td>378,000</td>
<td>60</td>
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</tbody>
</table>

MMS (Phase 2B) (NASA Navigator)

AMSAT-OSCAR 40 (Trimble TANS Vector)

GOES-16 (GD Viceroy 4)

GIOVE-A (Surrey SGR-GEO)
The Past and Future of High-Altitude GNSS

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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

<table>
<thead>
<tr>
<th>MMS Nav Performance (1σ)</th>
<th>Description</th>
<th>Phase 1</th>
<th>Phase 2B</th>
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<tbody>
<tr>
<td>Semi-major axis est. under 3 RE (99%)</td>
<td>2 m</td>
<td>5 m</td>
<td></td>
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<tr>
<td>Orbit position estimation (99%)</td>
<td>12 m</td>
<td>55 m</td>
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</table>
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

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)
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:

- **SSV Definition/Assumption Maturation**: Adopting the formal definition of the Multi-GNSS SSV
- **Constellation-Specific SSV Performance Data**: Publishing high-altitude performance characteristics for each GNSS constellation
- **Multilateral SSV Analysis**: Conducting an internationally-coordinated analysis of simulated multi-GNSS SSV performance
- **Multi-GNSS SSV Booklet**: Development of a formal UN publication (ST/SPACE/75) defining the Multi-GNSS SSV, its characteristics, benefits, and applications.
- **Beyond SSV studies**: Lunar vicinity GNSS performance and augmentation architecture studies
- **SSV Capabilities Outreach**: Coordinating a joint international outreach activity to raise awareness of the final policy.

Status:
- Completed 2017
- Completed 2015
- Completed 2017
- Completed 2018
- Ongoing
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 SVN 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
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
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**
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
### Extending: GPS use aboard Space Launch System

<table>
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<tr>
<th></th>
<th>EM-1</th>
<th>EM-2</th>
<th>SM-1</th>
<th>EM-3</th>
<th>EM-4</th>
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<td>2023</td>
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<td><strong>Cargo</strong></td>
<td>Block 1: ICPS</td>
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<td>Europa Clipper</td>
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<td>First crewed</td>
<td>First cargo</td>
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<td>Deliver Logistics Module</td>
<td>Deliver Airlock Element</td>
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<td></td>
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<td>- Gateway</td>
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<td><strong>Payloads</strong></td>
<td>13 CubeSat Payloads</td>
<td>Orion Capsule + Crew</td>
<td>Europa Clipper to Jupiter</td>
<td>LOP-G Habitat Module</td>
<td>LOP-G Logistics Module</td>
<td>LOP-G Airlock Element</td>
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<td><strong>Trajectory</strong></td>
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<td>Multi-TLI</td>
<td>Jupiter Direct</td>
<td>Near-Rectilinear Halo</td>
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<td>Orbit (NRHO)</td>
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<td>16-26 days</td>
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<td>Determination, Trans-Lunar</td>
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<td>Injection Burn and End-of-</td>
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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

GATEWAY A spaceport for human and robotic exploration to the Moon and beyond

HUMAN ACCESS TO & FROM LUNAR SURFACE
Astronaut support and teleoperations of surface assets.

U.S. AND INTERNATIONAL CARGO RESUPPLY
Expanding the space economy with supplies delivered aboard partner ships that also provide interim spacecraft volume for additional utilization.

SAMPLE RETURN
Pristine Moon or Mars samples robotically delivered to the Gateway for safe processing and return to Earth.

INTERNATIONAL CREW
International crew expeditions for up to 30 days as early as 2024. Longer expeditions as new elements are delivered to the Gateway.

COMMUNICATIONS RELAY
Data transfer for surface and orbital robotic missions and high-rate communications to and from Earth.

SCIENCE AND TECH DEMOS
Support payloads inside, affixed outside, free-flying nearby, or on the lunar surface. Experiments and investigations continue operating autonomously when crew is not present.

GATEWAY SPECS
4 Crew Members
30-90 Day Crew Missions
125 m² Pressurized Volume
Up to 75mt with Orion docked

ACCESS
384,000 km from Earth
Accessible via NASA’s SLS as well as international and commercial ships.

SIX DAYS TO ORBIT THE MOON
The orbit keeps the crew in constant communication with Earth and out of the Moon’s shadow.

A HUB FOR FARTHER DESTINATIONS
From this orbit, vehicles can embark to multiple destinations: The Moon, Mars and beyond.
>20 upcoming lunar missions

**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
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.