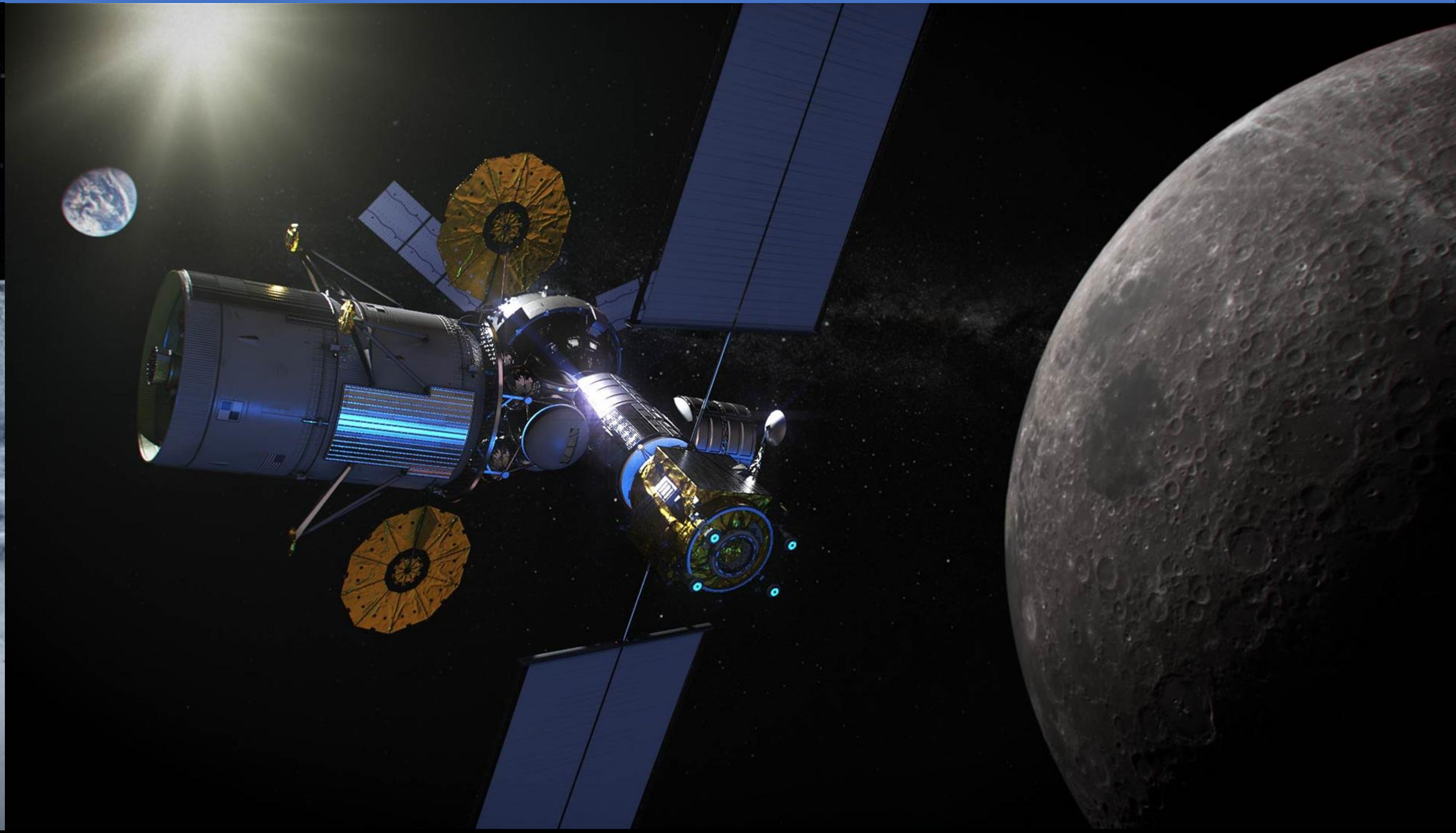
NASA Space User Update: Advancing Interoperability and Lunar PNT



Commercial Lunar Lander (Left) and the Lunar Gateway (Right), two potential applications of Lunar PNT international collaboration

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U.S. National Aeronautics and Space Administration

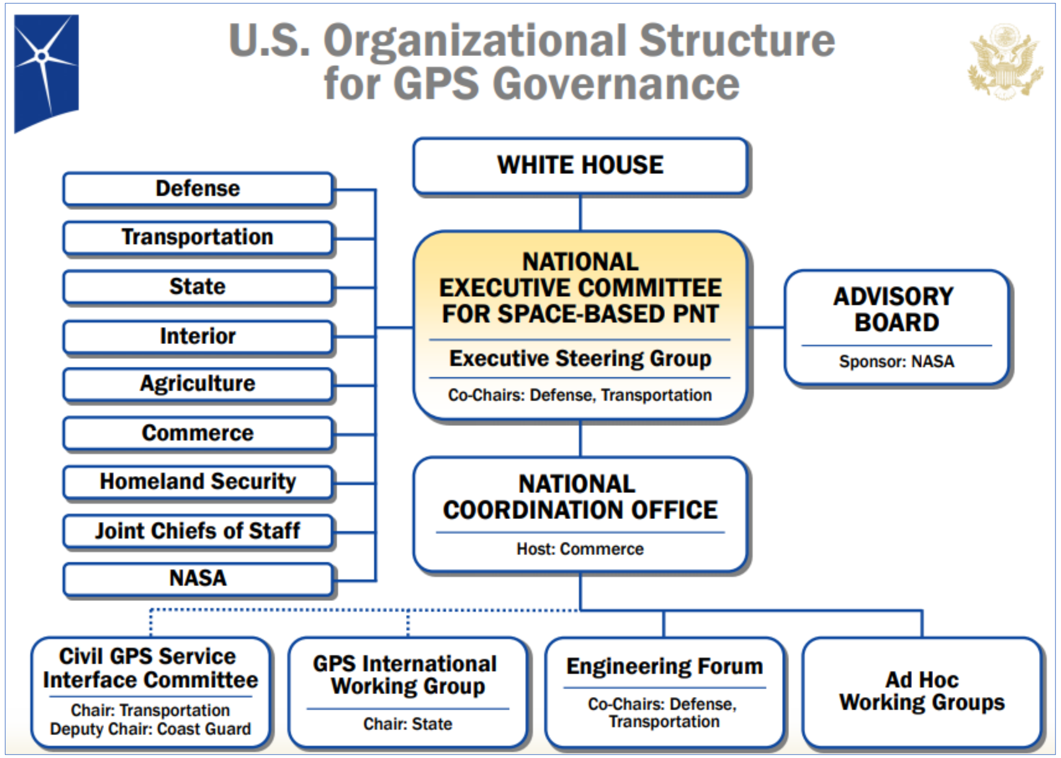
September 22, 2020

NASA's Role in U.S. PNT / Space Policy

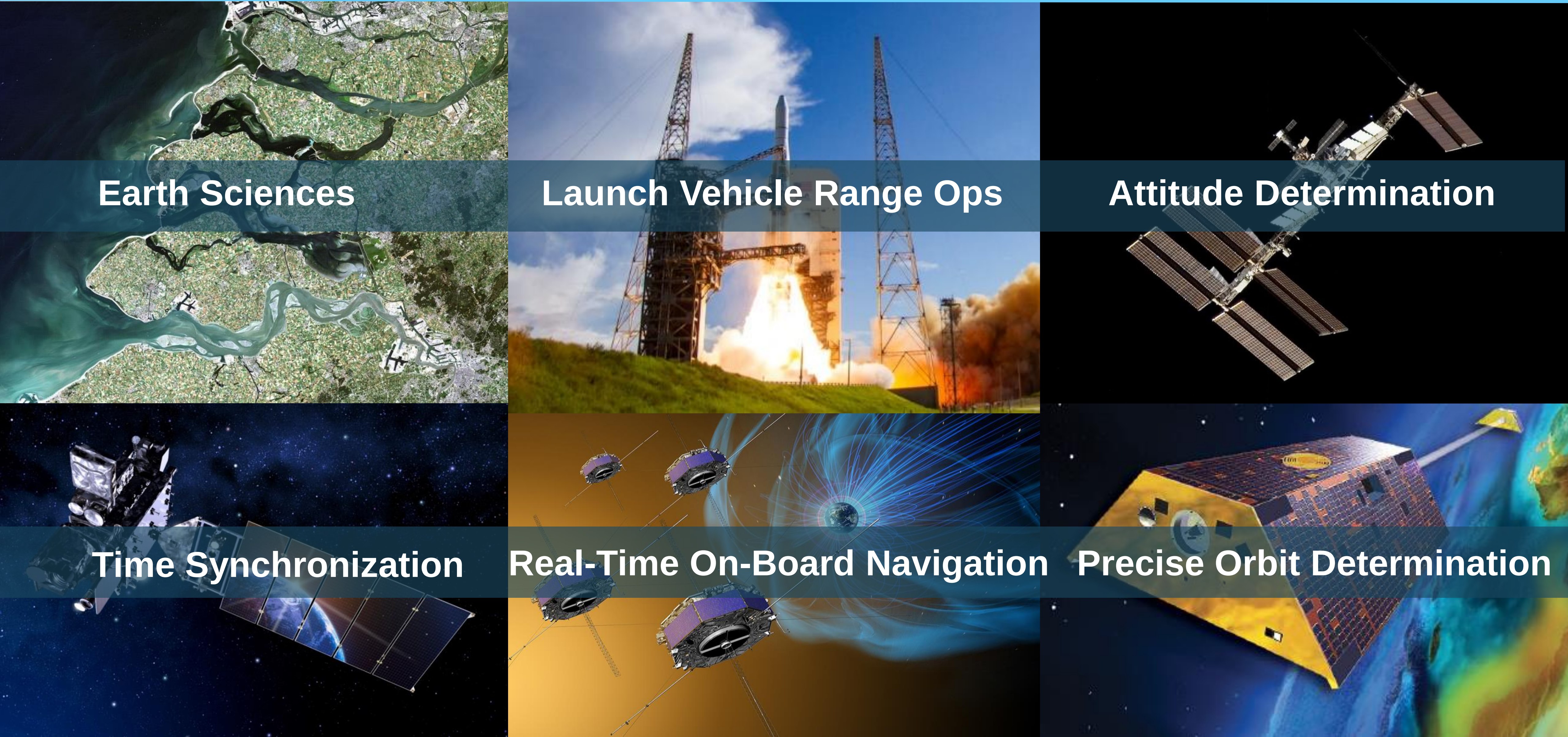
- The U.S. Space-Based Positioning, Navigation, and Timing (PNT) Policy tasks the NASA Administrator to develop and provide requirements for the use of GPS & its augmentations to support civil space systems
- NASA works with the Air Force to contribute making GPS services more accessible, interoperable, robust, and precise
- The 2010 National Space Policy reaffirmed PNT Policy commitments to GPS service provisions, international cooperation, and interference mitigation
- In 2018 the National Space Council recommended to develop protections for the radiofrequency spectrum [such as that used by GPS] facilitating commercial space activities

The PNT Advisory Board has implemented a "**PTA**" program to:

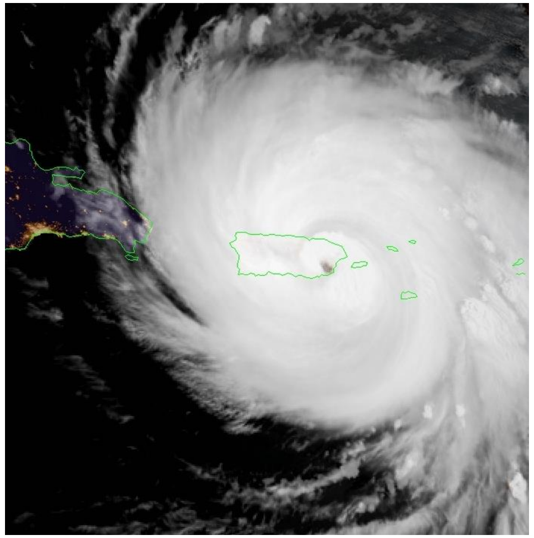
- **Protect** the radio spectrum + identify + prosecute interferers
- **Toughen** GPS receivers against natural and human interference
- **Augment** with additional GNSS/PNT sources and techniques

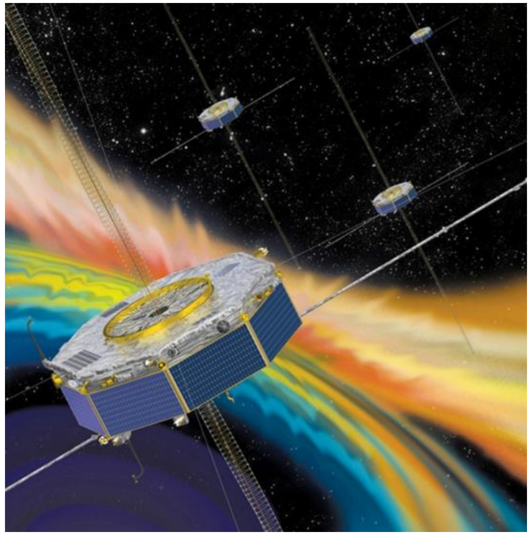


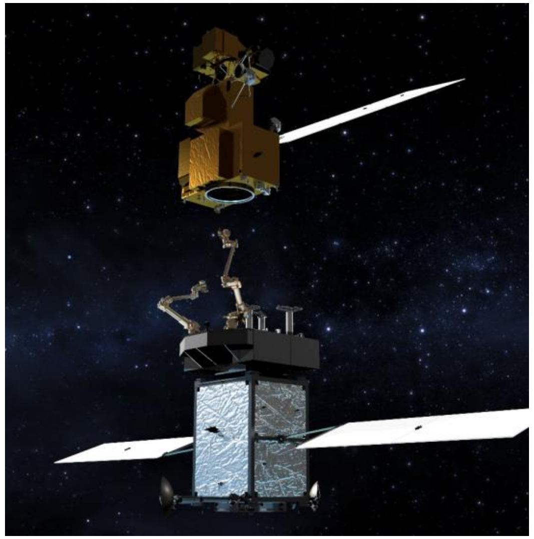
Space Uses of
Global Navigation Satellite Systems (GNSS)

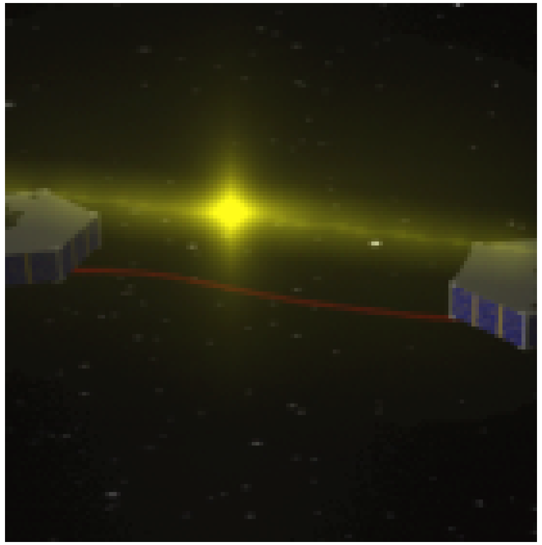


Demonstrated Benefits of GNSS for Space Navigation and Timing



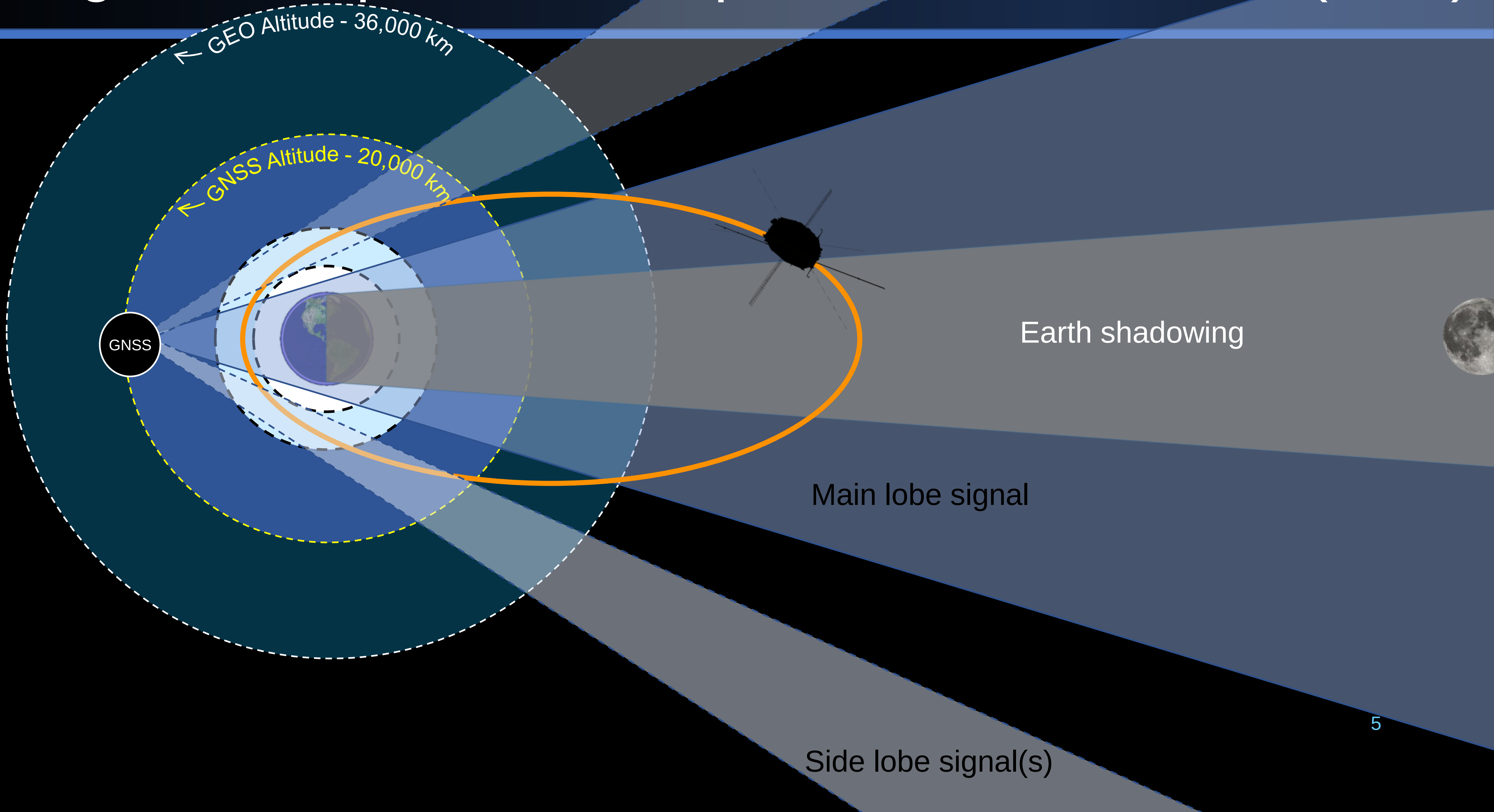






- Significantly **improves real-time navigation performance** (from km-class to meter-class)
- Supports **quick trajectory maneuver recovery** (from 5-10 hours to minutes)
- GNSS timing **reduces need for expensive on-board clocks** (from $100sK-$1M to $15K-$50K) in LEO/GEO
- Supports **increased satellite autonomy**, lowering mission operations costs (savings up to $500-$750K/year)
- Enables new/enhanced capabilities and better performance for High Earth Orbit (HEO), Geosynchronous Earth Orbit (GEO), and lunar missions

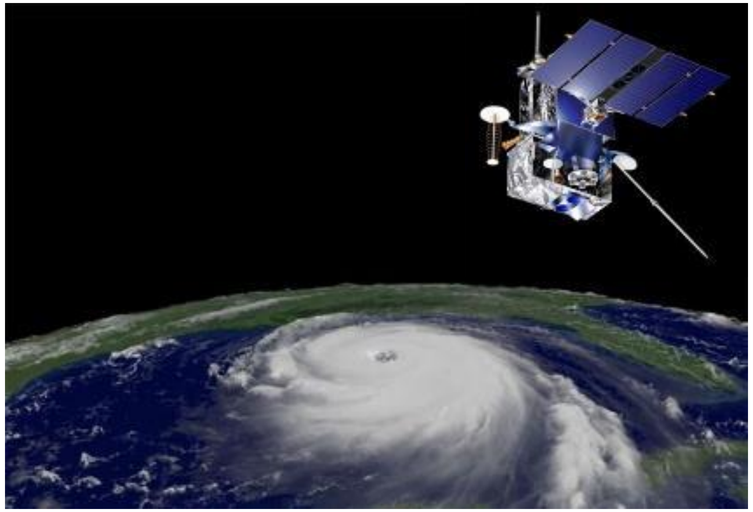
Signal Reception in the Space Service Volume (SSV)



Operational U.S. Missions using GNSS in the Space Service Volume & Beyond

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:

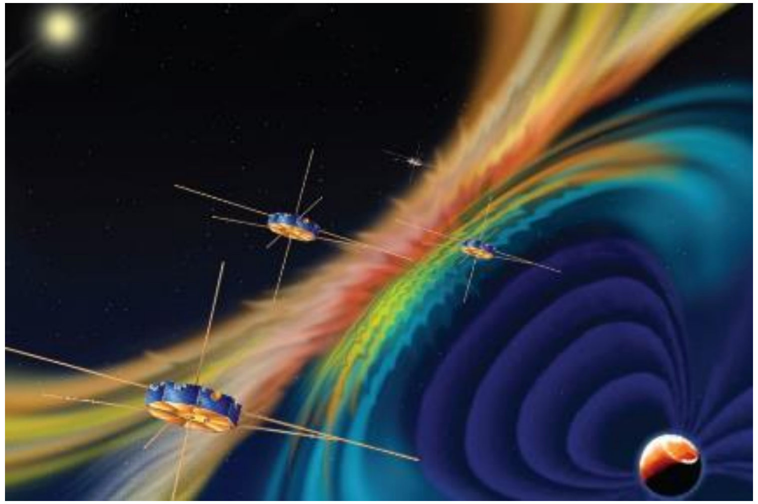
- Minimum SVs visible: 7
- DOP: 5–15

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



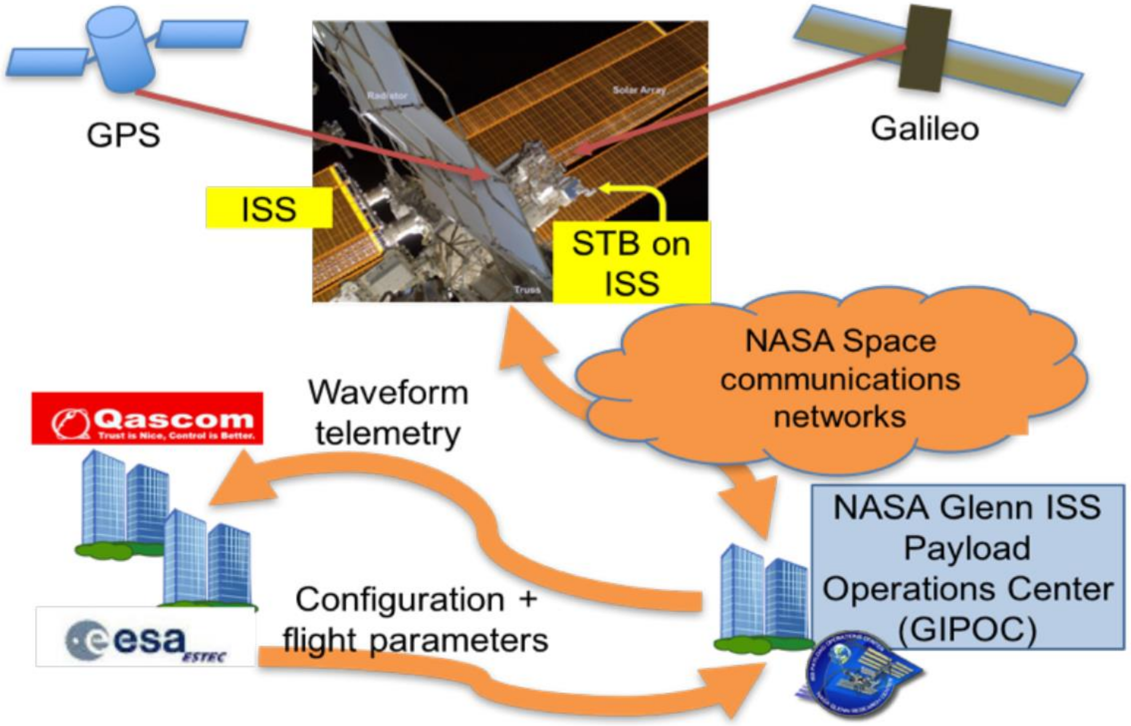
MMS Nav Performance (1σ)

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**

Multi-GNSS Interoperability

GAlileo Receiver for the ISS (GARISS)

- **Objectives:**
  - Demonstrate combined GPS/Galileo (L5/E5a) navigation receiver on-orbit with upload of Software Radio waveform
  - Add waveform to Space Telecommunications Radio Systems (STRS) waveform repository
- **Approach/Benefits:**
  - Adapt existing Galileo PNT code to Software Defined Radio (SDR) inside SCaN Test Bed (STB) onboard International Space Station (ISS)
  - Demonstrate operations, conduct PNT experiments on ISS
  - Flexibility of SDR technology, STRS operating environment
- **Timeline:**
  - Initial discussions at International meetings (mid-2014)
  - Project formulation/export license (mid-2016)
  - Waveform design and development (late 2016-mid 2017)
  - Qualification and test the Galileo/GPS waveform (mid 2017-late 2017)
  - On-orbit testing and experiments (2018)
  - Results published (2019)



See Enderle, "The joint ESA/NASA Galileo/GPS Receiver Onboard the ISS – The GARISS Project", ION GNSS+ 2019, for results.

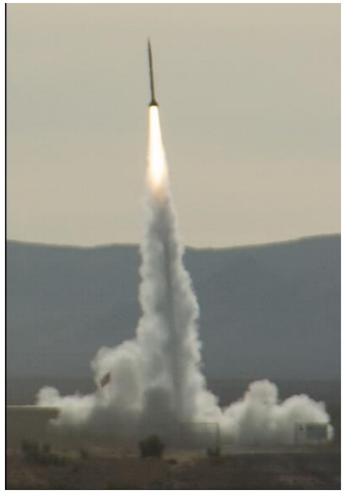
AFTS—First Employment on Human Spaceflight Mission: SpaceX Crew Demo 2

Autonomous Flight Termination (AFTS)

- Independent, self-contained subsystem onboard launch vehicle that automatically makes flight termination / destruct decisions
- Box on the vehicle (AFTU)
  - Tracking from GPS and INS sensors
  - Rule set built in pre-flight period; rule violation terminates flight
- Radar and command stations recede into the past
- Telemetry down-link drops from safety critical to situational awareness, post-flight, and mishap investigation
- **May 30, 2020: AFTS Provided safety critical support to NASA astronauts and the public during SpaceX Crew Demo-2—first launch of U.S. astronauts on U.S. soil in nearly a decade**

AFTS—NASA AFTU Flight Tests

Rocket Lab Electron Launch



UP Aerospace Spaceloft Launch

- **Flight Certifications:**
  - DARPA funded NASA to design, develop, test, qualify, and certify an operational AFTU for US Govt and US Commercial launch providers
  - First NASA AFTU developmental flight: Rocket Lab (RL) Electron from New Zealand in May 2017
  - Additional shadow/certification flights: Nine additional AFTU shadow/certification flights have been completed (6 on RL Electron, 2 on UP Aerospace Spaceloft and 1 on Wallops Sounding rocket)
  - The first NASA AFTU operational flight: RL Electron from New Zealand on Dec 6, 2019 under the FAA authority
  - NASA AFTU units are being used operationally by one provider, and many more have baselined them for operational use in the future.
    - Over 40 commercial/gov't entities are party to NASA's AFTU tech transfer package.
- **Interoperability Demonstrations:**
  - NASA Flight Opportunities Program hosted Qascom GPS/Galileo receiver on UP Aerospace SL-14 flight (2019) for interoperability demonstration as AFTS input (Joint NASA/ASI/Qascom experiment)
    - See Longo, "GARHEO Flight Experiment to Test GPS-Galileo Interoperability to Support Launchers and Space Missions" (ION GNSS+ 2020, Session B4) for SL-14 results.
  - NASA Flight Opportunities Program will host follow-on NASA/ASI and NASA/ESA experiments on UP Aerospace SL-15 flight (2021) to evaluate further use of multi-GNSS for AFTS input.

SSV International Collaborations

International Committee on GNSS (ICG)

- **The ICG emerged from 3rd UN Conference on the Exploration and Peaceful Uses of Outer Space (July 1999) to:**
  - Promote the use of GNSS and its integration into infrastructures, particularly in developing countries
  - Encourage compatibility & interoperability among global and regional systems
- **Members:** GNSS Providers (US—GPS, Europe—Galileo, Russia—GLONASS, China--BeiDou, India—NavIC, Japan—QZSS), Other Member States of the United Nations
- **Observers**: International organizations (e.g. Interagency Operations Advisory Group), others
- **Annual Meetings**:
  - 13th ICG hosted by China in Xi'an, November 4-9, 2018 (http://icg13.beidou.gov.cn/)
  - 14th ICG hosted by India in Bangalore, December 8-13, 2019 (https://www.unoosa.org/oosa/en/ourwork/icg/meetings/ICG-2019.html)
  - 15th ICG to be held at the UN in Vienna, Austria, September 27-October 1, 2021 (Postponed from 2020 due to COVID-19)

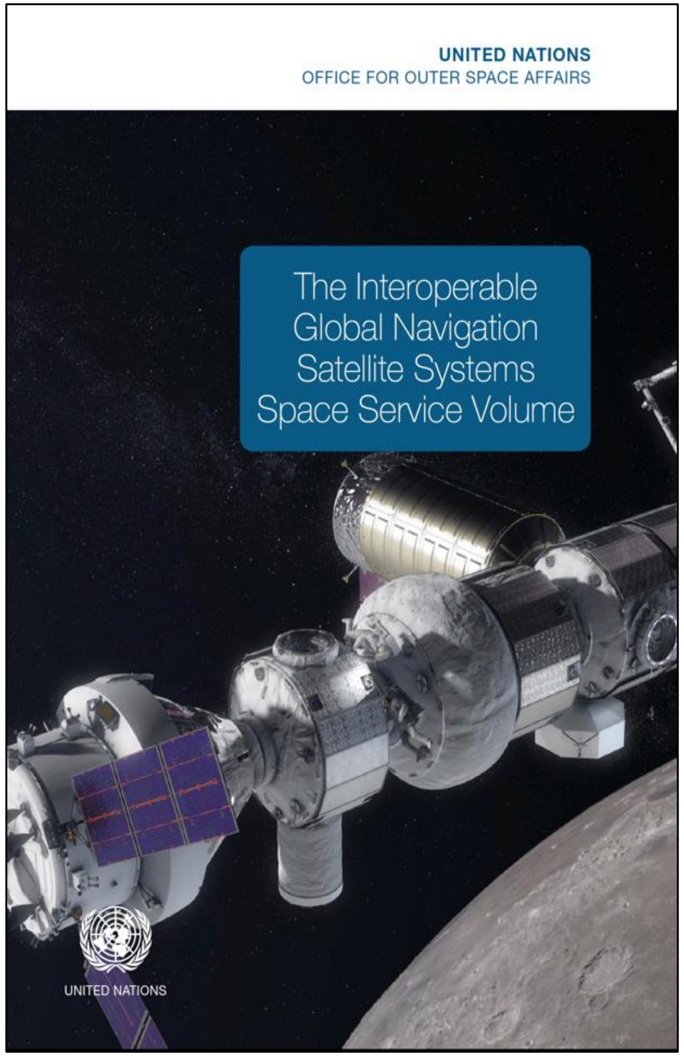
https://www.unoosa.org/oosa/en/ourwork/icg/icg.html

ICG – WG-B Space Users Subgroup (SUSG)

- **Created at ICG-13 (2018) to focus efforts on GNSS interests for space user community**
  - **Chairs**: US, Europe, China,
  - **Participants**: US, Europe, China, India, Japan, Russia.
  - **Meetings**: held monthly

- **Main Objectives of SUSG, as defined in the Terms of Reference**
  - Lead evolution of the Interoperable Multi-GNSS Space Service Volume including the use of GNSS for missions beyond the existing SSV (e.g. lunar)
  - Encourage developments of space-based user equipment and emerging user community
  - Encourage coordination with Interagency Operations Advisory Group (IOAG) and International Space Exploration Coordination Group (ISECG)
  - Encourage development of new services and augmentations beneficial to space users
  - Promote space user community needs within ICG.

WG-B SUSG Product: Interoperable Multi GNSS SSV Booklet



- **December 2018: First publication of SSV performance characteristics for each GNSS constellation**
  - Received signal power, signal availability, pseudorange accuracy to GEO distance for each band
  - Conservative performance employing main lobe signals only
- **Global and mission-specific visibility analyses provide real-world examples for spacecraft project managers to compare**
  - GEO
  - Highly-elliptical
  - Lunar
- **Book Identifier: ST/SPACE/75**
- **Electronically available at:** https://undocs.org/st/space/75
- **Hard copies are provided to UNHQ (New York) for public sales.**

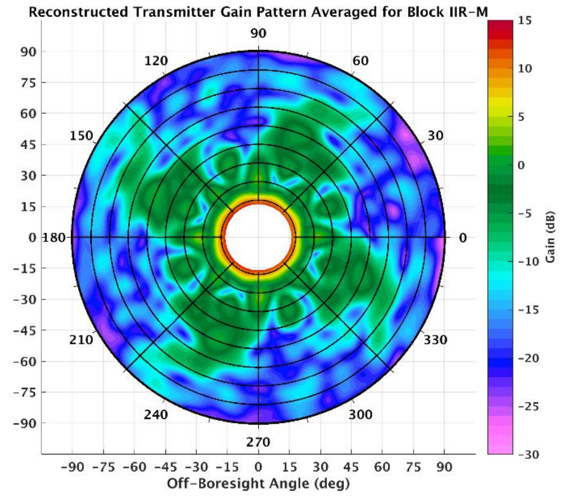
Space Users Subgroup (SUSG) – Work Plan 2019 to 2021

- **SSV Booklet – 2nd Edition to be published in 2021**
  - Full revision and update of all chapters, including GNSS constellation updates
  - New content – Flight Experiences, Geometric Dilution Indicator (GDI) (similar to DOP)
  - Milestones:
    - Completed analysis comparison between NASA & ESA; analysis concurred by international SUSG team
    - ICG-15: SSV Booklet planned release (Fall 2021)
- **SSV Video – Full release in 2021**
  - Four minute video, developed as an outreach tool to:
    - Explain utility and benefits of a multi-GNSS SSV
    - Show how it will transform navigation use in space, and
    - Describe how it will impact humanity—in space and on Earth
  - Co-Sponsors: NASA and National Coordination Office for Space-based Positioning, Navigation and Timing
  - Expected release: Late 2020/early 2021

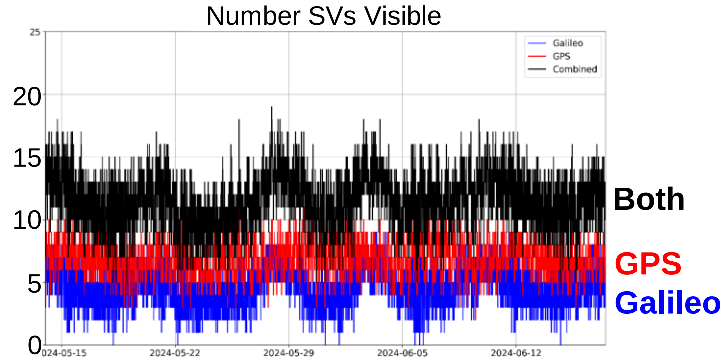
- **New activities**
  - Release and inclusion of GNSS antenna side lobe data
  - Development of space user requirements for multi-GNSS time reference
  - Initiation of potential GNSS space use standards via CCSDS
  - Cislunar initiatives
    - Identification and analysis of major Moon and Mars use cases
    - Analysis of benefits of GNSS augmentations for lunar activities
    - Standardization aspects for GNSS SSV space users including cislunar and beyond
    - Exploration with a focus usage of GNSS for Moon missions

Enabling the SSV: Interagency & International Collaborations

- **2017 Joint NASA-USAF SSV MOU**
  - As US civil space representative, provides NASA insight into GPS IIIF satellite procurement, design and production from an SSV perspective
  - Intent is to ensure SSV signal continuity for future space users
  - Currently working on release of GPS III (SV1-10) antenna data
- **GPS Antenna Characterization Experiment**
  - First complete mapping of GPS L1 side lobes for all GPS satellites via GEO-based bent pipe
  - Data set available at https://esc.gsfc.nasa.gov/navigation
- **Galileo released calibrated phase center offset (PCO) data**
  - Recommendation by ICG; offers a tremendous science benefit
- **Release of expected Lunar GNSS performance employing Galileo main and side lobe signals**
  - Resulting from joint ESA/NASA collaboration on Lunar Gateway
- **Cautiously optimistic that Galileo side lobe antenna models to be released soon**
  - Release will provide space users substantially improved performance characterization of Galileo in and above the SSV
- **NASA encourages public release of all GPS antenna patterns per recommendation by the ICG**

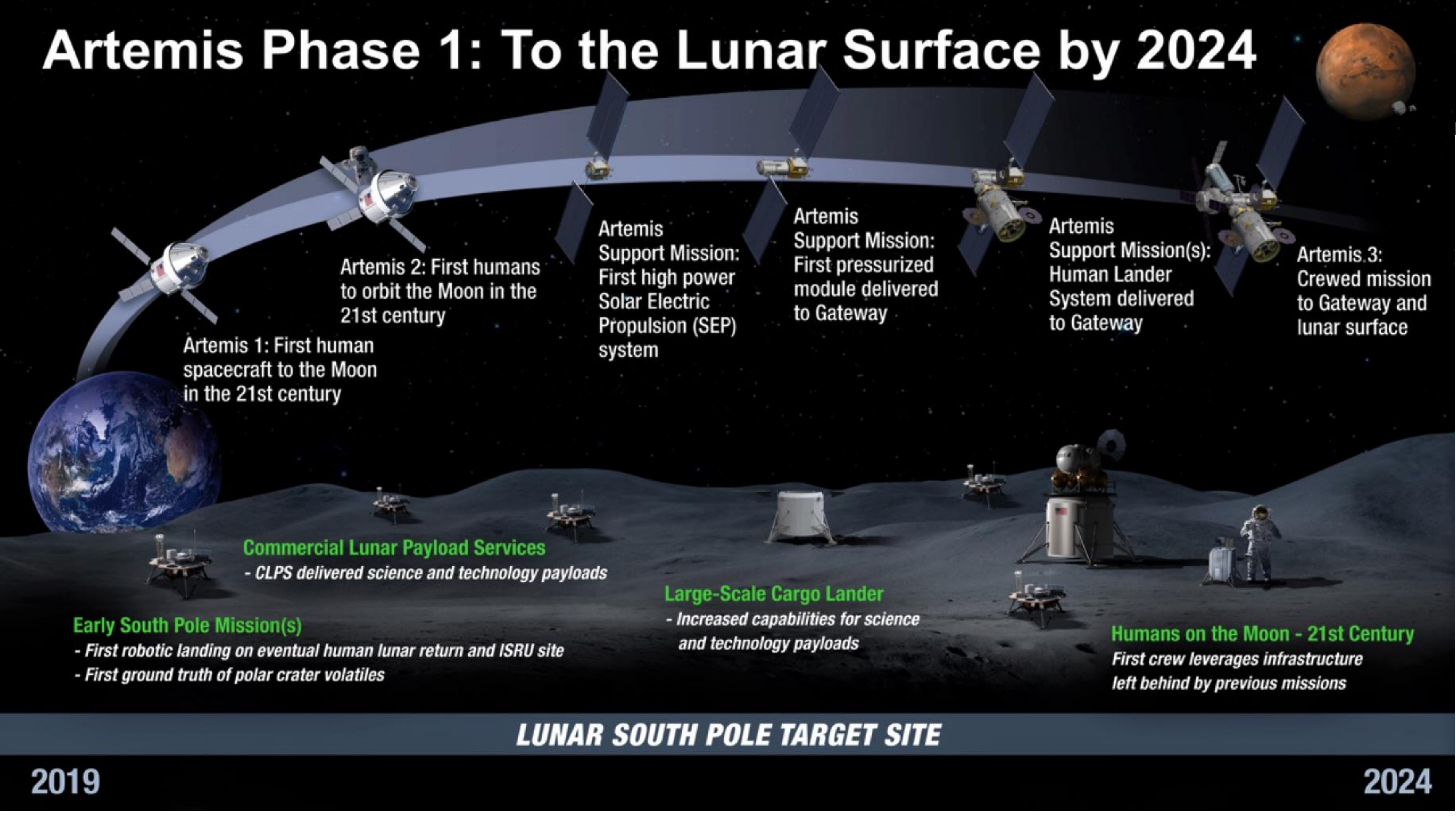


Block IIR-M reconstructed pattern from GPS ACE



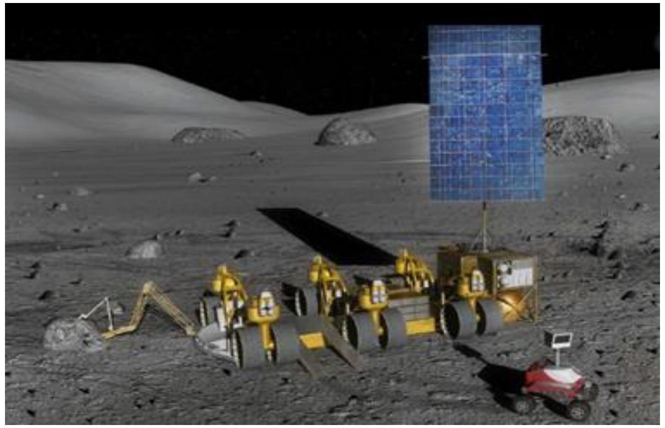
Predicted Gateway GPS/Galileo visibility
(20 dB-Hz; courtesy ESA)

Next SSV Opportunity: Employing GNSS for Lunar Exploration

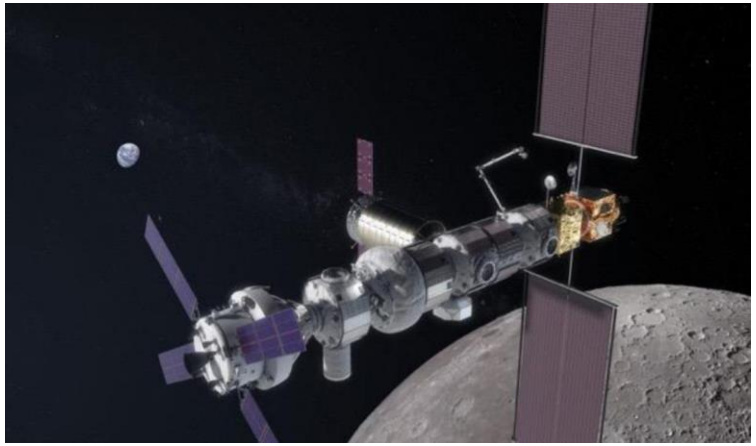


Artemis Phase 1: To the Lunar Surface by 2024
Artemis 1: First human spacecraft to the Moon in the 21st century
Artemis 2: First humans to orbit the Moon in the 21st century
Artemis Support Mission: First high power Solar Electric Propulsion (SEP) system
Artemis Support Mission: First pressurized module delivered to Gateway
Artemis Support Mission(s): Human Lander System delivered to Gateway
Artemis 3: Crewed mission to Gateway and lunar surface
Commercial Lunar Payload Services
- CLPS delivered science and technology payloads
Early South Pole Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE
2019
2024

Lunar Exploration Mission Classes Benefited by GNSS Navigation & Timing

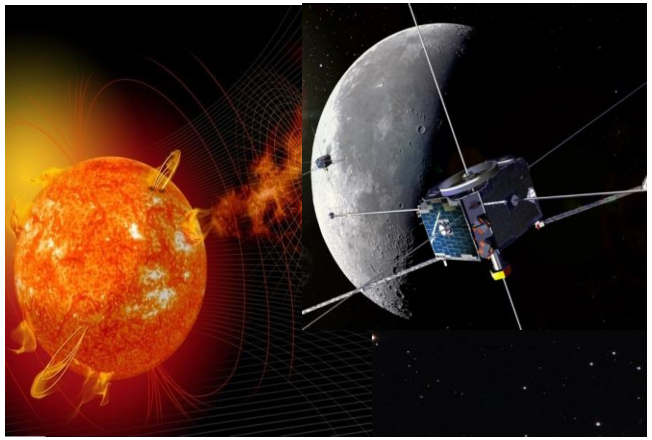


Lunar Surface Operations, Robotic Prospecting, & Human Exploration

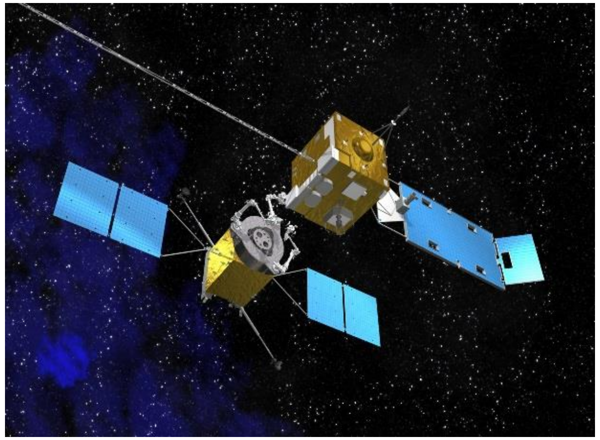


Human-tended Lunar Vicinity Vehicles (Gateway)

Robotic Lunar Orbiters, Resource & Science Sentinels



Earth, Astrophysics, & Solar Science Observations



Satellite Servicing

Lunar Exploration Infrastructure, Lunanet

Opportunity: Artemis-1/Orion

- **Background**
  - Orion (human capsule) has first lunar flight on Artemis-1, Apr 2021
  - Carries Honeywell receiver with NASA fast-acquisition technology (not weak-signal)
  - Intended for LEO (reentry) use only
  - Receiver will remain on and collecting data through entire lunar phase
- **Status**
  - Analysis activity underway to predict Artemis-1 expected GPS lunar performance.
    - Employing on-orbit data from Exploration Test Flight 1 (EFT-1) and MMS to simulate expected GPS performance around the moon

Opportunity: Lunar Gateway

- **Studies underway on benefits & performance of GNSS receiver on Lunar Gateway platform**
- **Benefits include:**
  - **Leverage existing *always-on* Earth-based infrastructure for navigation and timing**
    - Improves vehicle autonomy, responsiveness, operational robustness
    - Reduces ground ops burden, scheduling and cost
    - Improves PNT accuracy and stability; reduces orbit maintenance ΔV; supports visiting vehicles
  - **Reduce network loading and increase onboard mission capability**
  - **Enable crewed autonomous navigation and timing in the event of loss of communication**
  - **Enable real-time precise onboard PNT distribution for all Gateway payloads**
    - Better science, smaller payloads (ISS lesson learned)
    - Eliminates need for payload to provide separate PNT systems, antennas, etc.
    - Necessary to deliver PNT services to lunar customers, e.g. via relay
- **NASA/ESA collaboration demonstrates benefits of GPS/Galileo combined receiver for improved visibility**

Gateway: Projected GNSS Performance at the Moon

"GPS Based Autonomous Navigation Study for the Lunar Gateway"

Winternitz et al. 2019

- Considered performance on Gateway of MMS-like navigation system with Earth-pointed high-gain antenna (~14 dBi) and GEONS flight filter software
- Calibrated with flight data from MMS Phase 2B
- L2 southern Near Rectilinear Halo Orbit (NRHO), 6.5 day period
- 40 Monte Carlo runs for cases below, w/ & w/o crew
- Uncrewed & crewed (w/ disturbance model) 3 x RMS average over last orbit:

Uncrewed	Position (m)		Velocity (mm/s)		Update Rate
	Range	Lateral	Range	Lateral	
Ground Tracking (8 hr/pass, 3–4 passes/orbit)	**33**	**468**	**1**	**10.6**	**Hours, Ground-Based**
GPS + RAFS*	**9**	**31**	**0.2**	**1.2**	**Real-Time, Onboard**

*Rubidium Atomic Frequency Standard

Conclusions

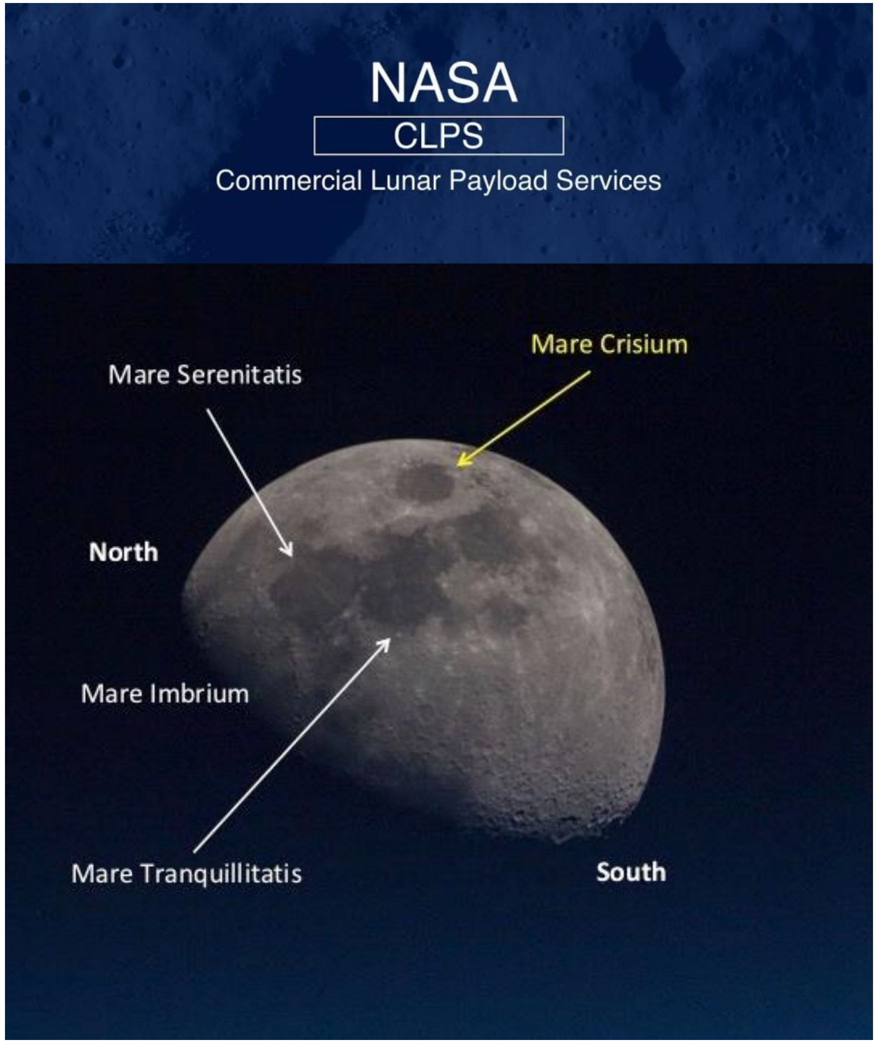
- Average of 3 GPS signals tracked in NRHO
- Fewer Ground Station tracks, larger gaps than GPS
- GPS shows additional improvement over typical ground-based tracking when crew perturbations are included
- Ground tracking Nav: ***Hours***; GNSS Nav: ***Seconds***
- Beacon augmentations can further improve nav performance
- ***GNSS can provide a simple, high-performance, onboard, real-time navigation solution for Gateway***

Crewed	Position (m)		Velocity (mm/s)		Update Rate
	Range	Lateral	Range	Lateral	
Ground Tracking (8 hr/pass, 3–4 passes/orbit)	**451**	**8144**	**18**	**155**	**Hours, Ground-Based**
GPS + RAFS*	**21**	**77**	**4**	**12**	**Real-Time, Onboard**

Interoperable multi-GNSS GPS-Galileo capability improves system redundancy, resiliency, & robustness while also enhancing navigation & timing performance

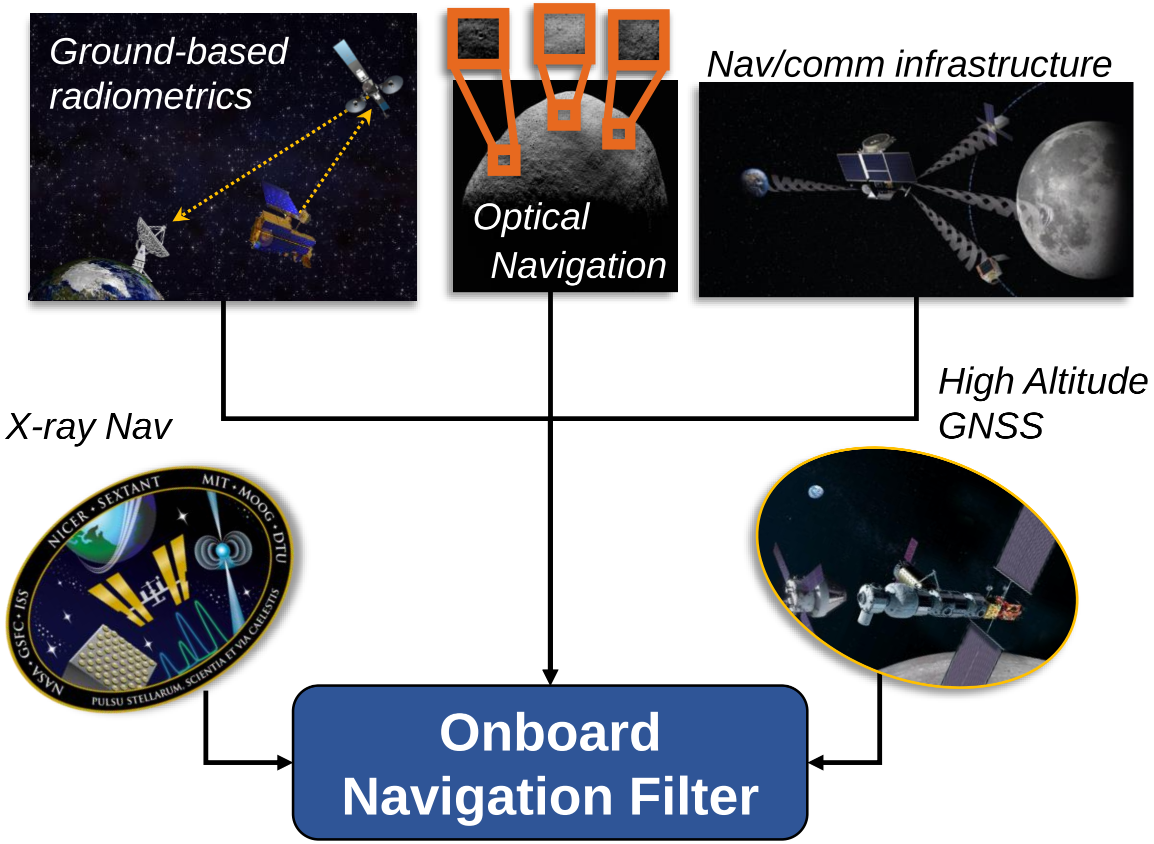
Opportunity: Lunar GNSS Receiver Experiment (LuGRE)
CLPS "19D" Payload

- **Flight Opportunity**
    - CLPS "19D" RFP
    - Flight to lunar mid-latitude region, landing NLT June 30, 2023
    - Award to CLPS vendor expected Winter 2020
    - Expected surface duration: one lunar day (12 Earth days)
- **Payload**
    - Objectives
        - Obtain first GNSS fix on the lunar surface
        - Utilize received data for development of operational lunar GNSS systems
        - Utilize received data to benefit collaborative science
    - Partnership w/ ASI (Italian Space Agency)
    - Payload is ASI-provided high-altitude GPS+Galileo receiver & NASA antenna/front end
    - Integration at NASA GSFC
- **Status**
    - Accepted as 10th payload in CLPS "19D" draft RFP
    - Milestones:
        - Jul 31: Draft RFP published
        - Aug 19–20: Payload Workshop
        - Winter 2020: Award (expected)



ESA-NASA Vision for Deep Space GNSS

Critical Capability for a Diversified Portfolio to Support Lunar Navigation & Timing



Robust cislunar PNT relies on a diversity of navigation sources, each with strengths and weaknesses

- GNSS
- Nav & comm infrastructure (lunar surface, Gateway, orbital)
- Ground-based tracking
- Optical navigation
- X-ray pulsar navigation
- LIDAR, radar
- Other sources (signals of opportunity, etc.)

Lessons learned with GNSS in cislunar space will accelerate & strengthen future exploration (Moon/Mars) nav & comm architectures/capabilities

Coordinated, Phased ESA-NASA Development/Deployment Approach for Gateway will optimize navigation and timing performance soonest, providing outstanding benefits to international science and technology missions in cislunar space

Conclusions

- NASA is engaged in enhancing the benefit of space use of GNSS on two fronts:
  - Increased interoperability improves performance and resilience by using multiple constellations
  - Extending the reach of the SSV to cislunar space benefits and simplifies navigation across the lunar architecture.
- Today, we continue to work to ensure that the GPS and GNSS capability keeps pace with user demands, including its expansion into lunar space
  – Results derived from MMS and GOES data show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven* receiver technology.
  – GARISS, SL-14 and SL-15 flights demonstrate utility of interoperable multi-GNSS for space users
  – ICG is a natural forum for these continuing discussions
- NASA and the U.S. Government are proud to work with the GNSS providers to contribute making GNSS services more accessible, interoperable, robust, and precise for all users, for the benefit of humanity.