NASA GNSS
Space Use Update

Mr. Joel J. K. Parker, PNT Policy Lead
NASA Goddard Space Flight Center

Mr. J. J. Miller, Deputy Director
Office of Policy and Strategic Communications
NASA Space Communications and Navigation

ICG-15 Working Group B
September 27, 2021
Active Space Uses of GNSS at NASA

- Real-Time On-Board Nav
- Launch Vehicle Range Ops
- Attitude Determination
- Time Synchronization
- Earth Sciences
- Precise Orbit Determination
In accordance with ICG WG-B recommendation: “GNSS Space User Database”, 2016
International Operations Advisory Group

Forum for identifying common needs across multiple international agencies for coordinating space communications policy, high-level procedures, technical interfaces, and other matters related to interoperability and space communications

It undertakes activities it deems appropriate related to multi-agency space communications

Goal to achieve full interoperability among member agencies

For more information: www.ioag.org

ICG-IOAG Collaboration: GNSS Space User Database

- IOAG has observer status in the ICG
- ICG recommendations encourage providers, agencies, and research organizations to publish details of GNSS space users and to contribute to IOAG database
- Database last updated on 13 Nov 2020 for IOAG-24a
- Key changes since previous update (8 Oct 2019):
  - Includes 125 total missions from 8 agencies + affiliates
  - Now includes historical data from decommissioned/descoped missions
- We continue encouraging service providers, space agencies and research institutions to contribute to the GNSS space user database via their IOAG liaison or ICG WG-B

IOAG Missions & Programs Relying on GNSS

<table>
<thead>
<tr>
<th>Agency*</th>
<th>Country</th>
<th>2019</th>
<th>2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASI</td>
<td>Italy</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>CNES</td>
<td>France</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>CSA</td>
<td>Canada</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>DLR</td>
<td>Germany</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>ESA</td>
<td>Europe</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japan</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>KARI</td>
<td>Republic of Korea</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>NASA</td>
<td>USA</td>
<td>44</td>
<td>46</td>
</tr>
</tbody>
</table>

*Includes affiliated organizations

https://www.ioag.org/Public Documents/Aggregate IOAG Missions Using GNSS 2020-11-13 (IOAG-24a).xlsx?d=wb2386aa737a443e5abea027305e01dbd
### Selected US Mission Database Updates

<table>
<thead>
<tr>
<th>№</th>
<th>Agency</th>
<th>Mission</th>
<th>GNSS System/s Used</th>
<th>GNSS Signals Used</th>
<th>GNSS Application</th>
<th>Orbit</th>
<th>Launch (Actual or Target)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>NASA</td>
<td>Orion</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit / navigation</td>
<td>LEO</td>
<td>2014 - Earth Orbit, 2021 Cislunar</td>
<td>Honeywell Aerospace 'Mercury' SPS GPS receiver with GSFC 'Navigator&quot; software.</td>
</tr>
<tr>
<td>86</td>
<td>CNES/NASA</td>
<td>Jason-3</td>
<td>GPS, GLONASS</td>
<td>L1 C/A, L1/L2</td>
<td>Precise Orbit Determination, Oceanography</td>
<td>LEO</td>
<td>1/17/2016</td>
<td>IGOR+ (BlackJack) receiver</td>
</tr>
<tr>
<td>88</td>
<td>NASA</td>
<td>GOES-16</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>GEO</td>
<td>11/19/2016</td>
<td>General Dynamics Viceroy-4</td>
</tr>
<tr>
<td>92</td>
<td>NASA/ESA</td>
<td>Sentinel-6, 2 SATELLITES</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, semi-codeless P2, L5</td>
<td>Occultation, Precise Orbit Determination</td>
<td>LEO</td>
<td>2020 and 2025</td>
<td>TriG receiver with MIL-STD-1553 interface</td>
</tr>
<tr>
<td>99</td>
<td>NASA/ISRO</td>
<td>NISAR</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, semi-codeless P2, L5</td>
<td>Precise Orbit Determination, timing</td>
<td>LEO</td>
<td>Sep. 2020</td>
<td>TriG Lite receiver</td>
</tr>
<tr>
<td>100</td>
<td>NASA/CNES</td>
<td>SWOT</td>
<td>GPS, GLONASS, Galileo</td>
<td>L1 C/A, L2C, L5, Galileo, GLONASS FDMA</td>
<td>Precise Orbit Determination - Real Time</td>
<td>LEO</td>
<td>Apr. 2022</td>
<td>TriG receiver with MIL-STD-1553 interface</td>
</tr>
</tbody>
</table>

Red = updated in this release
## Selected US Mission Database Updates

<table>
<thead>
<tr>
<th>Nº</th>
<th>Agency</th>
<th>Mission</th>
<th>GNSS System/s Used</th>
<th>GNSS Signals Used</th>
<th>GNSS Application</th>
<th>Orbit</th>
<th>Launch (Actual or Target)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>107</td>
<td>NASA</td>
<td>GOES-17</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>GEO</td>
<td>3/1/2018</td>
<td>General Dynamics Viceroy-4</td>
</tr>
<tr>
<td>108</td>
<td>NASA</td>
<td>GOES-T</td>
<td>GPS</td>
<td>L1 C/A</td>
<td>Orbit</td>
<td>GEO</td>
<td>Dec. 2021</td>
<td>General Dynamics Viceroy-4</td>
</tr>
<tr>
<td>115</td>
<td>NASA</td>
<td>Bobcat-1</td>
<td>GPS, GAL, GLO, BDS, QZSS, NavIC</td>
<td>GPS L1 C/A, L1C, L2C, L2P, L5 GLONASS L1, L2, L3, L5 BeiDou B1I, B1C, B2a, B2I, B3I Galileo E1, E5 AltBOC, E5a, E5b, E6 SBAS L1, L5 QZSS L1 C/A, L1C, L2C, L5, LEX NavIC (IRNSS) L5</td>
<td>Orbit, time</td>
<td>Ei (ISS)</td>
<td>2020</td>
<td>NovAtel OEM719 GNSS receiver</td>
</tr>
<tr>
<td>116</td>
<td>NASA</td>
<td>SunRISE</td>
<td>GPS, possibly others</td>
<td>L5 or L2C</td>
<td>Absolute and relative positioning of 6 6U cubesats, precise time transfer</td>
<td>GEO graveyard</td>
<td>2024?</td>
<td></td>
</tr>
<tr>
<td>117*</td>
<td>NASA/ASI</td>
<td>LuGRE</td>
<td>GPS, Galileo</td>
<td>GPS L1 C/A, L5 Galileo E1, E5a</td>
<td>Orbit, time</td>
<td>O</td>
<td>2023</td>
<td>NASA/ASI collaborative payload on Firefly Blue Ghost Mission 1 to demonstrate GNSS-based PNT during Earth-Moon transit, in lunar orbit, and on the lunar surface. Incorporates Qascom lunar receiver.</td>
</tr>
</tbody>
</table>

Red = updated in this release

*Added in upcoming database update
Source:
“GPS Constellation Modernization Impact on Sidelobe Capable GPSR in GEO”,
ENC 2021, paper #223
Graeme Ramsey
Jim Chapel
Mark Crews
Douglas Freesland
Alexander Krimchansky
Background: GOES-R Satellites

• Geostationary Operational Environmental Satellite, R series
  – Earth-observing and Sun-observing instruments
  – The GOES-R spacecraft provide dramatic improvements in geostationary (GEO) weather observation capabilities over the previous generation
• Two GOES-R satellites currently on-orbit, GOES-16 (East) and GOES-17 (West)
• GD Viceroy GPSR and LNA
  – 12-channel L1 C/A Receiver
  – Internal EKF Nav solution output
• LM designed GPS L1 Rx antenna
  – Peak gain at ~20 deg off-boresight
• Signal capabilities
  – Sidelobe capable
  – Signals on the order of 10^{-18} W
• Benefits of GPSR
  – Vehicle position, velocity and time (PVT) knowledge is improved
  – Demand upon ground support is reduced
  – Real-time PVT available to the Flight Software increases automaton
GPS Block-Type Tx Antenna Patterns

Average

Maximum

Gain (dBi)

Off GPS Boresight (deg)

IIR L1
IIRM L1
IIF L1
III L1
Block-Type Tracking

GOES-16

Data: March 15th - 17th 2021

GOES-17

G. Ramsey

GPS Modernization Impact on Sidelobe Capable GPSR at GEO

ESA GNC Conference June 2021
GPS Modernization Impact on Sidelobe Capable GPSR at GEO

GOES-16

Data: March 15th - 17th 2021

GOES-17
GPS III tracks add good diversity of geometry at reasonable power levels.

The modernized constellation should continue to provide usable sidelobe signals to the GOES-R GPSR system resulting in nominal performance.
Artemis

Source:  
Dr. Benjamin Ashman,  
“Applications and Benefits of GNSS for Lunar Exploration”,  
SpaceOps 2021
NASA Lunar Exploration Activities

Artemis
• Series of SLS launches carrying the Orion crew capsule that will return humans to the surface of the Moon

Gateway
• Orbiter in cislunar space that will serve as a platform for science and technology payloads as well as a crew staging point for lunar surface or deep space missions

Commercial Lander Payload Services (CLPS)
• Robotic precursor landers designed for tech. demonstration and science that will pave the way for crewed missions
ARTEMIS I
The First Uncrewed Integrated Flight Test of NASA’s Orion Spacecraft and Space Launch System Rocket

1. LAUNCH
   SLS and Orion lift off from pad 39B at Kennedy Space Center.

2. JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM
3. CORE STAGE MAIN ENGINE CUT OFF
   With separation.

4. PERIGEE RAISE MANEUVER
5. EARTH ORBIT
   Systems check with solar panel adjustments.

6. TRANS LUNAR INJECTION (TLI) BURN
   Maneuver lasts for approximately 20 minutes.

7. INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL
   The ICPS has committed Orion to TLI.

8. OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS
   As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).

9. OUTBOUND POWERED FLYBY (OPF)
   60 nmi from the Moon; targets DRO insertion.

10. LUNAR ORBIT INSERTION
    Enter Distant Retrograde Orbit.

11. DRO DEPARTURE
    Leave DRO and start return to Earth.

12. RETURN POWERED FLYBY (RPF)
    RPF burn prep and return coast to Earth initiated.

13. RETURN TRANSIT
    Return Trajectory Correction (RTC) burns as necessary to aim for Earth’s atmosphere.

14. CREW MODULE SEPARATION
    FROM SERVICE MODULE

15. ENTRY INTERFACE MODULE

16. SPLASHDOWN
    Pacific Ocean landing within view of the U.S. Navy recovery ship.

Source [3]
Orbit Determination Toolbox (ODTBX) simulation of GPS signal availability over Artemis I trajectory

- Signal available/visible if received C/N0 exceeds receiver acquisition/tracking threshold
- GPS constellation modeled using per-vehicle Antenna Characterization Experiment side lobe patterns and per-block public main lobe data, calibrated with MMS and GOES-16 flight data
- Four antennas around Orion capsule nose, receiver and antenna properties calibrated with EFT-1 flight data

Signal availability is only part of the story, but it’s clear **antenna placement and pointing are critical for feasibility** of GNSS at the Moon

Baseline case in red models planned configuration for Artemis I. Alternate configurations illustrate potential availability with changes to hardware and/or pointing.
Lunar Gateway

- Considered performance on Gateway of MMS-like navigation system with Earth-pointed high-gain antenna (~14 dBi) and Goddard Enhanced Onboard Navigation System (GEONS) flight filter software
- Calibrated with flight data from MMS Phase 2B
  - GPS constellation modeled with per-vehicle GPS ACE patterns, IGS yaw model, solar noise model
- L2 southern Near Rectilinear Halo Orbit (NRHO), 6.5 day period
- Cases for both crewed and uncrewed perturb. models:
  - GPS only with Rubidium Atomic Frequency Standard (RAFS)
  - DSN only without atomic clock
  - GPS + DSN

Ground tracking assumptions
- Three contacts per orbit (uncrewed) or continuous (crewed)
- Data Cutoff (DCO) 24 hrs before orbit maintenance maneuvers

Ground tracking sim. parameters

<table>
<thead>
<tr>
<th>Noise/Bias Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Rate</td>
<td>10 s</td>
</tr>
<tr>
<td>Range Noise</td>
<td>1.0 m (1-sigma)</td>
</tr>
<tr>
<td>Range Bias</td>
<td>2.5 m (1-sigma)</td>
</tr>
<tr>
<td>Doppler Noise</td>
<td>0.33 mm/s (1-sigma)</td>
</tr>
</tbody>
</table>
Lunar Gateway

- Position and velocity goals: 10 km and 10 cm/s, respectively
- 70 Monte Carlo cases
- Evaluated max OD error at the Data Cutoff (DCO) and at the final two perilunes and apolunes
- Observations:
  - Under our assumptions, analysis shows GPS can provide greatly improved performance vs. DSN, on-board, in real-time, without reliance on ground-based assets.

Crewed: Max steady-state errors

<table>
<thead>
<tr>
<th>Position [m]</th>
<th>Case</th>
<th>DCO</th>
<th>Apolune</th>
<th>Perilune</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DSN</td>
<td>1469.7</td>
<td>1326.4</td>
<td>319.8</td>
<td>2353.6</td>
</tr>
<tr>
<td></td>
<td>GPS</td>
<td>60.4</td>
<td>84.5</td>
<td>73.0</td>
<td>118.7</td>
</tr>
<tr>
<td></td>
<td>DSN+GPS</td>
<td>57.7</td>
<td>81.7</td>
<td>107.0</td>
<td>117.4</td>
</tr>
</tbody>
</table>
Lunar GNSS Receiver Experiment (LuGRE)

Source:
Mr. Joel J. K. Parker, LuGRE PI
joel.j.k.parker@nasa.gov
LuGRE Mission Overview

Mission
- NASA HEOMD payload for CLPS “19D” flight
- Joint NASA/Italian Space Agency mission
- “Do No Harm” class
- Firefly Blue Ghost commercial lander
- Transit + surface observation campaign
- Expected surface duration: one lunar day (~12 Earth days)

Payload objectives
1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
3. Utilize collected data to support development of GNSS receivers specific to lunar use.

Measurements
- GPS+Galileo, L1/L5 (E1/E5)
- Onboard products: multi-GNSS point solutions, filter solutions
- Observables: pseudorange, carrier phase, raw baseband samples

Utilization
- Data + lessons learned for operational lunar receiver development
- Potential collaborative science: heliophysics, lunar geodesy
- Lunar human and robotic real-time onboard PNT

Payload Delivery
- ASI-provided payload
- Qascom receiver

Timeline:
- CLPS Lander Award: Feb 2021
- LuGRE SRR: Apr 2021
- ETU Delivery: Oct 2021
- LuGRE CDR: Sept 2021
- FM Delivery: early 2022
- Payload Delivery: NLT Nov 1, 2022
- Launch+Ops: Jul–Sep 2023
- Analysis: late 2023
1) CLPS-19D Mission
Launch mid-2023
(Launch provider = SpaceX)

2) Phasing Orbits
(1.5–4.5 orbits in 15-49 days)

3) Lunar Phasing Orbits
(2–12 days)

4) Powered Descent

5) Continuous GNSS Data Collection
Antenna deployed, Earth-tracking
12 Earth days primary mission
2x baseband sample collection opportunities

6) LuGRE Data
(Downlink X-band 10 Mbps via reorient)

7) Joint Operations
GPS and Galileo

8) LuGRE Data
(Downlink X-band 10 Mbps)

9) Public Distribution
Mare Crisium
18° N, 62° E

Firefly “Blue Ghost” Lander
LuGRE antenna
(Co-located w/ lander X-band ant.
Earth pointing via gimbal)

LuGRE receiver and
FEA (internal)
LunaNet

Source:
Mr. Andrew Petro, NASA Space Communications and Navigation (SCaN)
Communication and navigation infrastructure lowers the barriers to entry for new missions and capabilities and supports expanding robotic and human activities on the Moon.

September 2021
Networking Services (Data Transmission)
Data transmitted to Earth in real time or aggregated and transmitted in store-and-forward mode
Data exchange among lunar users (avoid transfer to and from Earth)
Multiple relays used interchangeably, as needed

PNT Services (Position, Navigation, Timing)
LunaNet nodes generate and exchange PNT information
Nodes can share PNT data to support and enhance their operations

Messages, Alerts, Radio/Optical Science
LunaNet nodes can host sensors and disseminate space weather alerts, conjunction alerts and science measurements

September 2021
Lunar Communications and Navigation Interoperability Standards

In collaboration with other agencies, international partners and private companies, NASA is seeking to define a framework of mutually agreed-upon standards to be applied by lunar users and service providers in a set of cooperating networks. The framework would apply to communication transmission services for science, exploration and commercial operations, distribution of navigation and timing references, and sharing of information. These standards can be introduced as part of the earliest missions and accommodate expansion as new commercial and government users and service providers join in an open and evolving architecture.

An initial version of these proposed standards has been drafted and can be found at the link below. https://go.nasa.gov/3BQrCOk
Technology Updates
Autonomous Flight Termination System (AFTS)

Source:
Ms. Lisa Valencia, Senior Systems Engineer, Overlook Systems Technologies
Autonomous Flight Termination

NASA, in partnership with DARPA, built an Autonomous Flight Termination Unit

- Box on the vehicle (AFTU)
  - Uses Tracking data from GPS and INS/IMU sensors
  - Rule set built in pre-flight period
  - If a rule is violated the flight is terminated
- Radar and Command stations recede into past
- Telemetry down-link drops from safety critical to situational awareness, post-flight analysis, & mishap investigation

Advantages
- Cost reduction due to decreased need for ground-based assets
- Global coverage (vehicle does not have to be launched from a range)
- Increased launch responsiveness
- Boundary limits increase
- Can support multiple vehicles simultaneously (such as flyback boosters)

NASA performed Qualification and Certification of the AFTU HW & SW

- The NASA/DARPA AFTU has been flying operationally since Dec 2019
- Prior to operational use, NASA performed many shadow flights of the AFTU including:
  - UP Aerospace SL-14 (last shadow flight before operational use)
  - NASA AFTU with integrated GPS receivers
  - Note: As a secondary experiment, a stand-alone ASI/Qascom GARHEO multi-GNSS (GPS + Galileo) signal recorder was flown in record-only mode to evaluate the receiver’s performance in a highly dynamic launch environment – it was not integrated with the AFTU and no data was transmitted in real-time. The mission was a success, and the receiver performed nominally.
SL-15 Launch with AFTS and GNSS

- NASA has two International Agreements with the Italian Space Agency (ASI) and with the European Space Agency (ESA) to fly two GPS-Galileo receivers on a sounding rocket
- Builds on the success of the SL-14 launch
  https://www.youtube.com/watch?v=fE_S88wzWzM
- SL-15 Objective: Assess GPS-Galileo performance in a highly dynamic environment, including potential to augment GPS in range safety system
- Includes two multi-GNSS receivers, one GPS receiver, and two AFTUs on UP Aerospace Space Loft (SL)-15 sounding rocket

SL-15 Mission provided by NASA’s Flight Opportunities Program:
- Scheduled for launch in March 2022 from Spaceport America, NM
- Utilizing L1/E1/L2/E5a

Mission profile
- Launch and boost phase (12 s)
- Ascent coasting until 100 km Apogee
- Descent, re-entry, and landing
- Total duration: 13 minutes
- Maximum speed: 1400 m/s
- Maximum acceleration: 13.5 G
- Maximum Spin rate: 7 Hz
ESA/Fraunhofer GOOSE Receiver:
- **Weight:** 1.591 kg
- **Size:** 6.9 cm x 12.0 cm x 14.55 cm
- **Power:** 15W, 1.67A, 12V

ASI/Qascom GARHEO Receiver:
- **Weight:** 0.7 Kg
- **Size:** 16.8cm x 12.6cm x 3.5 cm
- **Power:** 5W, 1A, 5V

AFTU:
- **Weight:** 1.3kg
- **Size:** 5cm X 14cm X 19cm
- **Power:** 7W, 5.5A, 28V DC

Javad Receiver:
- **Weight:** 1.3kg
- **Size:** 2cm X 5cm X 8cm
- **Power:** 5.3W, 5.3A, 28V DC

SL-15 Multi-GNSS Payload Hardware
Receiver Development

Source:
TriG/Cion: Dr. Yoaz Bar-Sever, Jet Propulsion Laboratory, California Institute of Technology
NavCube: Mr. Munther Hassouneh, NASA Goddard Space Flight Center
Continuing a Long Legacy of Remote Sensing and Navigation Space Receivers

12 Trig-class receivers successfully operating in space

Cosmic-2: Navigation + RO
Sentinel-6: Navigation + RO
Jason-3: Navigation

Deep Space Atomic (DSAC):
Navigation and ultra-precise timing
(https://www.nature.com/articles/s41586-021-03571-7.pdf)

GRACE FO: Navigation,
crosslink interferometry, RO

Cion - A new Low-Cost, High Performance Class of GNSS Science Receivers
• TriG technology heritage but with low-cost, low-power components
• High-performance, high-reliability RTGx navigation software
• Radio occultation version flying on GeoOptics’ Cicero cubesats since 2017

Will provide navigation and timing in geosynchronous orbits for SunRISE and NTS-3
• Weak signal capability
• Multi GNSS, multi-frequency
• Survey GNSS SSV signals

Upcoming missions relying on the Trig

NISAR (2022): Navigation
SWOT (2022): Navigation
NTS-3 Experimental GPS satellite (2023)
NavCube 3.0 mini GNSS Receiver

NavCube 3.0 mini (NC3m)
- Low SWaP-C GNSS receiver appropriate for all orbit regimes including cislunar space and lunar orbit
- Rad-hard RF front-end card
- Wide-band, dual-frequency RF card provides GPS L1 C/A and either L2C or L5
  - Galileo E1 and E5a also possible for additional SWaP-C
- Supports onboard or an external reference clock
- Builds on proven GSFC MMS Navigator flight heritage
  - Fast acquisition/weak signal acquisition capabilities
  - Currently operating at 29.3 Re (halfway to the moon)
- On-orbit upgradeable software and firmware adaptable to new mission types and operations concepts
- Integrated Goddard Enhanced Onboard Navigation System (GEONS) navigation filter provides multi-sensor fusion and prediction onboard

Status
- NC3m is currently in development
- Standalone version of NC3m will be TRL6 in February 2022 (estimated)
Enabling the SSV

- NASA-USAF Memorandum of Understanding
  - Signed in 2017 to ensure SSV signal continuity for future space users
  - NASA representative in the GPS IIIF procurement cycle

- GPS data released to public
  - Late 2020: IIR/IIR-M antenna gain pattern data (re-release)
  - Late 2020: GPS III SVN 74-77 phase center, group delay, and inter-signal bias data
    - Response to request from ICG IGMA Task Force
  - USSF Space and Missile Systems Center (SMC) assessing public release of all available GPS data (Blocks IIR through III SV1–10)

https://www.navcen.uscg.gov/?pageName=gpsTechnicalReferences

Conclusions

• NASA reports GNSS use on at least 40 current and future missions in every orbit regime, including LEO, GEO, HEO, and soon lunar.

• Ongoing technology development targets high-precision, high-altitude, and high-dynamic use cases.

• Lunar PNT remains the next frontier in space use of GNSS. NASA is pursuing this capability via multiple open, collaborative activities, including Artemis, LuGRE, and LunaNet.

• Policy coordination, including via the ICG, enables robust utilization of GNSS in space.
Backup
IOAG Database of GNSS Missions

• The full “Aggregate IOAG Missions Using GNSS” is available at:

https://www.ioag.org/Public%20Documents/Aggregate%20IOAG%20Missions%20Using%20GNSS%202020-11-13%20(IOAG-24a).xlsx?d=wb2386aa737a443e5abea027305e01dbd

• Also embedded here:
Signal Reception in the Space Service Volume (SSV)

- Main lobe signal
- Side lobe signal
- Earth shadowing
- MEO/GNSS Altitude - 20,000 km
- GEO Altitude - 36,000 km
GPS Constellation Modernization Impact on Sidelobe Capable GPSR in GEO

Graeme Ramsey
Jim Chapel
Mark Crews
Douglas Freesland
Alexander Krimchansky

ESA GNC 2021: Paper #223
• GPS Constellation Modernization Impact on Sidelobe Capable GPSR at GEO

• Heritage and modern GPS transmit pattern comparison

• Relevant signal requirements as it pertains to GEO GPSR facilitation

• GOES-R GPSR acquisition and tracking characterization regarding the first four operational GPS III vehicles
Background: Orbit, Attitude and Signal Regimes
# GPS Modernization Impact on Sidelobe Capable GPSR at GEO

**ESA GNC Conference June 2021**

G. Ramsey

#223

## GPS History

- First SV launched in 1978, fully operational in 1993, civilian use w/o impediments in 2000, first GPS III launched in 2018

## Current GPS Constellation Status

- 31 operational satellites
- 8 IIR, 7 IIR-M, 12 IIF and 4 III block-types

## GPS III

- The GPS III program includes 10 space vehicles (SVs)
- Six GPS III SVs awaiting launch, available for launch, or in production
- Performance improvements: 8x better anti-jamming, 3x better ground accuracy, 15 year life (+25%), L1C signal

### Background: GPS Modernization

<table>
<thead>
<tr>
<th>GPS III SV</th>
<th>01</th>
<th>02</th>
<th>03</th>
<th>04</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVN</td>
<td>74</td>
<td>75</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td>PRN</td>
<td>04</td>
<td>18</td>
<td>23</td>
<td>14</td>
</tr>
<tr>
<td>Orbit Slot</td>
<td>F4</td>
<td>D6</td>
<td>E5</td>
<td>B6</td>
</tr>
</tbody>
</table>
GOES-16 and GOES-17 On-Orbit Data

- Data presented in this section are from both GOES-16 (East Station) and GOES-17 (West Station) over common time spans.

- Stations
  - East Station: 75.2 West longitude
  - West Station: 137.2 West longitude
  - Delta in the repeatable geometry between the vehicles

- Time spans
  - March 15th - 17th 2021
  - Two days of data allows for two repeatable relative geometry cycles
GPSIII Tracking Skyplots

GOES-16

PRN 4
PRN 14
PRN 18
PRN 23

Elevation (deg)
Azimuth (deg)

GOES-17

PRN 4
PRN 14
PRN 18
PRN 23

Elevation (deg)
Azimuth (deg)
Previously Defined GOES-R GPSR Navigation Performance

![Graph showing position difference over time with radial, in-track, and cross-track tracking, along with a table summarizing performance metrics for position and velocity.](image)

### Previously Defined GOES-R GPSR Navigation Performance

<table>
<thead>
<tr>
<th>Metric</th>
<th>Radial</th>
<th>In-Track</th>
<th>Cross-Track</th>
<th>SEP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Position (m)</strong></td>
<td>max</td>
<td>mean</td>
<td>max</td>
<td>R61</td>
</tr>
<tr>
<td></td>
<td>23.2</td>
<td>2.6</td>
<td>11.2</td>
<td>8.4</td>
</tr>
<tr>
<td><strong>Velocity (cm/s)</strong></td>
<td>0.42</td>
<td>0.02</td>
<td>0.91</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>0.4</td>
<td>0.28</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>0.09</td>
<td>0.09</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>
The overall on-orbit GEO GPSR sidelobe tracking performance continues to be more than sufficient to support the GOES-R mission needs regardless of block-type.

The impact due to the GPS III transmit pattern gain decrease above 40 degrees off GPS boresight is mitigated in part by the design of the GOES-R GPS receive antenna and otherwise by the robustness of the GPSR system.

All future GEO satellites using GPSR need to take into consideration changes in the constellation makeup and the resulting performance implications, particularly with regard to the receive antenna design, and GPSR acquisition and tracking sensitivity thresholds.
Commercial Lunar Payload Services (CLPS)

- Intuitive Machines 1 (2021)
- VIPER (2022)
- PRIME-1 (2022)
- Masten Mission 1 (2022)
- Peregrine Mission 1 (2021)
- Blue Ghost 1 (2023)

Image source [4]
Lunar Exploration: Roles for GNSS

- Lunar Surface Operations, Robotic Prospecting, & Human Exploration
- Human-tended Lunar Vicinity Vehicles (Gateway)
- Robotic Lunar Orbiters, Resource & Science Sentinels
- Earth, Astrophysics, & Solar Science Observations
- Satellite Servicing
- Lunar Exploration Infrastructure
Blue Ghost 1

- Firefly Aerospace Systems awarded CLPS 19D flight in Feb. 2021
- Launching July 2023 and landing in Mare Crisium near Mons Latreille
- 10 NASA payloads including the Lunar GNSS Receiver Experiment (LuGRE)
- Transit + surface observation campaign
- Surface duration of one lunar day (~12 Earth days)
Lunar GNSS Receiver Experiment (LuGRE)

- **Goal:** Extend GNSS-based navigation to the Moon

- **Objectives**
  1. Receive GNSS signals at the Moon. Return data and characterize the lunar GNSS signal environment.
  2. Demonstrate navigation and time estimation using GNSS data collected at the Moon.
  3. Utilize collected data to support development of GNSS receivers specific to lunar use.
LuGRE Payload

- Global Navigation Satellite System (GNSS) receiver, antenna and front end provided by the Italian Space Agency (ASI)
  - GNSS receiver designed/built for lunar applications by Qascom leveraging heritage from their QN400 space receiver
- Payload can receive and process GPS (L1 and L5) and Galileo (E1 and E5a) signals
- Data: Raw RF samples, GNSS observables (pseudoranges, Doppler, C/N0, carrier phase), and navigation measurements (position, velocity and time from the onboard filter and instantaneous point solutions)
LuGRE Outcomes
*Specific investigations are coordinated via LuGRE Science Team

- Characterize the GNSS signal environment
  - Received carrier-to-noise spectral density ($C/N_0$)
  - Transmit antenna patterns for Galileo and GPS
  - Signal availability (average number of signals, max outage duration, outage frequency)
  - Dilution of Precision due to clock and signal geometry
  - Multipath (lunar surface, lander)
  - Ionospheric perturbations (Earth and Moon)

- Characterize navigation performance
  - Time to first position fix (and restarts)
  - Comparison to other navigation sources (lander, retroreflector)
  - Navigation solution accuracy over time
  - Filter versus point solution

- Share collected data
  - Commercial lunar landers
  - Lunar payloads
  - GNSS receiver developers
  - Mission designers (HEOMD, SMD)
  - Human Lander System (HLS) teams
  - International space agencies
  - GNSS community
  - Science community

- Facilitate adoption of capability
  - NASA Tech Memo of research conclusions
  - Publications within the wider GNSS and space navigation, operations, and mission planning community
  - Provide lessons learned to GNSS hardware and software developers
  - Improve modeling tools to predict GNSS-based navigation performance for future lunar missions

*Specific investigations are coordinated via LuGRE Science Team
Now to 2024

**NEEDS**
- Far Side science mission
- South Pole human exploration
- PNT services

**IMPLEMENTATION**
- Existing ground networks
- Initial relay capabilities
- LunaNet compatibility

2024 to 2028

**NEEDS**
- Global coverage
- Longer, more complex missions, greater mobility

**IMPLEMENTATION**
- Comprehensive relay network
- Surface comm & nav assets
- Full LunaNet services

2028 and Beyond

**NEEDS**
- Sustained surface and orbital presence

**IMPLEMENTATION**
- Evolution of infrastructure
- Infusion of new technology

Lunar Communications & Navigation Evolution

September 2021
On the Ground: Complete GNSS Monitoring and Integration of all Space geodetic Techniques

Real-time monitoring of GPS, GLONASS, BeiDou, Galileo, QZSS, and NAVIC by the Global Differential GPS (GDGPS) System

Real-time monitoring of earthquakes and tsunamis using ground motion and ionospheric sensing

GipsyX/RTGx software added VLBI to its multi-technique capabilities, already including GNSS, DORIS, and SLR

• Preparing JPL’s contribution to the next International Terrestrial Reference Frame (ITRF2020)
NC3m as an Add-on to MARES

Rad-hard GNSS RF front-end down conversion card

GPS software and firmware runs on MARES processor/FPGA

Front-end assembly
  - Low Noise Amplifier (LNA)
  - Filter
  - RF cables

GNSS antenna

Option for enhanced external reference clock
NC3m Details

- Rad-hard RF front-end card
- Wide-band, dual-frequency RF card provides GPS L1 C/A and either L2C or L5
  - Galileo E1 and E5a also possible for additional SWaP-C
- Supports onboard or an external reference clock
- Provides 1 Pulse Per Second (1PPS) output
- GPS software and firmware builds on proven GSFC MMS Navigator flight heritage
- On-orbit upgradable software and firmware adaptable to new mission types and operations concepts
- Integrated GEONS navigation filter provides filtered GPS solution and propagates solution through GPS outages

Status:
- NC3m is currently in development
- NC3m is being integrated on MARES
- Standalone version of NC3m will be TRL6 in February 2022 (estimated)
- An NTR submitted for this technology
NC3m Applications and Benefits

Provide precise position, velocity, and time (PVT) for missions in all orbit regimes

Provides 1PPS output referenced to GPS time

Raw GNSS signal measurements can be directly used for science in some cases (e.g., study of TEC=total electron content)

Support reliable onboard autonomous navigation and time, reducing reliance on ground-based navigation