Improving GNSS & Pursuing Interoperability for Space Users

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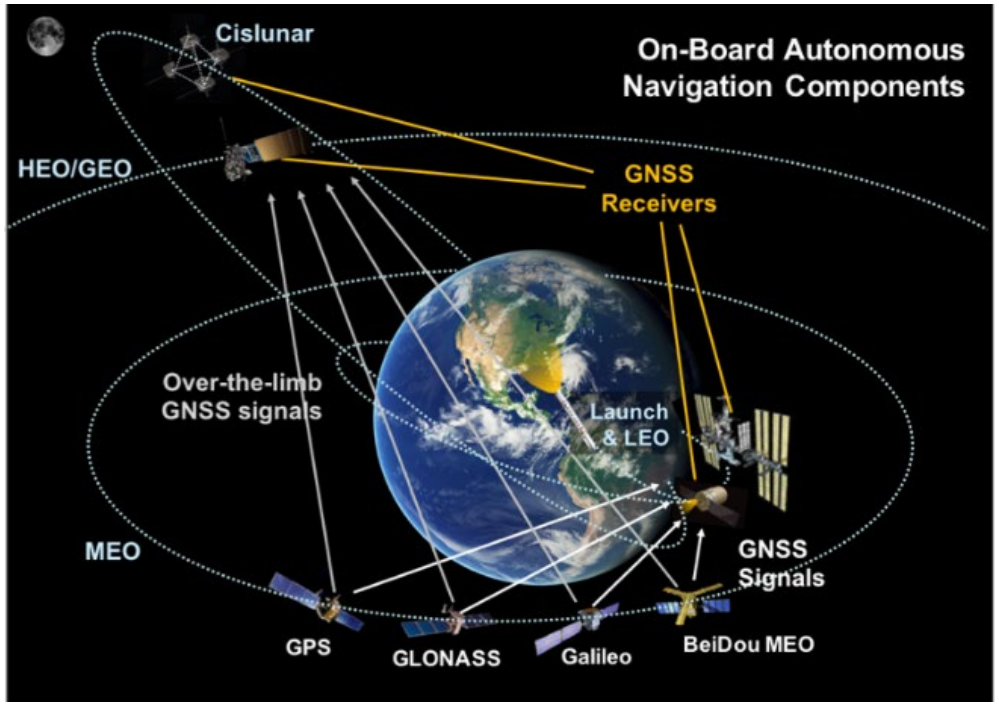
Multi-GNSS Asia 12th Annual Conference
March 10-11, 2022

Image: NASA Blue Ghost-1 lander on Mare Crisium. Includes a multi-GNSS experiment as one of ten hosted science payloads. Launch planned late 2023.

NASA Use of GNSS Services

NASA executes national policy through technology applications:

- Technical contributions & leadership improve space operations and science for all (civil, commercial, military)
- Enhancing GPS enables “cutting edge” science that improves GPS performance & availability – “positive feedback loop”



Earth Sciences: GPS used as a remote sensing tool supports atmospheric and ionospheric sciences, geodesy, and geodynamics -- from monitoring sea levels & ice melt to measuring the gravity field

Launch Range Operations: GPS supports launch vehicle flight termination function, providing safety to people/property during launch & enabling higher launch cadence

Attitude Determination: Enables some missions to meet their attitude determination requirements, such as ISS

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

Time Synchronization: Enables precise time-tagging of science observations and synchronization of on-board clocks – enhances autonomy of space platforms

GPS capabilities are further improved by pursuing compatibility and interoperability with other GNSS

Global Positioning System (GPS) Status
November 20, 2021

37 Satellites • 30 Set Healthy
Baseline Constellation: 24 Satellites

Satellite Block	Satellites	Set Healthy	Average Age (yrs)	Oldest
GPS IIR	12	7	19.9	24.3
GPS IIR-M	8	7	14.1	16.2
GPS IIF	12	12	7.8	11.5
GPS III	5	4	1.6	2.9

As of 20 Nov 2021

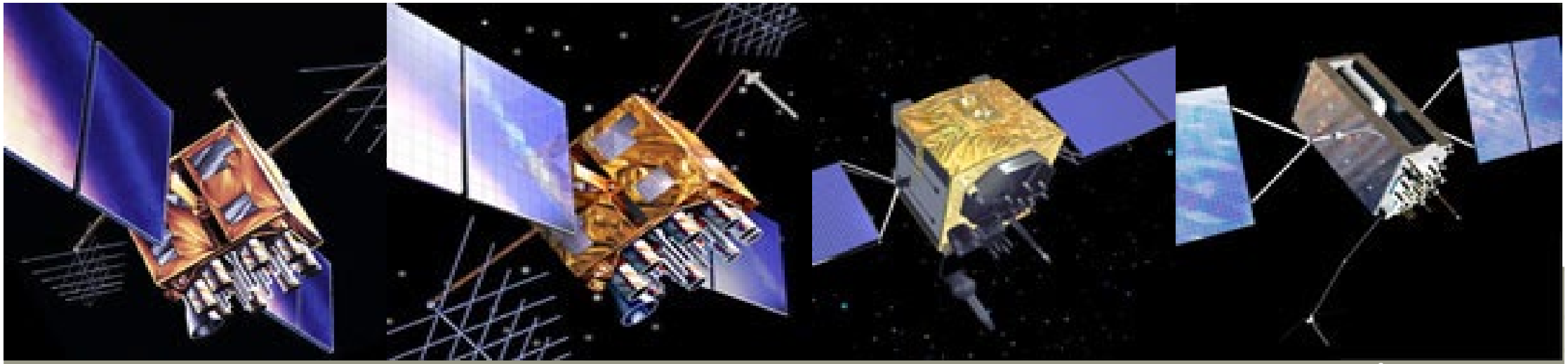
GPS Signal in Space (SIS) Performance

From 20 Nov 2020 to 20 Nov 2021

Average URE*	Best Day URE	Worst Day URE
48.1 cm	31.5 cm (20 Apr 2021)	70.4 cm (13 Mar 2021)

*All User Range Errors (UREs) are Root Mean Square values

GPS Modernization Program



GPS IIR	GPS IIR-M	GPS IIF	GPS III/IIIF
• C/A code on L1 • P(Y) code on L1 & L2 • On-board clock monitoring • 7.5-year design lifespan • Launched in 1997-2004	• All legacy signals • 2nd civil signal on L2 (L2C) • New military M-code signals for enhanced jam resistance • Flexible power levels for military signals • 7.5-year design lifespan • Launched in 2005-2009	• All Block IIR-M signals • 3rd civil signal on L5 frequency (L5) • Advanced atomic clocks • Improved accuracy, signal strength, and quality • 12-year design lifespan • Launched in 2010-2016	• All Block IIF signals • 4th civil signal on L1 (L1C) Enhanced signal reliability, accuracy, & integrity • No Selective Availability • 15-year design lifespan • First launch in 2018 • Block IIIF (SV 11-32) includes: laser retro-reflector payload; search & rescue repeater (launch > 2026)

Space Policy Directive 7 (SPD-7)
15 January 2021

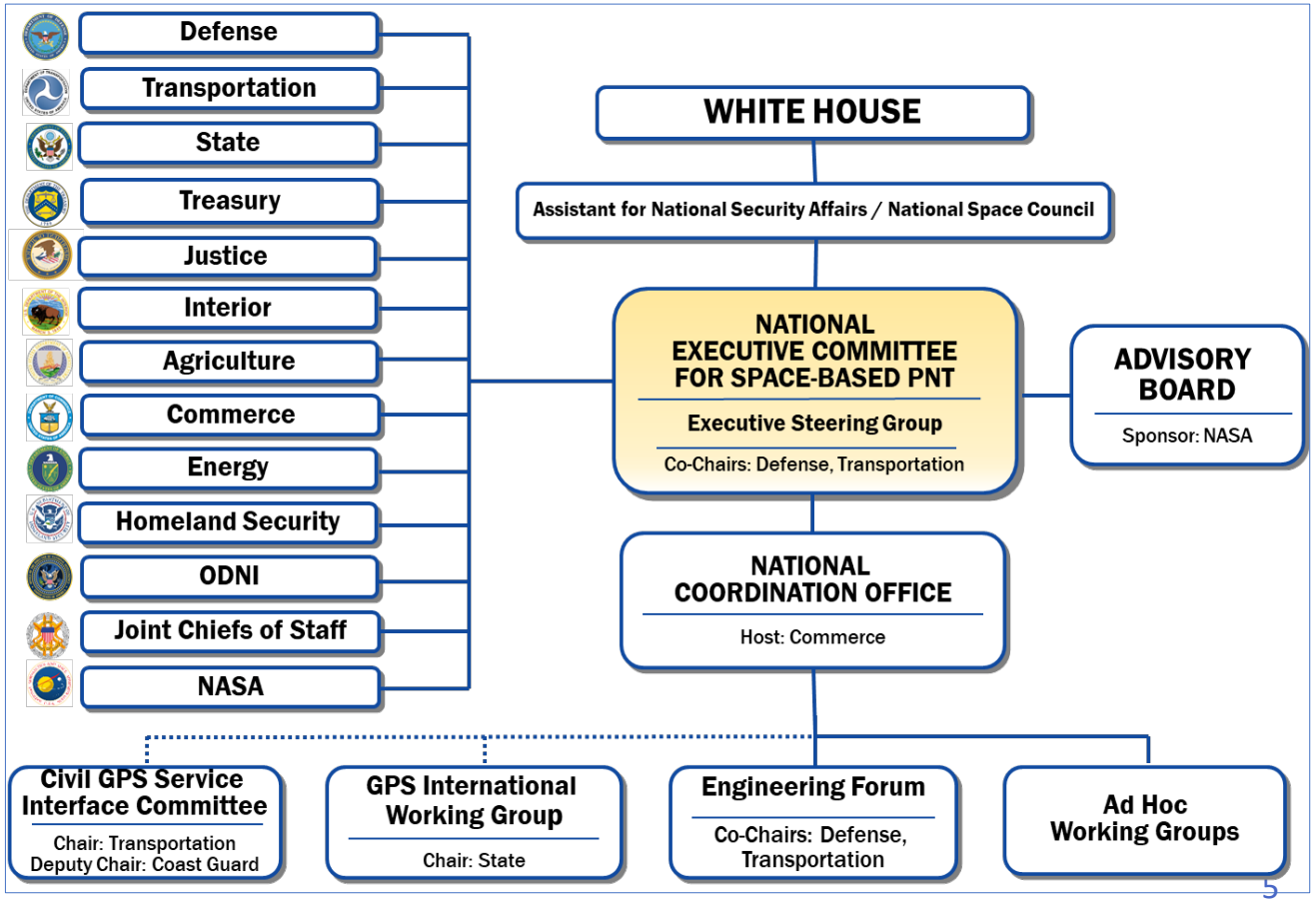
Supersedes Space-Based Positioning, Navigation, & Timing (PNT) Policy of 2004

Goal:

- Maintain leadership in the service provision, and responsible use of Global Navigation Satellite Systems (GNSS), including GPS & foreign systems

Key Updates:

- Increases focus on protecting GPS and denying hostile use
- Incorporates principles of Responsible Use of GPS
- Provides new direction on adding cybersecurity protections for GPS & federal user equipment
- Reaffirms PNT Executive Committee (PNT EXCOM) & expands membership from 9 to 13 agencies
- Provides new direction to protect GPS spectrum environment



National Space-Based PNT Advisory Board

Established in 2007 to provide independent counsel to the National Space-Based PNT EXCOM

Organization

- Established under presidential authority & operates per Federal Advisory Committee Act (FACA) provisions
- Provides independent technical and policy counsel to PNT EXCOM
- Members nominated by PNT EXCOM departments/agencies, approved by PNT EXCOM Co-Chairs, and appointed by NASA Administrator
- Charter allows establishment of ad-hoc task forces and subcommittees

Recent Activities

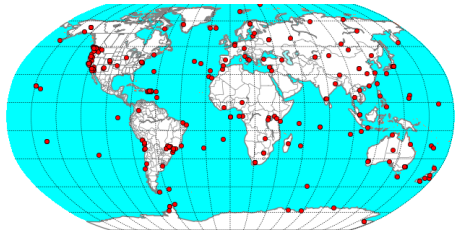
- Charter for 2021-2023 signed April 30, 2021. It expands membership ceiling from 25 to 30 to support expanded PNT EXCOM representation per SPD-7
- On Dec. 7, 2021 NASA Administrator Bill Nelson signed the appointment of 9 new members
- 25th session held Dec. 9-10, 2021 in Arlington, VA
- 26th session planned in May 2022 in Annapolis, MD

https://www.gps.gov/governance/advisory/

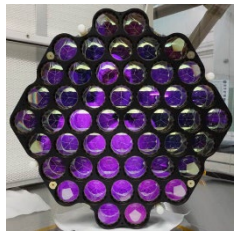
NASA Contributions to the GPS Enterprise: Protecting Services & Enhancing Capabilities for Space Users

Key NASA Activities

- Protect science users from radio frequency interference
- Develop protection standards for space users (cyber)
- Monitor GPS/GNSS performance
- Global Differential GPS System (GDGPS)
- Support GPS Modernization & GNSS Interoperability
  - Laser Retro-reflector Arrays (LRA)
  - Medium Earth Orbit Search and Rescue (MEOSAR)
  - GPS/GNSS Space Service Volume (SSV)
- Develop spaceflight receivers to capitalize on GNSS capabilities in high earth orbit & beyond
- Validate use of GNSS signals throughout Cislunar Space
- Pursue interoperability with GNSS service providers to enhance resilience and performance
- Improve space range safety with GPS/GNSS and the Autonomous Flight Termination System (AFTS)



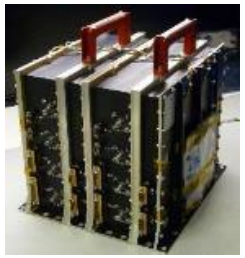
GDGPS



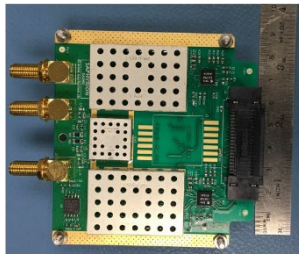
LRA

MEOSAR & Human Spaceflight

JPL Science Rx



GSFC Navigator Rx

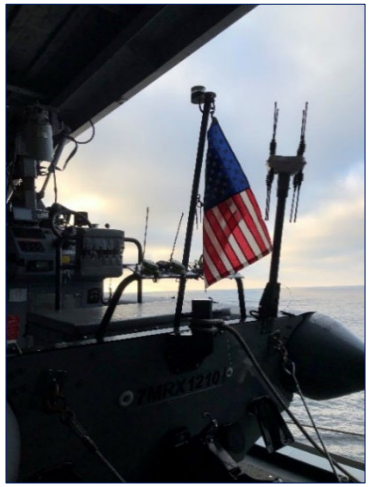


GSFC NavCube Rx

GNSS-Based Human Space Flight (HSF) Search and Rescue (SAR)

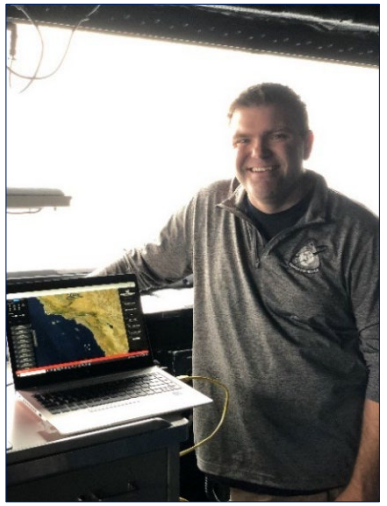
HSF SAR Support

- NASA Search and Rescue program provides support to human space flight launch and landings, including SpaceX/Dragon, Soyuz, and soon Artemis 1
- In an emergency, a beacon is activated tracked by SAR-capable GPS & Galileo satellites, and relayed to the NASA Search and Rescue Laboratory where the position is calculated & sent to rescuers



Recent Activities

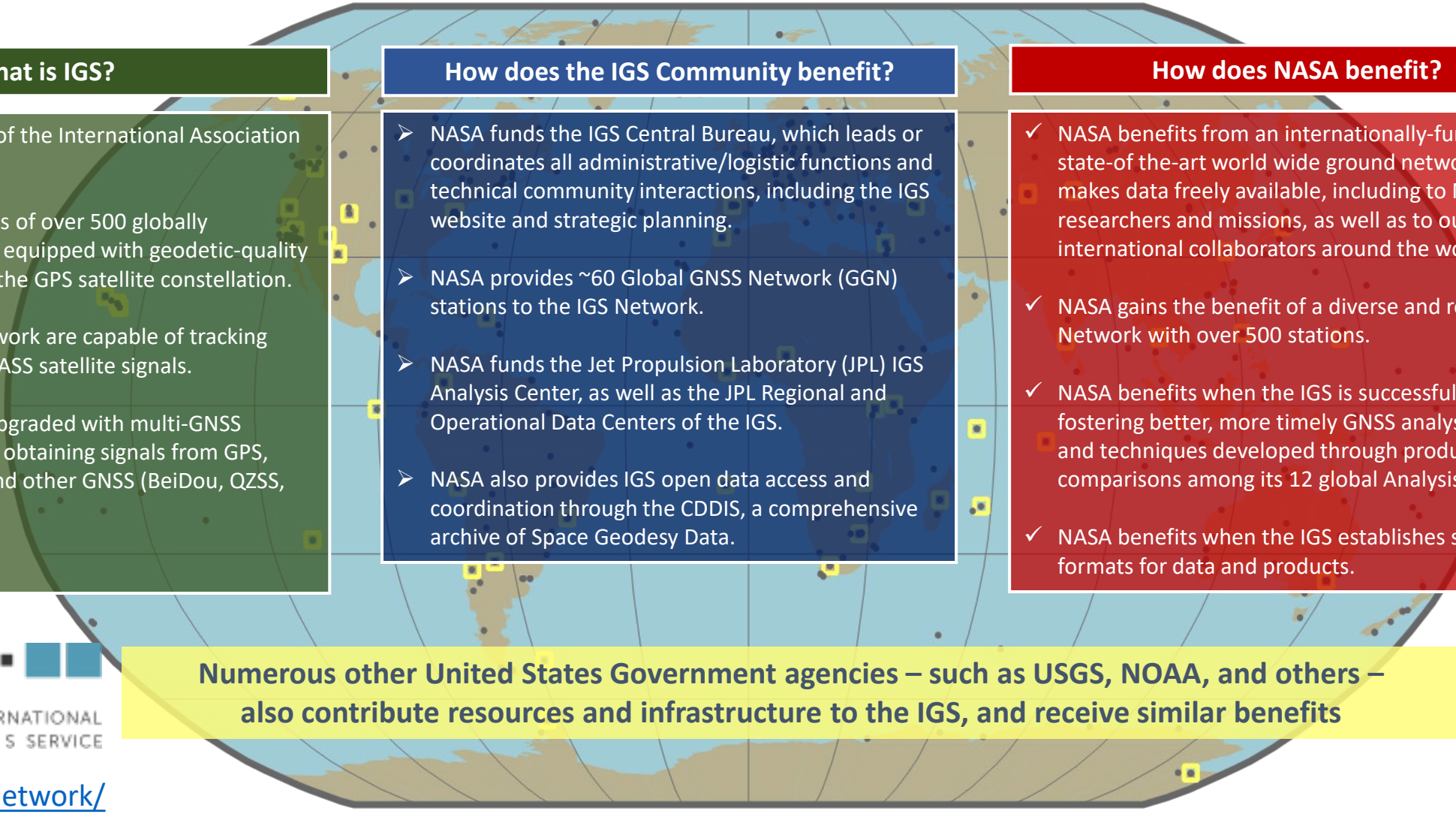
- Underway Recovery Test 9, held Nov. 2021 near San Diego, CA
  - Performed real-world testing of astronaut-worn Advanced Next-Generation Emergency Locator (ANGEL) beacons
  - Successfully demonstrated use GSFC-developed SAR Intelligent Terminal (SAINT) program for monitoring and relaying SARSAT data
  - SAR became the key data relay method for capsule location to rescue/recovery forces



https://www.nasa.gov/feature/goddard/2021/nasa-holds-dress-rehearsal-for-artemis-search-and-rescue/

Improving GNSS Services (1): International GNSS Service (IGS)

NASA & other U.S. agencies contribute to IGS for the benefit of International Geodesy Community



What is IGS?

- The IGS is a service of the International Association of Geodesy (IAG)
- Its network* consists of over 500 globally distributed stations, equipped with geodetic-quality receivers that track the GPS satellite constellation.
- A subset of this network are capable of tracking both GPS and GLONASS satellite signals.
- Some stations are upgraded with multi-GNSS receivers capable of obtaining signals from GPS, GLONASS, Galileo and other GNSS (BeiDou, QZSS, etc.).

How does the IGS Community benefit?

- NASA funds the IGS Central Bureau, which leads or coordinates all administrative/logistic functions and technical community interactions, including the IGS website and strategic planning.
- NASA provides ~60 Global GNSS Network (GGN) stations to the IGS Network.
- NASA funds the Jet Propulsion Laboratory (JPL) IGS Analysis Center, as well as the JPL Regional and Operational Data Centers of the IGS.
- NASA also provides IGS open data access and coordination through the CDDIS, a comprehensive archive of Space Geodesy Data.

How does NASA benefit?

- ✓ NASA benefits from an internationally-funded, state-of the-art world wide ground network that makes data freely available, including to NASA researchers and missions, as well as to our international collaborators around the world.
- ✓ NASA gains the benefit of a diverse and robust IGS Network with over 500 stations.
- ✓ NASA benefits when the IGS is successful in fostering better, more timely GNSS analysis products and techniques developed through product comparisons among its 12 global Analysis Centers.
- ✓ NASA benefits when the IGS establishes standard formats for data and products.

IGS INTERNATIONAL GNSS SERVICE

Numerous other United States Government agencies – such as USGS, NOAA, and others – also contribute resources and infrastructure to the IGS, and receive similar benefits

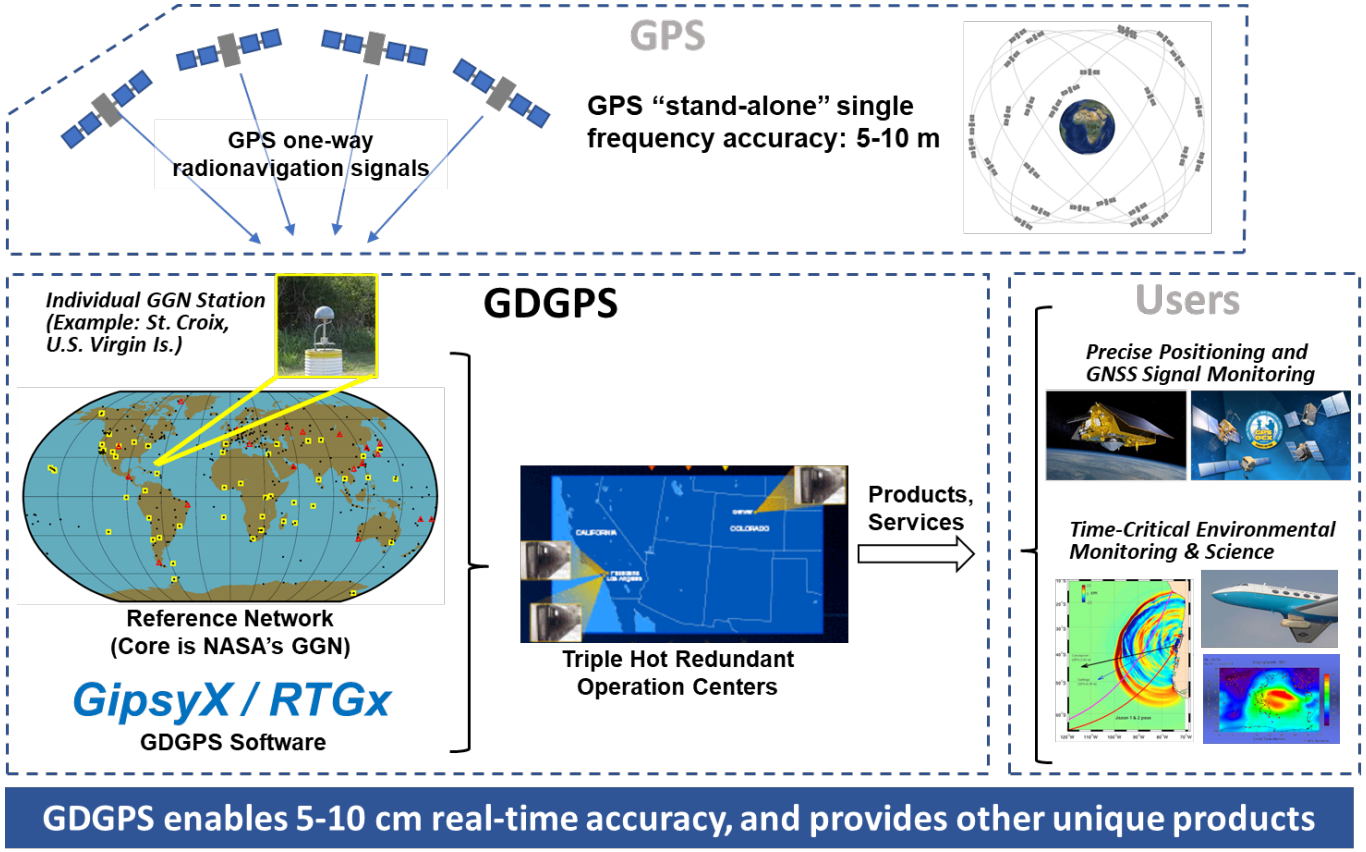
(*) https://igs.org/network/

Improving GNSS Services (2): Global Differential GPS System (GDGPS)

Use of Unique GDGPS Real-Time Products

- NASA
  - Support to Earth Observation Satellites
  - Repeat-pass interferometry for UAVSAR
  - Open access to GPS real-time raw ranging data
  - Tsunami Warning & Earthquake Monitoring Research
  - Deep Space Network operations (ionosphere & troposphere calibrations, Earth orientation)
  - Interoperable GNSS capabilities for space users
  - Data on performance of GNSS signals
- U.S. Interagency
  - Supports real-time integrity monitoring of GPS constellation
  - Provides real-time space weather ionosphere data
  - Supports GPS III OCX Development
  - Precise GPS position and orbit determination
- Other Research & Applications
  - Imagery Registration
  - Assisted GNSS & E911 Information for Cellular Users

Architecture



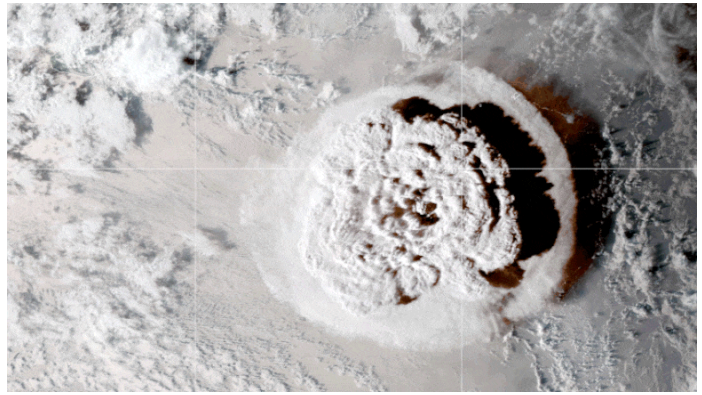
GDGPS enables 5-10 cm real-time accuracy, and provides other unique products

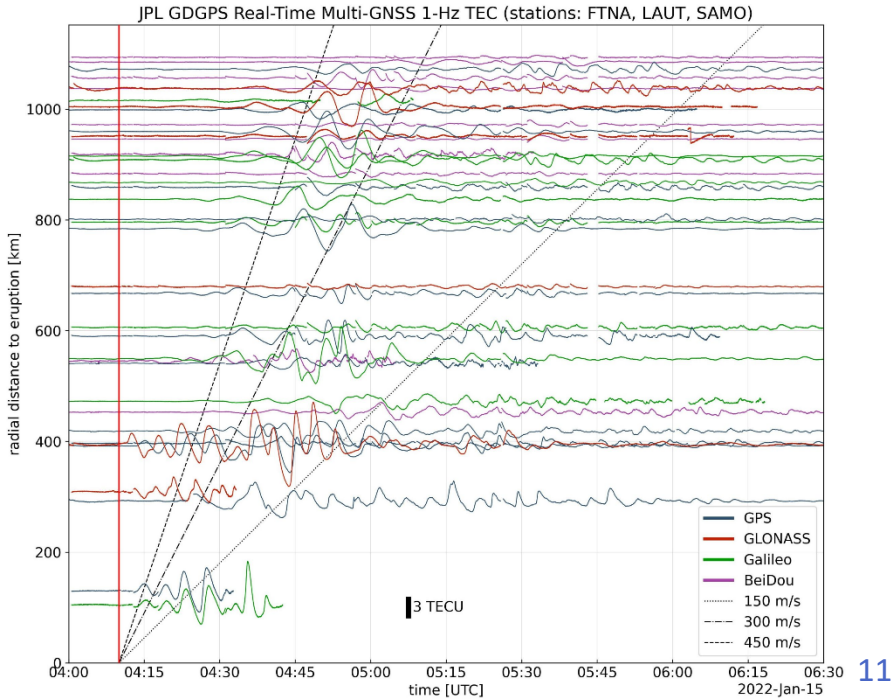
Improving GNSS Services (3): GNSS for Earthquake Monitoring & Tsunami Prediction

Using GNSS to Detect Volcanic Eruptions & Tsunamis

- On Jan. 15, 2020, the Hunga Tonga-Hunga Ha'apai underwater volcano erupted, unleashing a 4-10 megaton explosion
  - Produced an acoustic shockwave strong enough to perturb the ionosphere
  - Caused a tsunami, which was enhanced by the atmospheric pressure waves of the explosion – a phenomenon known as a **meteotsunami**
  - Deformation of ocean surface from these waves further disturbed the ionosphere
- GDGPS observed in real-time the ionospheric disturbances caused by the explosion and subsequent meteotsunami
  - Observed Total Electron Count (TEC) perturbations on 40+ GNSS satellites after the eruption using real-time GNSS TEC data
  - Multi-constellation (GPS, GLONASS & Galileo) 1-Hz measurements captured the acoustic & gravity waves propagating across the Pacific Ocean
  - Used 55 stations around the Pacific ocean to image the ionospheric signatures

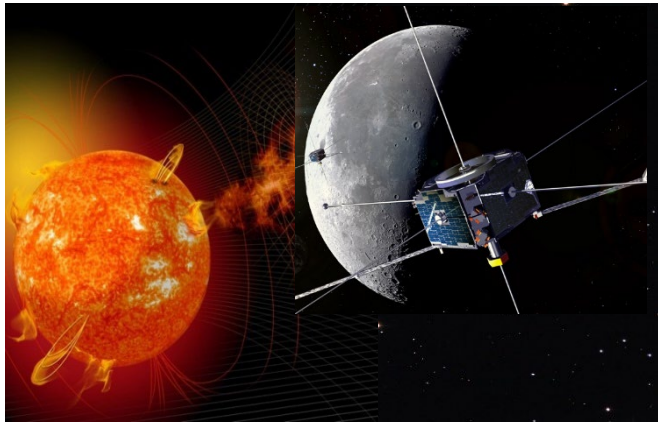
GNSS data can serve an important role in contributing to tsunami early warning systems & save lives



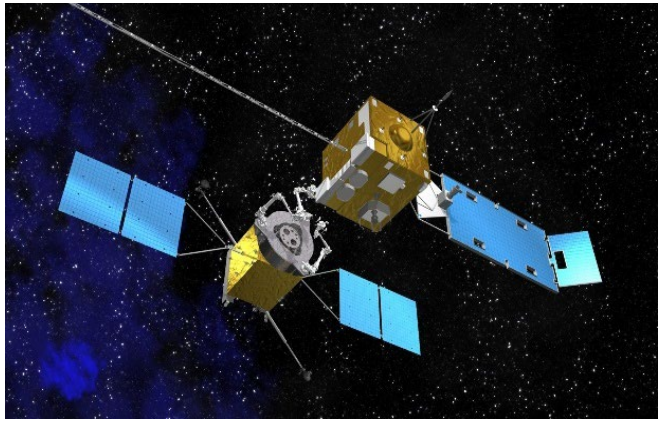


Electron Density Profiles during Tonga Eruption

GNSS Supporting Space Operations & Science in Cislunar Space

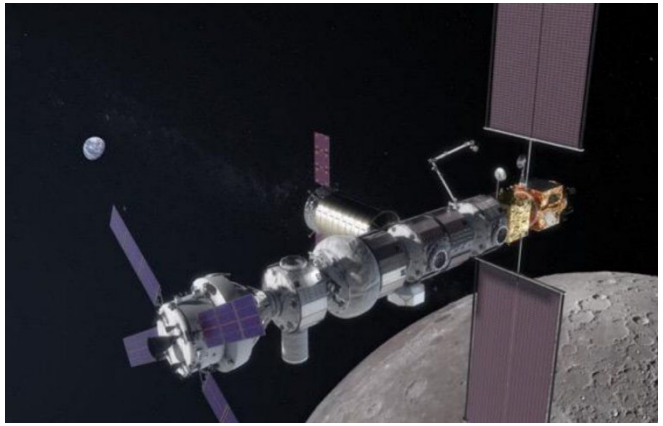


Earth, Astrophysics, & Solar Science Observations

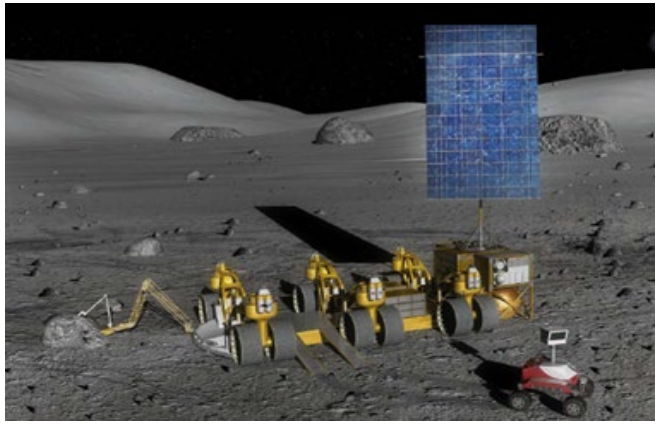


Satellite Servicing

Lunar Exploration Infrastructure



Human-tended Lunar Vicinity Vehicles (Gateway)



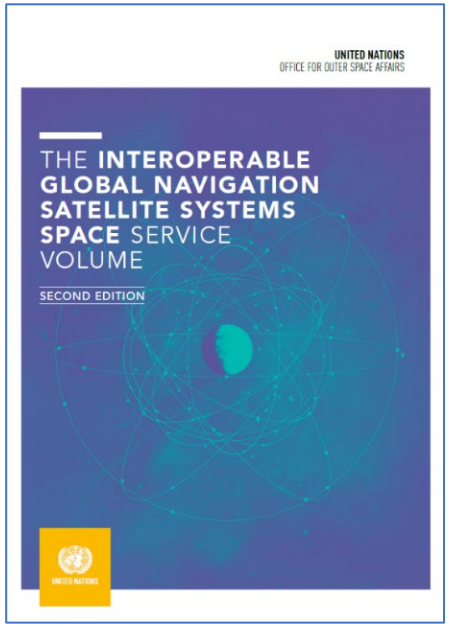
Lunar Surface Operations, Robotic Prospecting, & Human Exploration

Robotic Lunar Orbiters, Resource & Science Sentinels

Developing an Interoperable GNSS Space Service Volume (SSV) for Space Operations and Science

International Committee on GNSS (ICG)

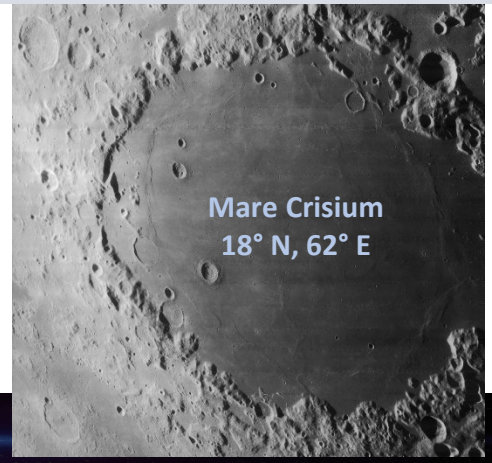
- ICG-15 meeting in Vienna Sep. 27 – Oct. 1, 2021
- WG-B Space Use Sub-Group (SUSG)
  - Established 2018; NASA co-chairs w/ ESA, CAST
  - Virtual meetings held monthly on rotating basis
  - ICG-15 full-day session held Sep 24
  - Established forward 2021+ work plan
- SSV Booklet 2nd Edition, "The Interoperable GNSS SSV"
  - Officially released on Sep 28: https://undocs.org/ST/SPACE/75/REV.1
  - Major improvements from 1st Edition:
    - Updated BeiDou (China) & QZSS (Japan) constellation data
    - Added geometric dilution indicator
    - Added flight experiences section
- SSV Video, "The Multi-GNSS SSV: Earth's Next Navigation Utility"
  - Released at ICG-15 alongside booklet: https://www.youtube.com/watch?v=-1ngun6OfgQ
- ICG-16 meeting in Abu Dhabi, UAE, Oct. 2022

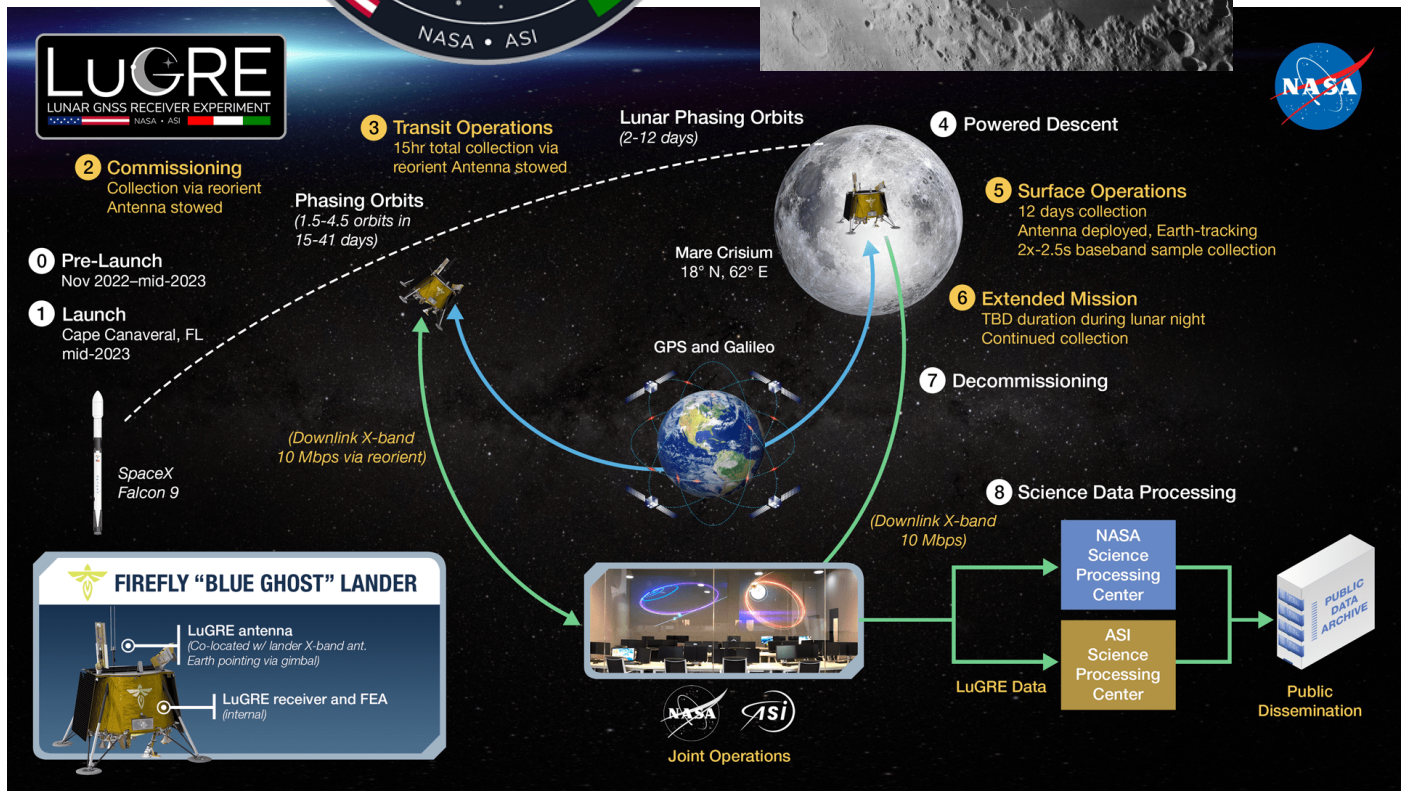


Developing GNSS Capabilities for Lunar Operations & Science (1)

Lunar GNSS Receiver Experiment (LuGRE)

- Mission
  - Payload on CLPS Mission 19D lunar lander
  - Joint NASA / Italian Space Agency experiment
  - Firefly Blue Ghost commercial lander
  - Includes transit + surface observation campaign
  - Expected surface duration: one lunar day
  - Launch in late 2023, to land in Mare Crisium
- LuGRE Payload Objectives
  - Receive GNSS (GPS+Galileo) signals at the Moon
  - Return data and characterize the lunar GNSS signal environment
  - Demonstrate navigation & time estimation using GNSS data collected at the Moon
  - Utilize collected data to support development of GNSS receivers for lunar use

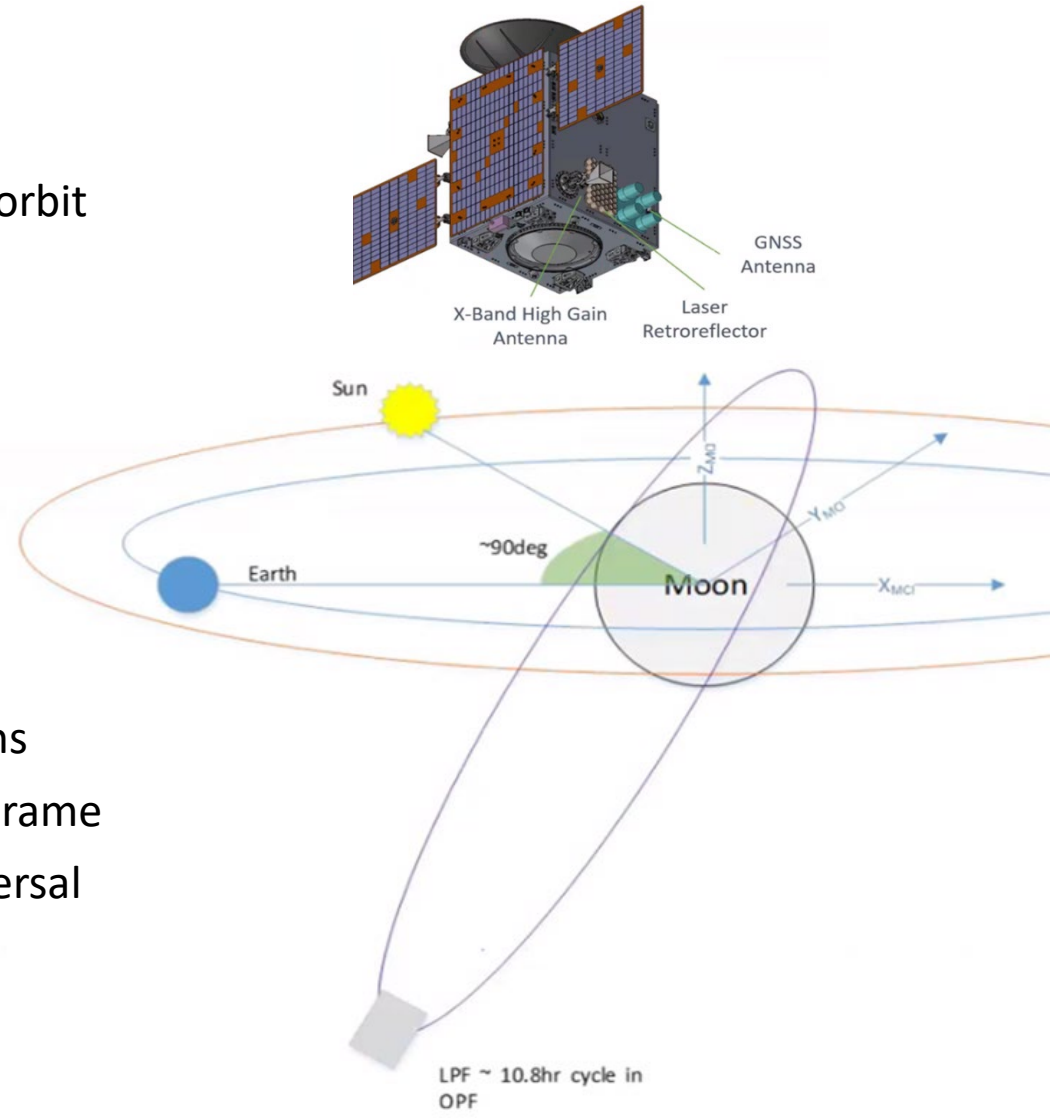




Developing GNSS Capabilities for Lunar Operations & Science (2)

Collaboration with ESA on Lunar Pathfinder

- Mission
  - European Space Agency (ESA) communications relay satellite in lunar orbit
  - Hosted Experimental payloads:
    - GNSS Navigation In-Orbit-Demonstration payload – provided by ESA
    - Radiation Monitor payload – provided by ESA
    - Laser Retro-Reflector (LRR) payload – **provided by NASA**
- LRR Experiment Goals
  - Demonstrate two-way laser ranging in support of precision orbit determination
  - Validation of GNSS-based (GPS & Galileo) positioning for lunar missions
  - Improve tie between Terrestrial Reference Frame & Lunar Reference Frame
  - Demonstrate use of lunar orbiter for improved determination of Universal Time (Earth's rotation angle)
- Status
  - Tentative launch date: Q4 2024



National Space Policy
9 December 2020

Addresses the U.S. in the provision of GPS services and the responsible use of GNSS

Key Provisions:

- Provide continuous worldwide access for peaceful civil uses free of direct user fees;
- Engage with international GNSS providers to ensure compatibility, encourage interoperability with like-minded nations, promote transparency in civil service provision, and enable market access for U.S. industry;
- Operate and maintain the GPS constellation to satisfy civil and national security needs;
- Improve the cybersecurity of GPS, its augmentations, and federally-owned GPS enabled devices;
- Allow for the continued use of allied & other trusted international PNT services in conjunction with GPS;
- Invest in domestic capabilities and support international activities to detect, analyze, mitigate, and increase resilience to harmful interference to GNSS;
- Identify and promote multiple and diverse complementary PNT systems or approaches for critical infrastructure and mission-essential functions; and
- Promote the responsible use of U.S. space-based PNT services and capabilities in civil and commercial sectors, including the utilization of multiple and diverse complementary PNT systems or approaches for national critical functions.

National Space Council (NSpC) Users' Advisory Group (UAG)

Established in 2017 to ensure interests of industry, other non-Federal entities, & other persons involved in aeronautical and space activities are represented at the NSpC

Organization

- Reports to the Vice President's Office
- Operates in accordance with FACA provisions
- Chaired by Adm J. Ellis Jr. (USN, ret.), and since 2019 James J. Miller is Executive Sec.
- Five public meetings have been held to-date, where the UAG discusses and approves finding and recommendations for submitting to the NSpC
- UAG EXCOM & subcommittees hold fact-finding mtgs on bi-weekly basis

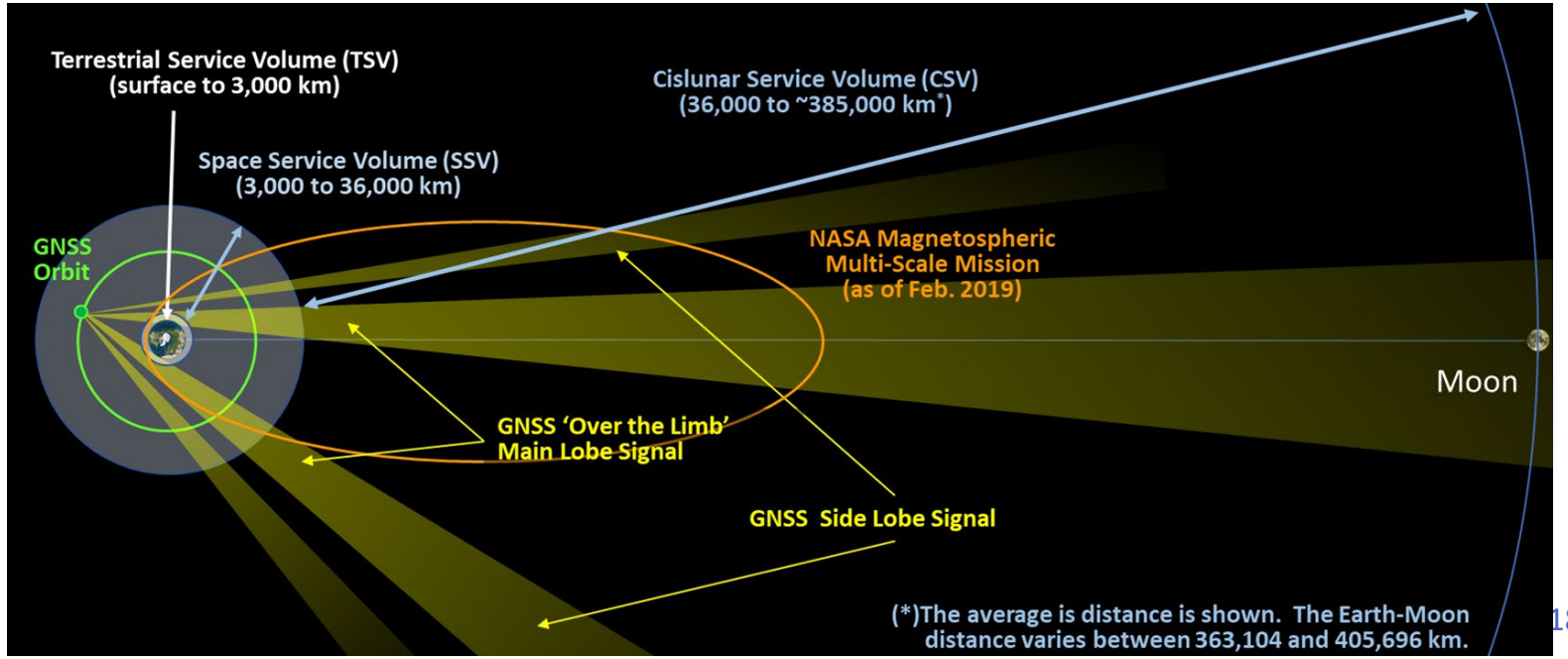
Recent Activities

- ~200 member nominations submitted Nov. 5, 2021 for White House review
- On Dec. 1, 2021 UAG Chair, Adm J. Ellis Jr (USN, ret.) addressed 1st NSpC meeting of new Administration
- Updated charter signed by NASA Administrator on Dec. 3, 2021
  - Establishes six subcommittees 2021-2023 term: Exploration & Discovery; National Security; Economic Development & Industrial Base; STEM Education, Diversity & Inclusion; Climate & Societal Benefits; and Data & Emerging Technology

https://www.nasa.gov/content/national-space-council-users-advisory-group

NASA's Role in U.S. PNT and National Space Policy

- **2004**: NSPD-39 (U.S. PNT Policy) released
  - Tasks NASA Administrator to develop requirements for GPS use to support civil space systems
  - Since then, NASA been working with USAF & USSF to make GPS services more accessible, interoperable, robust, & precise
- **2007**: First meeting of NASA-sponsored PNT Advisory Board
- **June 2017**: National Space Council (NSpC) reestablished along with Users' Advisory Group (UAG)
- **Aug. 2019**: NASA Administrator appoints SCaN as UAG sponsor
- **Dec. 2020**: National Space Policy reaffirms PNT policy commitments, and calls for improved GPS cybersecurity protections and responsible use of GPS
- **Jan. 2021**: SPD-7 released
  - Tasks NASA Administrator to:
    - Provide technical requirements for GPS use to support civil & commercial space systems
    - Develop requirements for GPS use within Space Service Volume
    - Sustain & modernize GPS Search and Rescue location capabilities
  - GPS to support Space Situation Awareness & Space Traffic Management in **Cislunar Service Volume**



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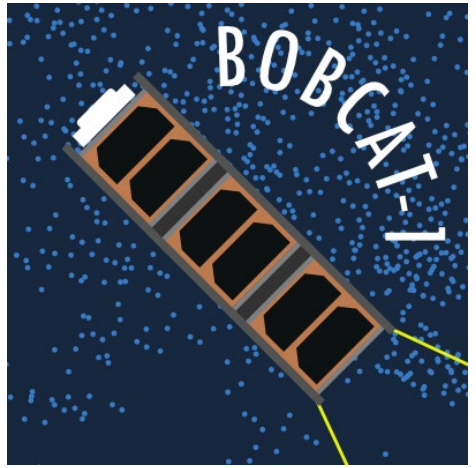
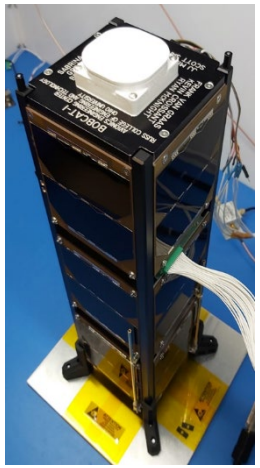
Backup Slides

Improving Multi-GNSS PNT for Space Operations and Science

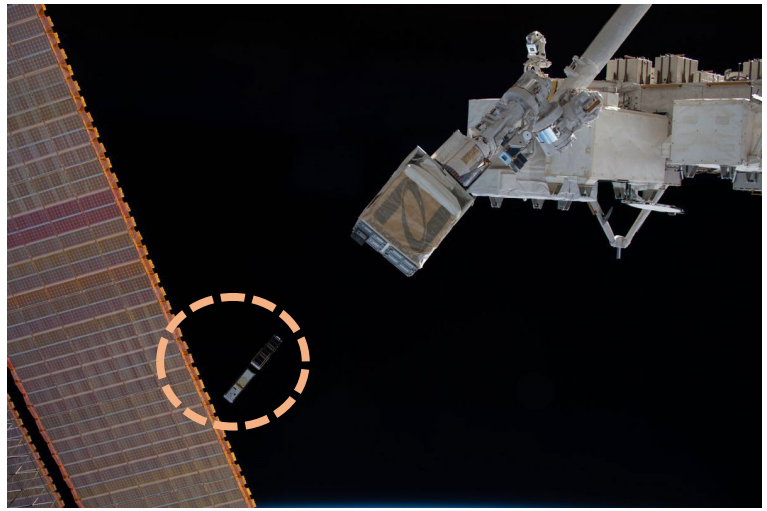
BobCat-1 CubeSat / Time Offset Experiment

- Mission
  - SCaN-sponsored Glenn Research Center – Ohio University collaboration
  - Primary objective is to measure the GNSS inter-constellation offset estimate, and in-turn improve multi-GNSS PNT
  - Includes a Qascom GPS-Galileo software defined receiver
  - Cubesat released from ISS on November 5, 2021
  - Designed for 8-9 months operation, and still working 14 months later (https://twitter.com/Bobcat1_Cubesat)
- Achievements (as of Feb. 2022)
  - In Jan. 2022 completed 14 months of in-orbit operations
  - Continued tracking and telemetry of Bobcat-1, data analysis, documentation development, and outreach program activities
  - Completed GPS-Galileo time offset feasibility study, which will enable real-time monitoring of time offsets between constellations
  - Completed multi-GNSS doppler processing, which will enable fast state estimation after spacecraft maneuvers





Release from ISS (Nov. 5, 2021)



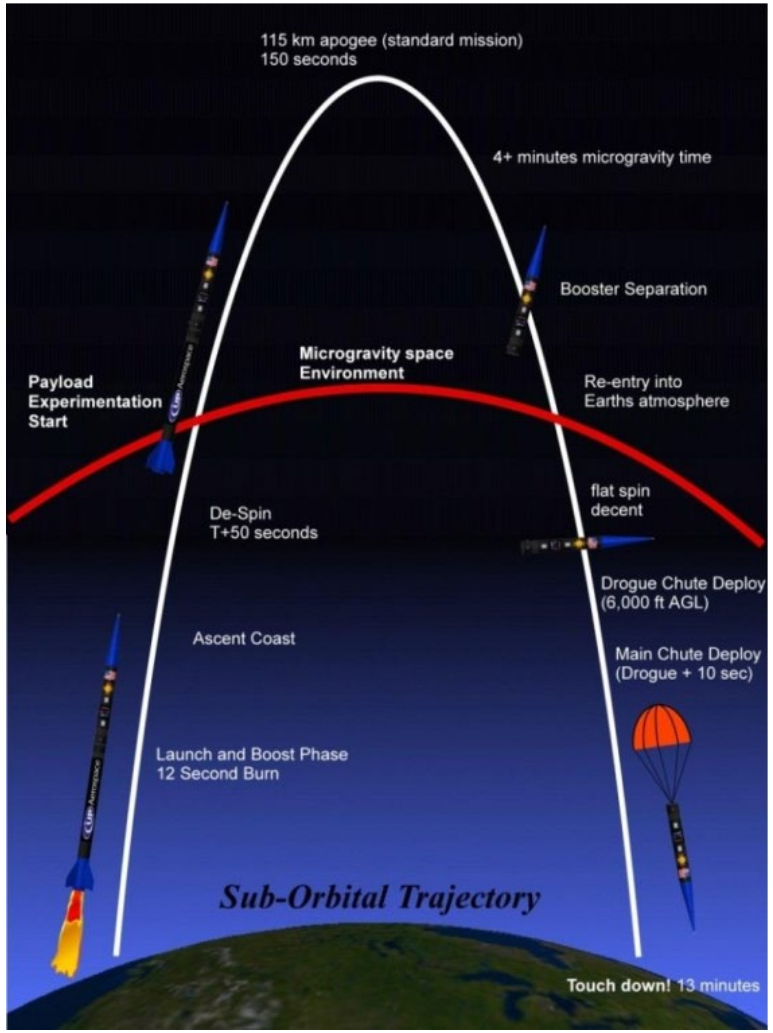
Developing Interoperable GNSS Capabilities for Launch Range Safety

Space Loft 15 Range Safety Experiment

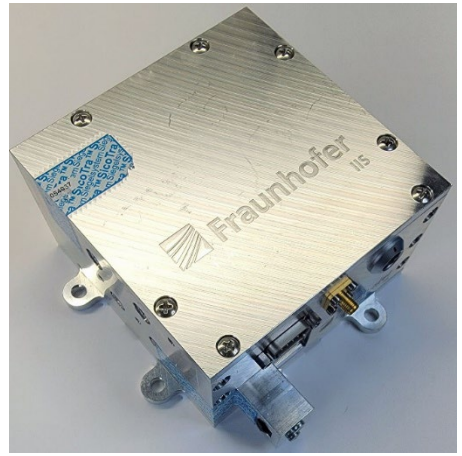
- Objective to assess GPS-Galileo performance in a highly dynamic environment, including potential to augment GPS in range safety system
- Builds on success of Space Loft 14 (SL-14) GNSS flight experiment, launched Nov. 2019
- Includes two multi-GNSS receivers (GARHEO* and GOOSE*), one GPS receiver, and two Autonomous Flight Termination Units (AFTUs) on a UP Aerospace SL-15 sounding rocket
- Integration testing of the GNSS receivers with the AFTU has begun
- SL-15 launch from Spaceport America, NM, planned for Nov. 2022

(*) GPS-GALILEO Receiver for Human Exploration & Operations
(**) GNSS Receiver with Open Software Interface (in German)

Mission Profile



GARHEO Receiver (ASI)



GOOSE Receiver (ESA)