NASA Space User Update

WG-B—Enhancement of GNSS Performance, New Services & Capabilities

Joel Parker, PNT Policy Lead, NASA Goddard Space Flight Center

On behalf of

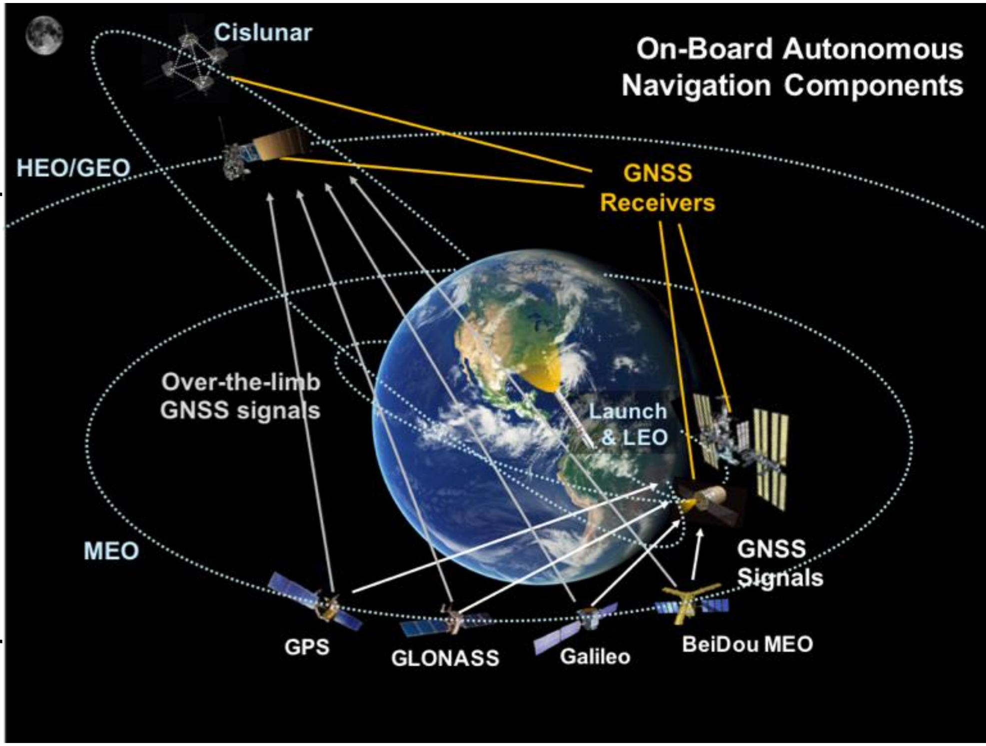
JJ Miller, Deputy Director, NASA SCaN Policy and Strategic Communications Office

Xi'an, China, November 4–9, 2018

joel.j.k.parker@nasa.gov

Space Uses of Global Navigation Satellite Systems (GNSS)

- **Real-time On-Board Navigation:** Precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences:** GPS as a measurement for atmospheric and ionospheric sciences, geodesy, and geodynamics
- **Launch Vehicle Range Operations:** Automated launch vehicle flight termination; providing safety net during launch failures & enabling higher cadence launch facility use
- **Attitude Determination:** Some missions, such as the International Space Station (ISS) are equipped to use GPS/GNSS to meet their attitude determination requirements
- **Time Synchronization:** Support precise time-tagging of science observations and synchronization of on-board clocks



GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

NASA GNSS User Segment

Status Update

In response to Recommendation ICG/WGB/2016-2:
GNSS Space User Database

Space User Database

- ICG-11 recommendation encourages providers, agencies, and research organizations to publish details of GNSS space users to contribute to IOAG database.
- IOAG database of GNSS space users updated on 20 September 2018
- Current database details included in backup slides – spreadsheet will be distributed separately.
- Please encourage your service providers, space agencies and research institutions to contribute to the GNSS space user database via your IOAG liaison or via WG-B.

Number of Missions / Programs by Agency

ASI	Agenzia Spaziale Italiana	4
CNES	Centre national d'études spatiales	10
CSA	Canadian Space Agency	5
DLR	German Aerospace Center	11
ESA	European Space Agency	17
JAXA	Japan Aerospace Exploration Agency	12
NASA	National Aeronautics and Space Administration	43
	Total	**102**

NASA GNSS User Update

Mission status updates and modifications:

Agency	Mission	GNSS Used	GNSS Signals Used	GNSS Application	Orbit	Launch	Notes
~~NASA~~	~~GRACE (2 satellites)~~	~~GPS~~	~~L1 C/A, L1/L2 semicodeless~~	~~Precise Orbit Determination, Occultation, precision time~~	~~LEO~~	~~2002~~	BlackJack receiver, joint mission with DLR. 2018 Update: Mission retired 13 October, 2017
NASA	Orion/MPCV	GPS	L1 C/A	Orbit / navigation	LEO/ Cislunar	2014 - Earth Orbit, 2020 Cislunar	Honeywell Aerospace 'Mercury' SPS GPS receiver with GSFC 'Navigator" software.
NSPO/USAF/NASA	COSMIC IIA (6 satellites)	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2019	TriG receiver, 8 RF inputs, hardware all-GNSS capable, will track GPS + GLONASS at launch
NASA	DSAC	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Time transfer	LEO	2019	TriG lite receiver
NASA/ESA	Sentinel S6 (Jason-CS), 2 SATELLITES	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Occultation, Precise Orbit Determination	LEO	2020 and 2025	TriG receiver with 1553,
NASA	~~iSat~~	~~GPS~~	~~L1 C/A~~	~~Orbit Determination~~	~~LEO~~	~~2018~~	Iodine Satellite CubeSat. 1 Year LEO Mission. GPS = SpaceQuest (NovAtel) SQ-GPS-12-V1. 2018 update: The iSat mission has been tabled until Iodine Thruster issues are resolved.
NASA	~~MAPS~~	~~GPS~~	~~L1 C/A~~	~~Formation Flying pathfinder on ISS testbed~~	~~LEO~~	~~2018~~	2018 Update: De-scoped to no longer use GPS.

Red text indicates changes from ICG-12

Updates from Nov 2017 database, as of 20 Sep 2018; full database in backup

NASA GNSS User Update

Mission status updates and modifications:

Agency	Mission	GNSS Used	GNSS Signals Used	GNSS Application	Orbit	Launch	Notes
~~NASA~~	~~GRACE (2 satellites)~~	~~GPS~~	~~L1 C/A, L1/L2 semicodeless~~	~~Precise Orbit Determination, Occultation, precision time~~	~~LEO~~	~~2002~~	BlackJack receiver, joint mission with DLR. 2018 Update: Mission retired 13 October, 2017
NASA	Orion/MPCV	GPS	L1 C/A	Orbit / navigation	LEO/ Cislunar	2014 - Earth Orbit, 2020 Cislunar	Honeywell Aerospace 'Mercury' SPS GPS receiver with GSFC 'Navigator" software.
NSPO/USAF/NASA	COSMIC IIA (6 satellites)	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2019	TriG receiver, 8 RF inputs, hardware all-GNSS capable, will track GPS + GLONASS at launch
NASA	DSAC	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Time transfer	LEO	2019	TriG lite receiver
NASA/ESA	Sentinel S6 (Jason-CS), 2 SATELLITES	GPS, GLONASS FDMA, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Occultation, Precise Orbit Determination	LEO	2020 and 2025	TriG receiver with 1553,
NASA	~~iSat~~	~~GPS~~	~~L1 C/A~~	~~Orbit Determination~~	~~LEO~~	~~2018~~	Iodine Satellite CubeSat. 1 Year LEO Mission. GPS = SpaceQuest (NovAtel) SQ-GPS-12-V1. 2018 update: The iSat mission has been tabled until Iodine Thruster issues are resolved.
NASA	~~MAPS~~	~~GPS~~	~~L1 C/A~~	~~Formation Flying pathfinder on ISS testbed~~	~~LEO~~	~~2018~~	2018 Update: De-scoped to no longer use GPS.

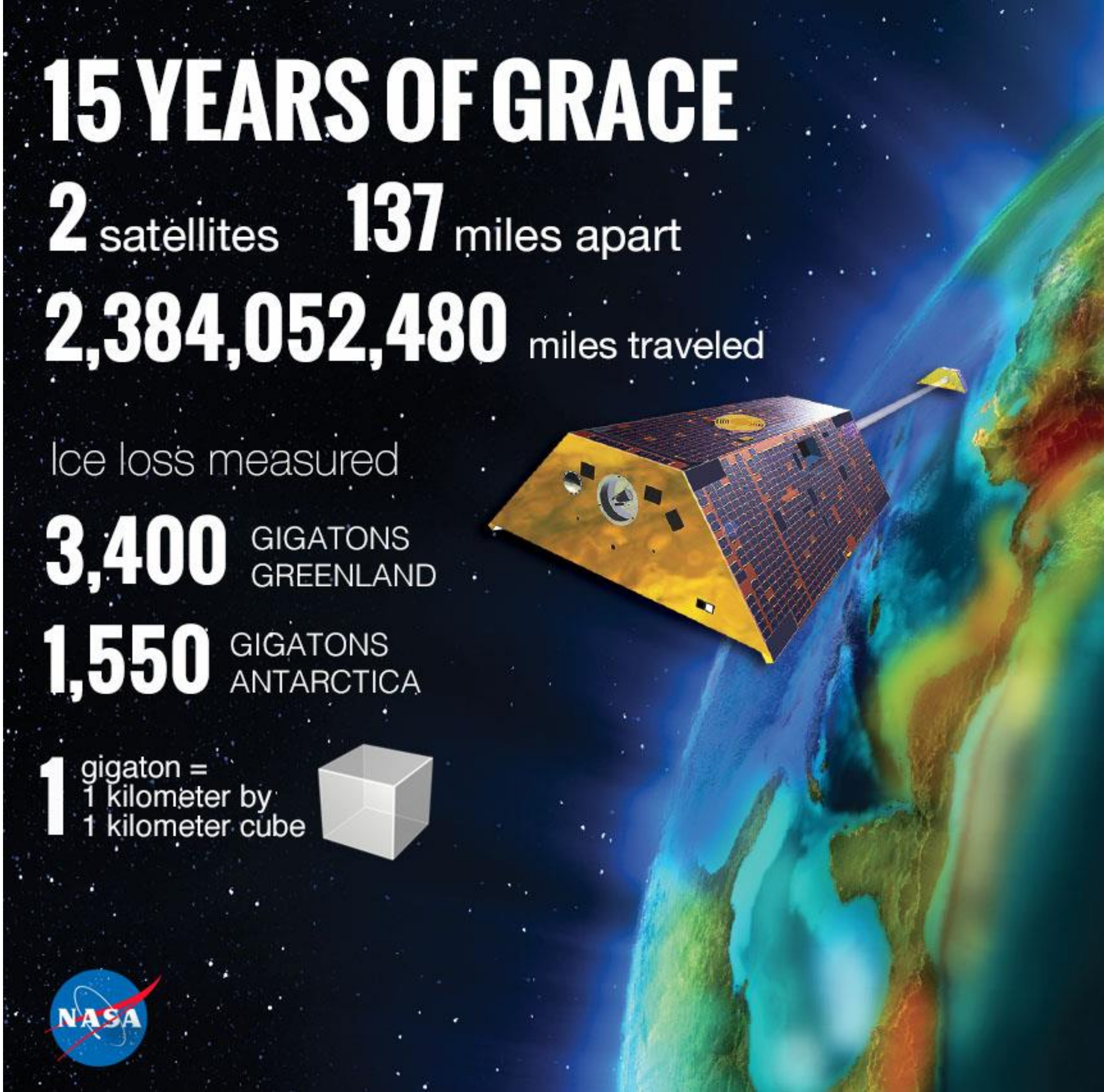
Red text indicates changes from ICG-12

Updates from Nov 2017 database, as of 20 Sep 2018; full database in backup

Main radiometric instrument:

NASA/JPL BlackJack GPS receiver modified to track gravity-sensing crosslinks, and to form star-camera solutions, while producing cm-level POD and 0.1 nanosecond relative time transfer.

The Onera accelerometer was also required to produce accurate gravity maps.



(image credit: NASA)

Results from GRACE

GRACE data have significantly improved understanding of: the global water cycle, mass and energy exchange within and between the Earth System components, the changes in ocean mass, the changing dynamics of polar ice caps and large continental aquifers and improved the prospects for assimilation of mass change data into climate models.

Examples of science applications include:

Sea level change

Surface and Deep Ocean Currents

Ocean heat storage

Polar and continental ice sheet melt

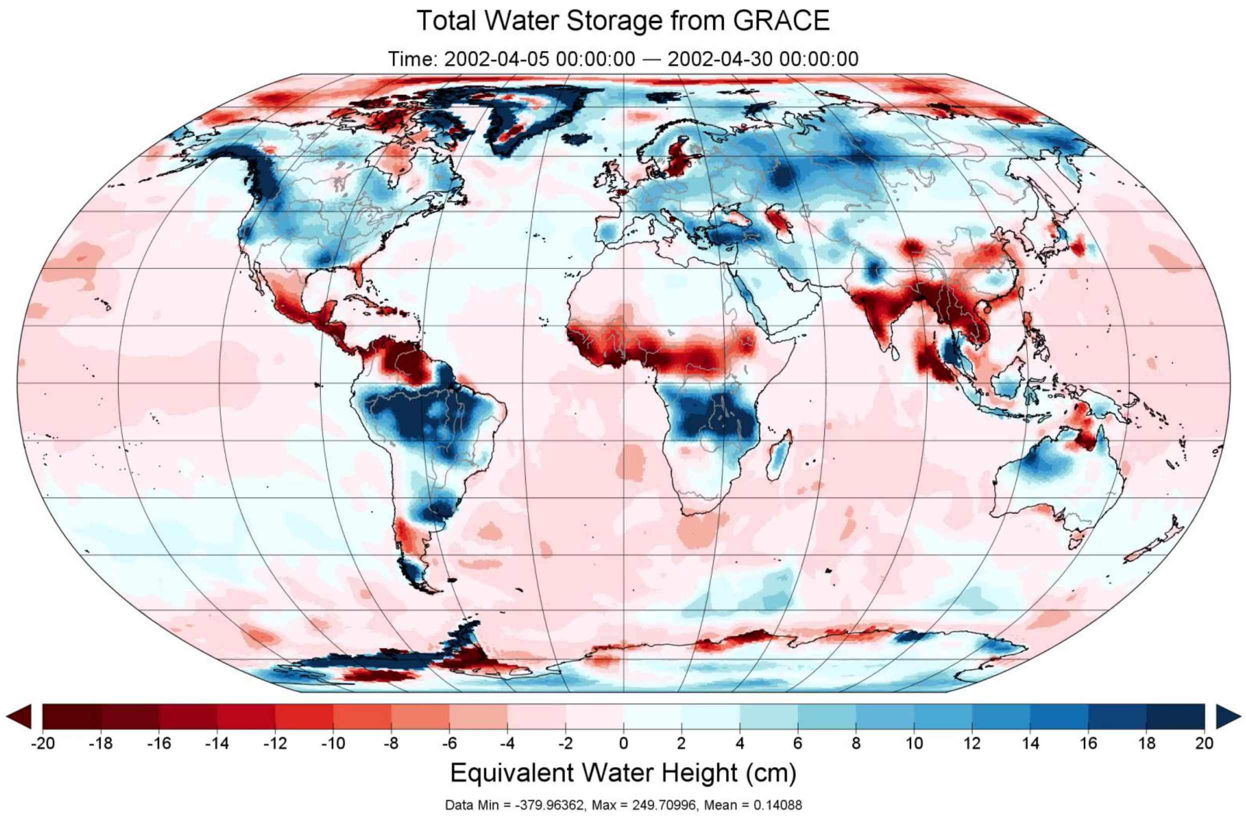
Earth system mass transport

Drought and flooding

Land surface total water storage

Modeling and assimilation

Earthquake assessment



NASA GNSS User Update

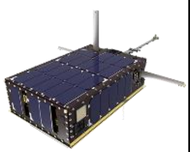
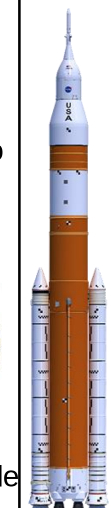
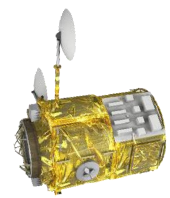
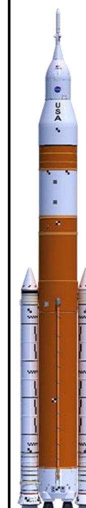
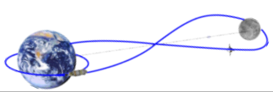
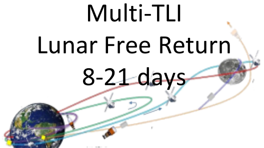
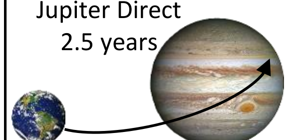
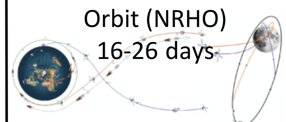
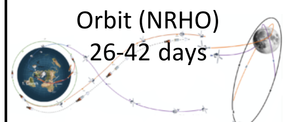
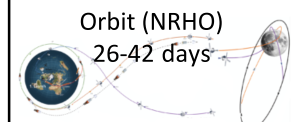
Mission status updates and modifications:

Agency	Mission	GNSS Used	GNSS Signals Used	GNSS Application	Orbit	Launch	Notes
NASA	SLS - ICPS (EM-1)	GPS	L1 C/A Receiver	Orbit Determination, TLI burn, End-of-Mission Disposal	Un-Crewed Cis-Lunar Trajectory	2021	Ascent: No GPS Orbit: Honeywell SIGI with SPS Trimble Force 524D
NASA	SLS - ICPS (EM-2)	GPS	L1 C/A Receiver	Orbit Determination, TLI burn, End-of-Mission Disposal	Crewed Multi-TLI Lunar Free Return	2022	Orbit: Honeywell SIGI with SPS Trimble Force 524D
NASA	SLS - EUS (SM-1)	GPS	L1 C/A Receiver	Orbit Determination, TLI burn, End-of-Mission Disposal	Jupiter Direct Science Cargo Mission	2023	Orbit: Honeywell Mercury L1 SPS GPS for operation at > 8,000 km altitude
NASA	SLS - EUS (EM-3)	GPS	L1 C/A Receiver	Orbit Determination, TLI burn, End-of-Mission Disposal	Near-Rectilinear Lunar Halo Orbit (NRLHO)	2024	Orbit: Honeywell Mercury L1 SPS GPS or operation at > 8,000 km altitude
NASA	SLS - EUS (EM-4)	GPS	L1 C/A Receiver	Orbit Determination, TLI burn, End-of-Mission Disposal	Near-Rectilinear Lunar Halo Orbit (NRLHO)	2025	Orbit: Honeywell Mercury L1 SPS GPS for operation at > 8,000 km altitude

Red text indicates changes from ICG-12

Updates from Nov 2017 database, as of 20 Sep 2018; full database in backup

GPS use aboard Space Launch System

EM-1 Exploration Mission 1	EM-2 Exploration Mission 2	SM-1 Science Mission 1	EM-3 Exploration Mission 3	EM-4 Exploration Mission 4	EM-5 Exploration Mission 5
2021	2022	2023	2024	2025	2026
Block 1: ICPS	Block 1: ICPS	Block 1B Cargo	Block 1B: EUS	Block 1B: EUS	Block 1B: EUS
Cargo	4 Crew	Europa Clipper	4 Crew	4 Crew	4 Crew
 Cis-Lunar Space Mission to confirm vehicle performance and operational capability.  13 CubeSat Payloads	 First crewed mission, to confirm vehicle performance and operational capability, same profile as EM-1.  Orion Capsule + Crew	 First cargo mission configuration.  Europa Clipper to Jupiter	 First Orion Docking to extract Habitat Module from EUS, deliver to Lunar Orbit Platform - Gateway  LOP-G Habitat Module	 Deliver Logistics Module to Lunar Gateway  LOP-G Logistics Module	 Deliver Airlock Element to Lunar Gateway  LOP-G Airlock Element
Cis-Lunar Trajectory 11-21 days 	Multi-TLI Lunar Free Return 8-21 days 	Jupiter Direct 2.5 years 	Near-Rectilinear Halo Orbit (NRHO) 16-26 days 	Near-Rectilinear Halo Orbit (NRHO) 26-42 days 	Near-Rectilinear Halo Orbit (NRHO) 26-42 days 
Honeywell SIGI with SPS Trimble Force 524D (L1 C/A Code Only) for Orbit Determination, Trans-Lunar Injection Burn and End-of-Mission disposal burn.	SIGI w/SPS Force 524D	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.	Honeywell Mercury SPS for High-Alt SLS Vehicle Nav.

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

NASA GNSS User Update

Newly-added NASA missions:

Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch	Notes
NASA	Restore-L	GPS	L1 C/A	Orbit determination, spacecraft timing, GNSS measurements part of multi-sensor nav filter for AR&D with Landsat 7	LEO (Earth Polar)	2022 (Target)	Ruag
NASA	PACE	GPS	L1 C/A	Orbit Determination	LEO	2022	

Red text indicates changes from ICG-12

Updates from Nov 2017 database, as of 20 Sep 2018; full database in backup

Restore-L

MISSION FACTS

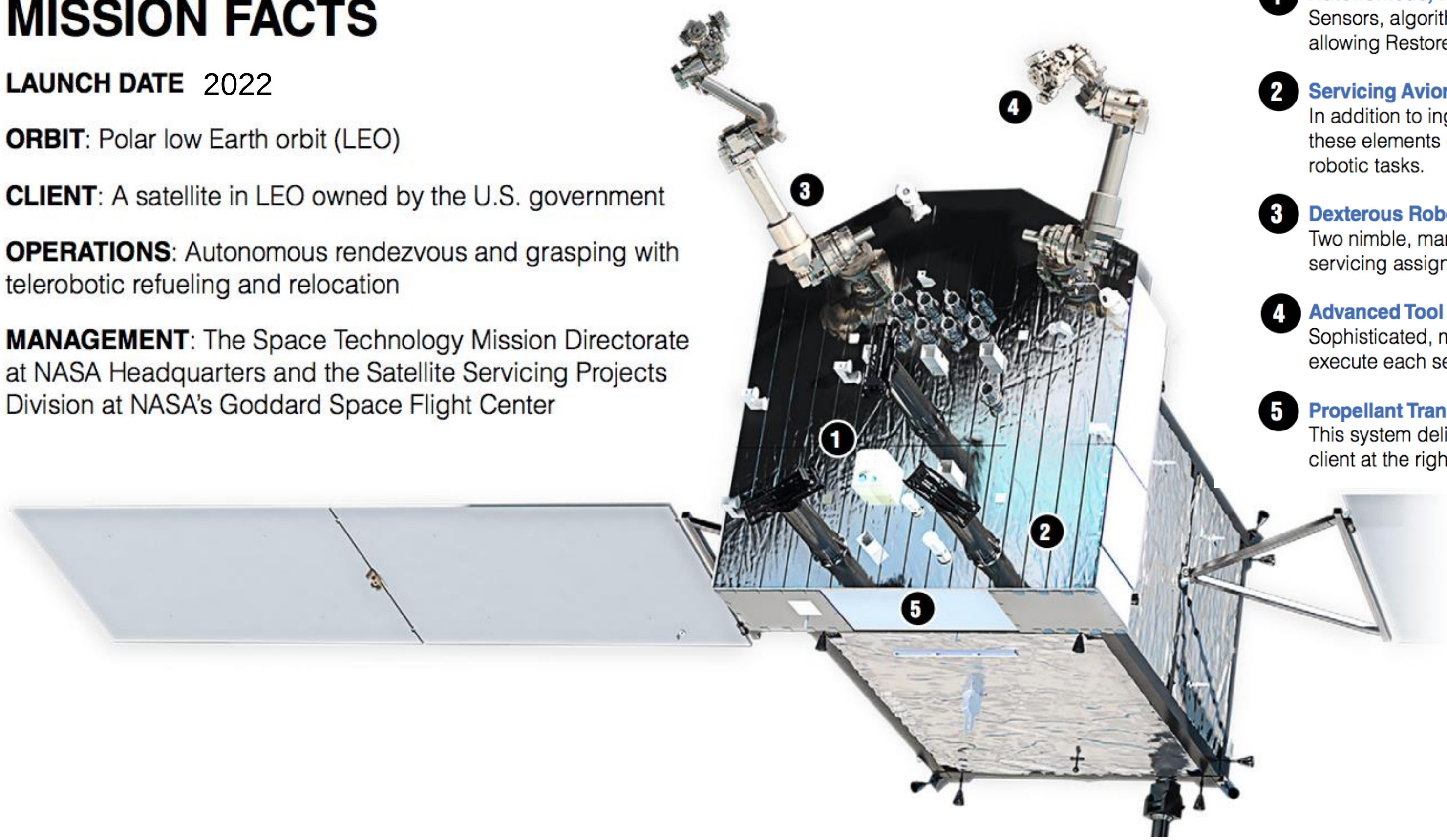
LAUNCH DATE 2022

ORBIT: Polar low Earth orbit (LEO)

CLIENT: A satellite in LEO owned by the U.S. government

OPERATIONS: Autonomous rendezvous and grasping with telerobotic refueling and relocation

MANAGEMENT: The Space Technology Mission Directorate at NASA Headquarters and the Satellite Servicing Projects Division at NASA's Goddard Space Flight Center



SERVICING TECHNOLOGIES

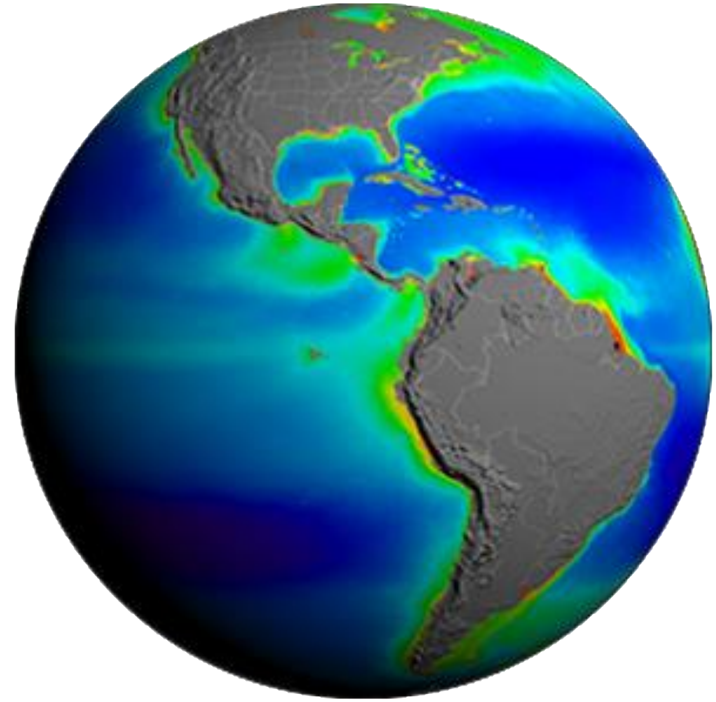
1. **Autonomous, Real-Time Relative Navigation System**
   Sensors, algorithms and processors join forces, allowing Restore-L to rendezvous safely with its client.
2. **Servicing Avionics**
   In addition to ingesting and crunching sensor data, these elements control Restore-L's rendezvous and robotic tasks.
3. **Dexterous Robotic Arms**
   Two nimble, maneuverable arms precisely execute servicing assignments. Software comes included.
4. **Advanced Tool Drive And Tools**
   Sophisticated, multifunction tools are manufactured to execute each servicing task.
5. **Propellant Transfer System**
   This system delivers measured amounts of fuel to the client at the right temperature, pressure and rate.

(image credit: NASA)

credit: NASA)

PACE MISSION

PACE will extend and improve NASA's 20 plus years of global satellite observations of our living ocean, atmospheric aerosols, and clouds and initiate an advanced set of climate-relevant data records. By determining the distribution of phytoplankton, PACE will help assess ocean health. It will also continue key measurements related to air quality and climate.



Science Goals

To extend systematic ocean color, atmospheric aerosol, and cloud data records for Earth system and climate studies. To address new and emerging science questions by detecting a broader range of color wavelengths that will provide new and unprecedented detail.

Key Mission Characteristics

- Hyperspectral ocean color instrument
- Two multi-angle polarimeters
- Launch readiness date: Fall 2022
- 675 km (419 mi) orbital altitude
- Sun-synchronous, polar orbit
- Global coverage every two days
- Managed by Goddard Space Flight Center

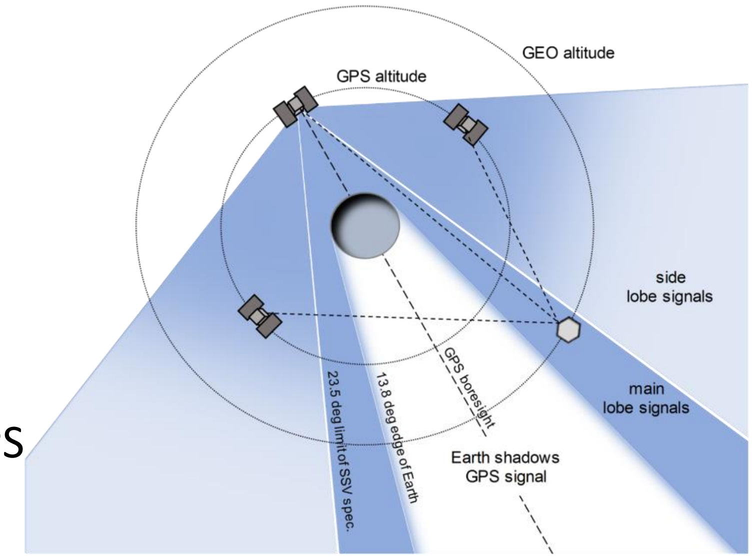
(image credit: NASA)

GPS Antenna Characterization Experiment

GPS Antenna Characterization Experiment (ACE)

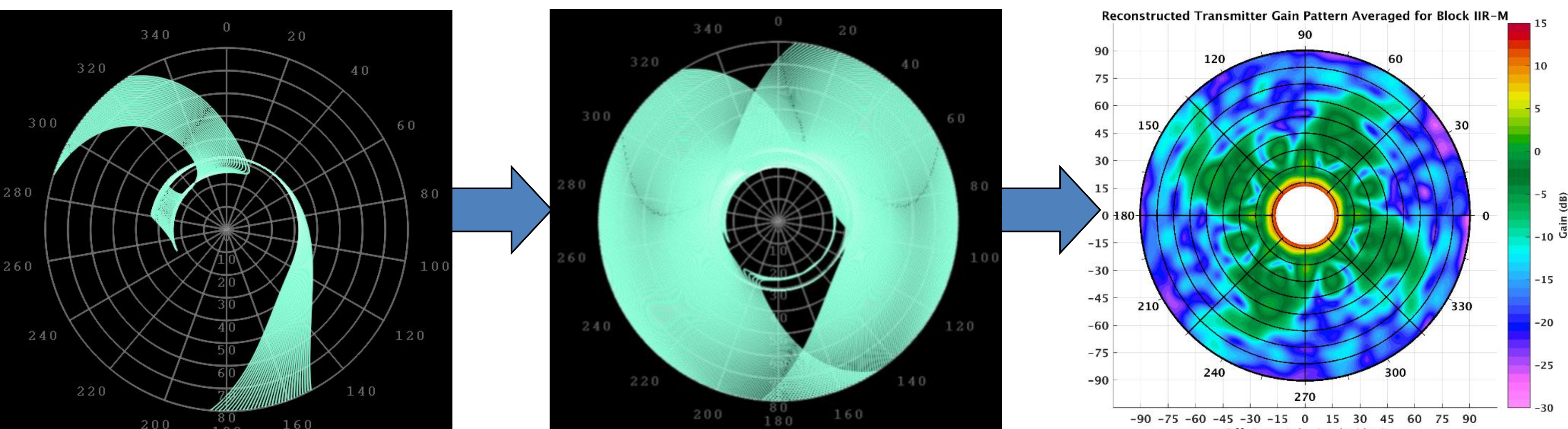
Overview

- GPS L1 C/A signals from GEO are available at a ground station through a “bent-pipe” architecture
- Map side lobes by inserting advanced, weak-signal tracking GPS receivers at ground station to record observations from GEO



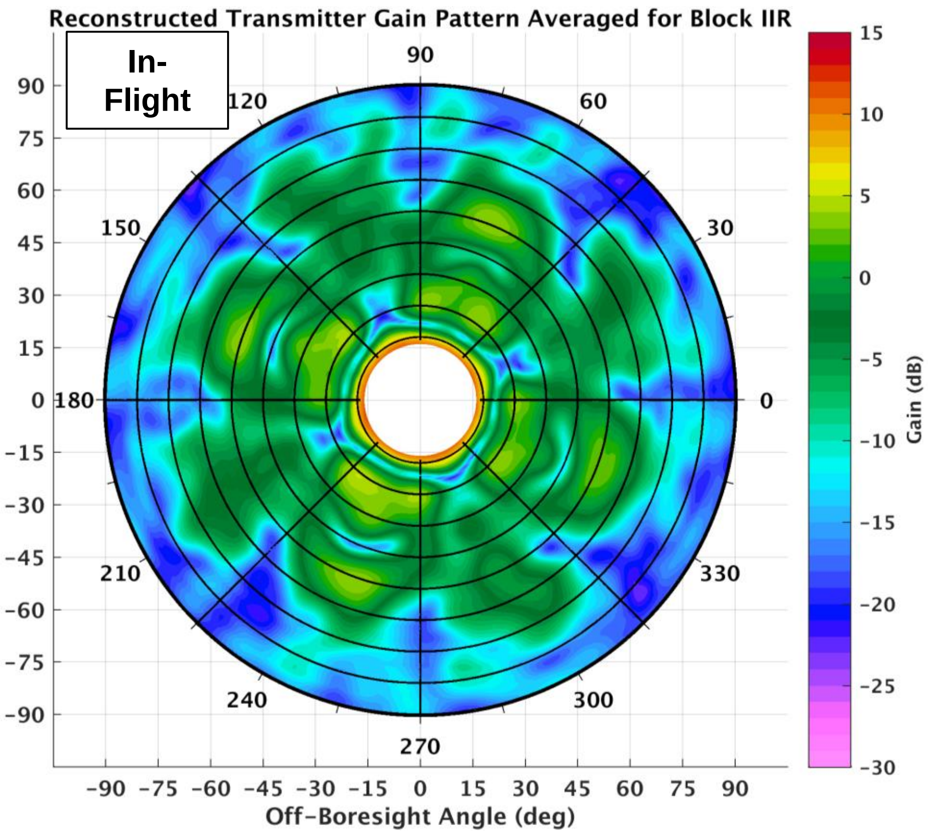
Data Collection & Visualization

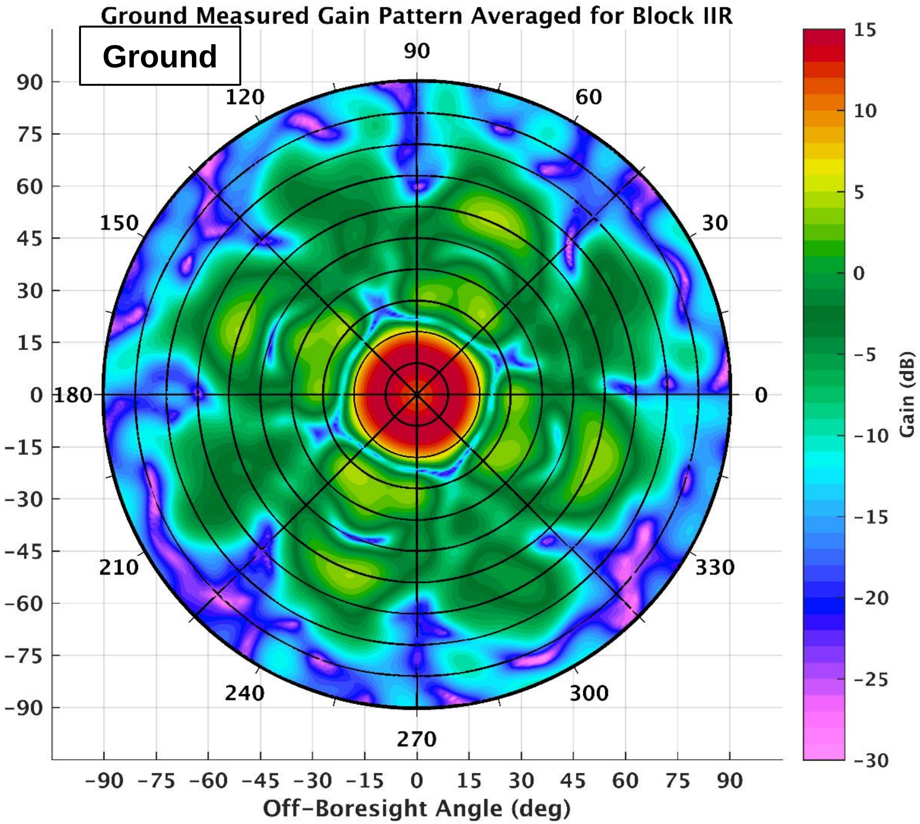
- Trace path of GEO vehicle in antenna frame of each GPS vehicle
- Reconstruct full gain pattern after months of tracking



ACE Results
Average Transmit Gain – Block IIR

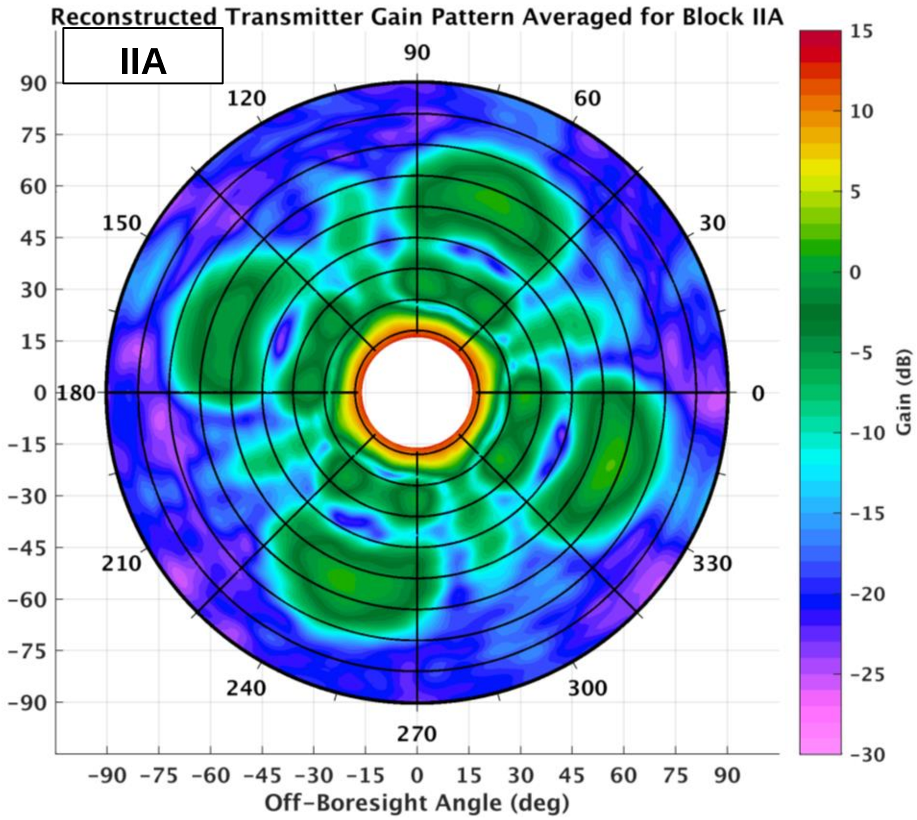
- In-flight averaged over all SVNs in block in 1 deg x 1 deg bins
- Remarkable similarity between average flight and ground measurements
  - Note matching patterns in nulls around outer edge

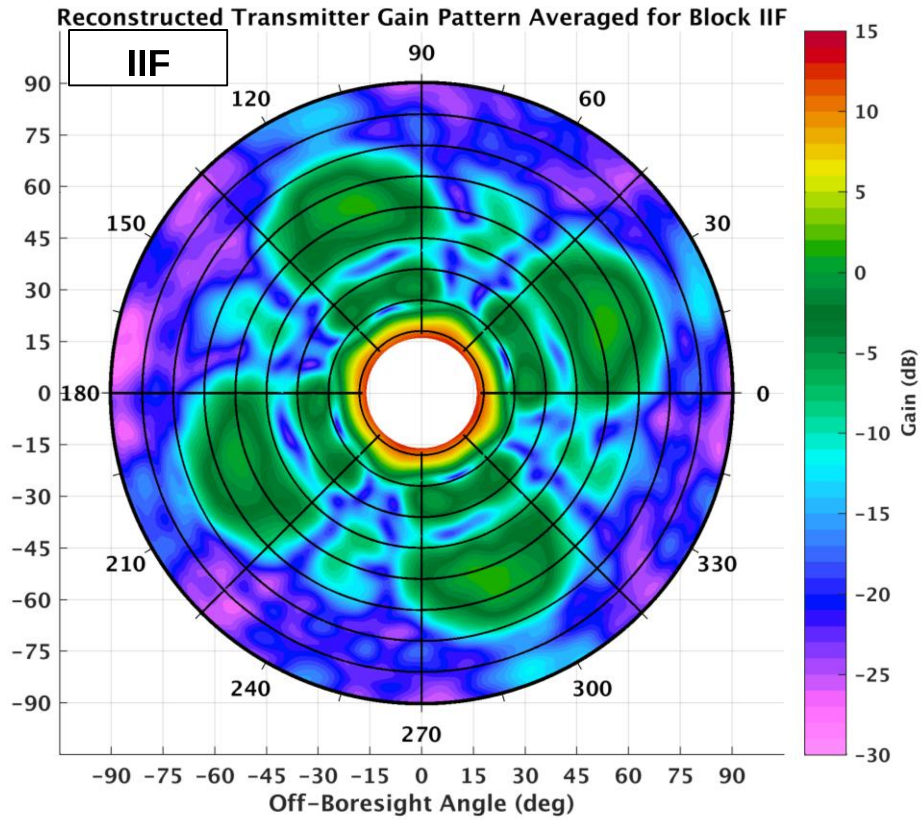




ACE Results
Average Transmit Gain – Block IIA/IIF

- 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





GPS ACE Conclusions

- **GPS ACE architecture permits tracking of extremely weak signals over long duration**
  - MGPSR produces signal measurements well into back lobes of GPS vehicles
  - 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**

NASA Beyond-SSV Activities

In response to Recommendation ICG/WGB/2017:
Use of GNSS for Exploration Activities
in Cislunar Space and Beyond

ICG-12 (Kyoto) Recommendation:
Use of GNSS for Exploration Activities in Cislunar Space and Beyond

Background/Brief Description of the Issue:
During the WG-B GNSS SSV Working Group activities associated with the generation of the GNSS SSV Booklet, it became clear that the use of GNSS signals in support of missions within and beyond cis-Lunar space is possible and could contribute to improved on-board navigation capabilities.

Discussion/Analyses:
It is essential to understand the user needs for missions to cis-Lunar space and beyond, and to perform detailed analyses of the GNSS SSV capabilities and potential augmentations related to the support of missions to cis-Lunar space and beyond.

Recommendation of Committee Action:
WG-B will lead and Service providers, Space Agencies and Research Institutions are invited to contribute to investigations/developments related to use of the full potential of the GNSS SSV, also considering the support of exploration activities in cis-Lunar space and beyond.

Recent Results: Lunar GPS

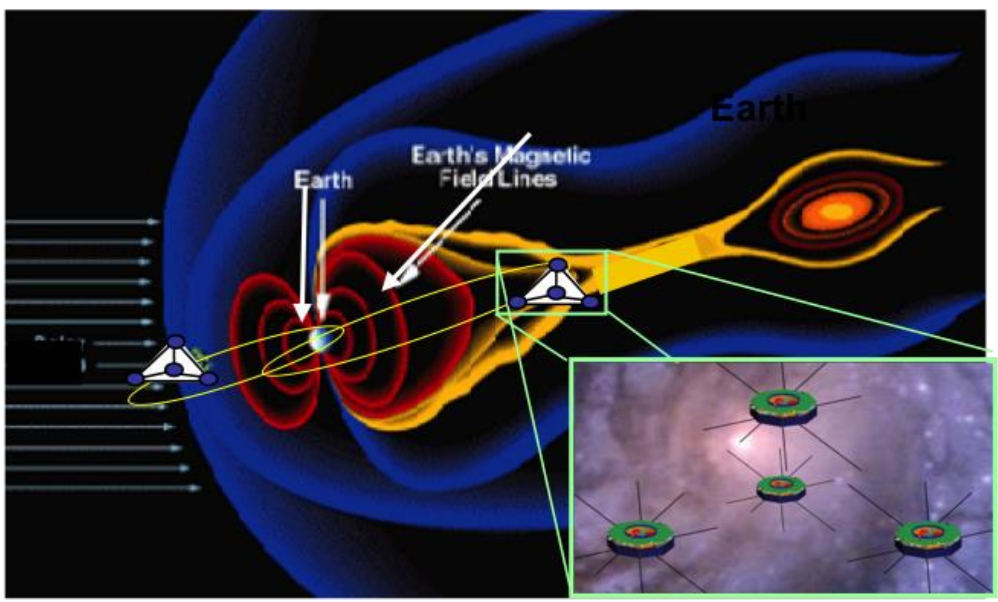
- NASA has recently published two studies looking at the feasibility of GPS navigation at lunar distances:
  - **ION GNSS+ 2017: Winternitz, et al**[1]
    - Published MMS Phase 2 results using GPS to 25 RE
    - Projected MMS performance to lunar distance
  - **AAS GN&C 2018: Ashman, et al**[2]
    - Looked broadly at GPS visibility for different antennas and C/N0 receiver threshold values
    - Validated results vs. MMS and GOES-16 flight data

- These studies represent early GPS-only analyses that could be used as basis for WG-B in-depth analysis.

[1]Winternitz, Luke B., Bamford, William A., Price, Samuel R., "New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances," *Proceedings of the 30th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2017)*, Portland, Oregon, September 2017, pp. 1114-1126.
[2]Ashman, Benjamin W., Parker, Joel J. K., Bauer, Frank H., "Exploring the Limits of High Altitude GPS for Future Lunar Missions," American Astronautical Society Guidance and Control Conference, Breckenridge, Colorado, USA, February 2–8, 2017.

NASA's Magnetospheric MultiScale (MMS) Mission

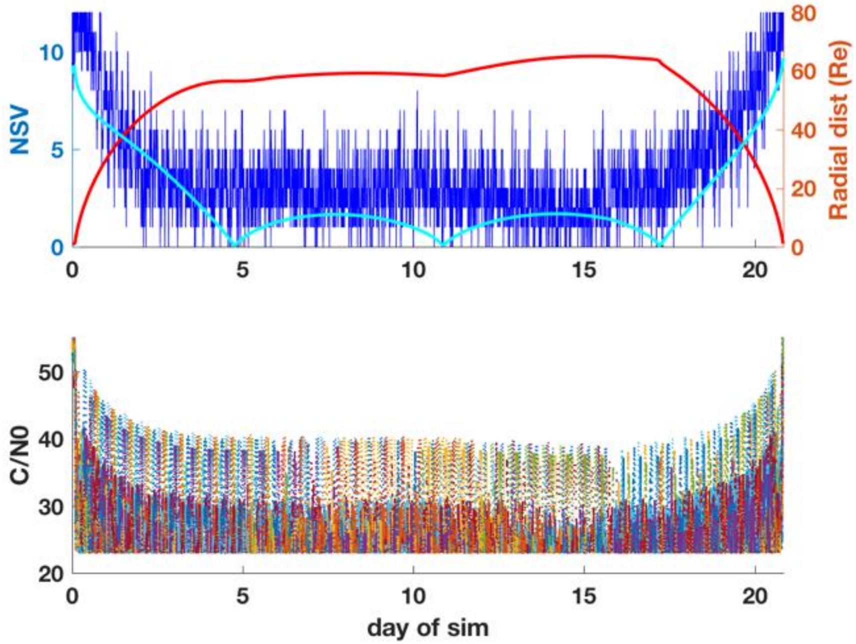
- Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere.
- Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 10km
- Flying in multiple highly-elliptical orbits:
  - Phase 1 1.2x12 R_E (magnetopause) Mar '14-Feb '17
  - Phase 2B 1.2x25 R_E (magnetotail) May '17-present
  - 2019: Apogee raise to **1.2x29** RE



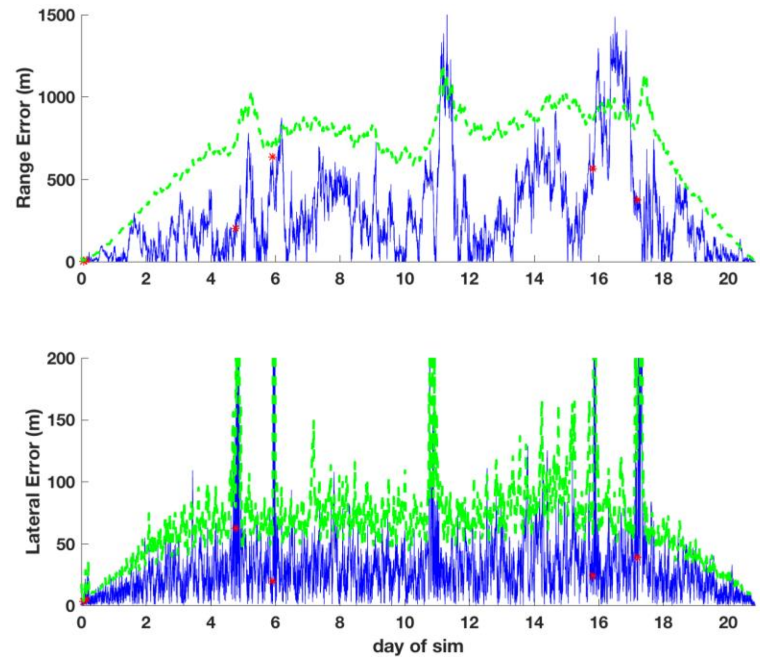
2017 MMS study: Concept Lunar mission

- **Study: How will MMS receiver perform if used on a conceptual Lunar mission with 14dBi high-gain antenna?**
- **GPS measurements simulated & processed using NASA GEONS filter.**
- **Visibility similar to MMS Phase 2B, as high-gain makes up for additional path loss**
  - Avg visibility: ~3 SVs; C/N0 peaks > 40dB-Hz (main lobes) or > 30 dB-Hz (side lobes)
- **Range/clock-bias errors dominate – order of 1-2 km; lateral errors 100-200 m**
  - With atomic clock, or, e.g., periodic 2-way range/Doppler, could reduce range errors to meas. noise level

Top: Signals tracked and radial dist to Earth (red) and Moon (cyan); Bottom: C/N_0



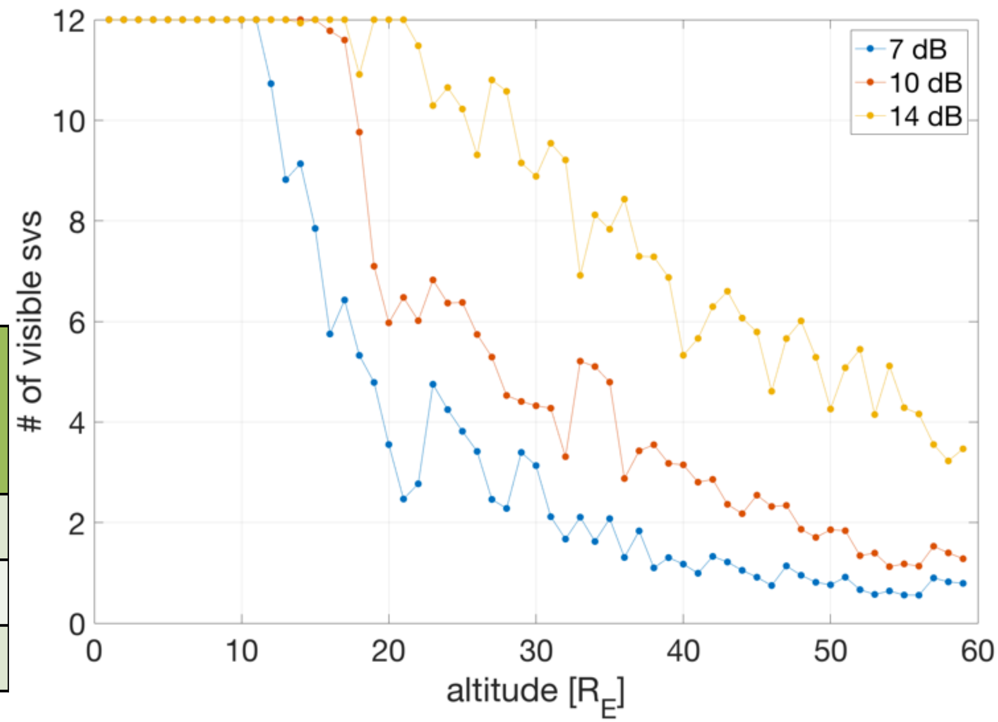
Filter position formal (3σ) and actual errors



2018 Lunar GPS Visibility Study

- GPS constellation modeled as accurately as possible, including sidelobe signals; validated with GOES-16 and MMS flight data
- Calibrated models applied to outbound lunar near-rectilinear halo orbit (NRHO) GPS receiver reception with 22 dB-Hz acq/trk threshold

Peak Antenna Gain	1+ Vis.	4+ Vis.	Maximum Outage
7 dB	63%	8%	140 min
10 dB	82%	17%	84 min
14 dB	99 %	65%	11 min

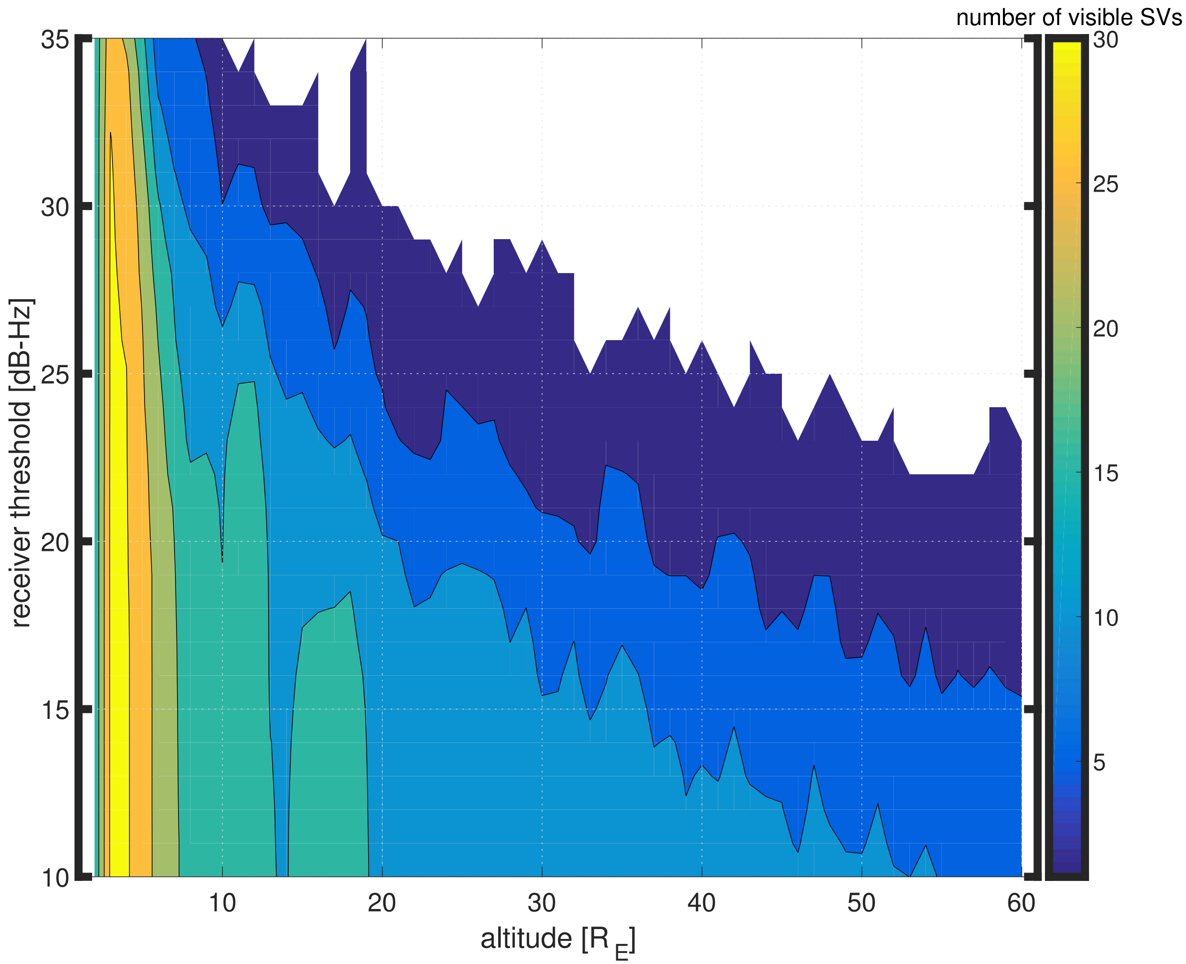


- A modest amount of additional antenna gain or receiver sensitivity increases coverage significantly

2018 Lunar GPS Visibility Study

Conclusions

- These results show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven* receiver technology.
- A modest increase in gain or receiver sensitivity increases visibility significantly.
- Future work must extend these specific studies to full navigation analysis of cis-lunar spacecraft, including effects of DOP, and utilizing the *full capability* of multi-GNSS signals.
- ICG WG-B is a natural forum for these discussions and analyses, in keeping with the ICG-12 recommendation for analysis for cis-lunar missions and beyond.

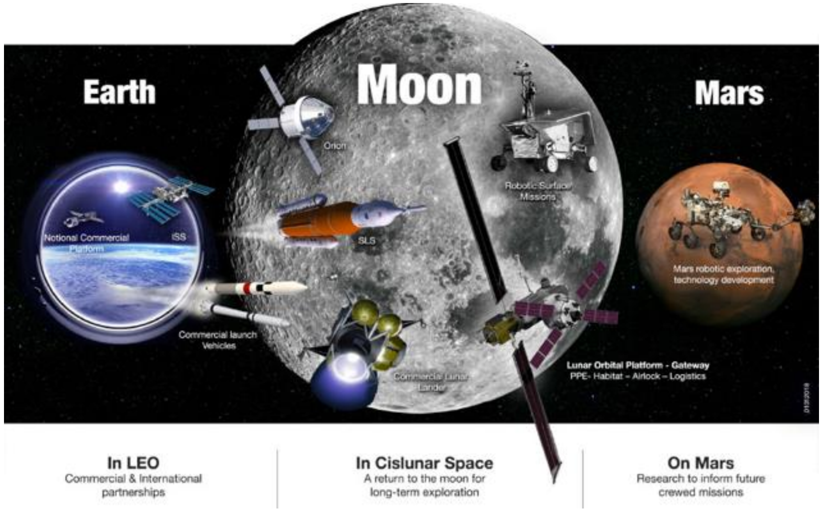


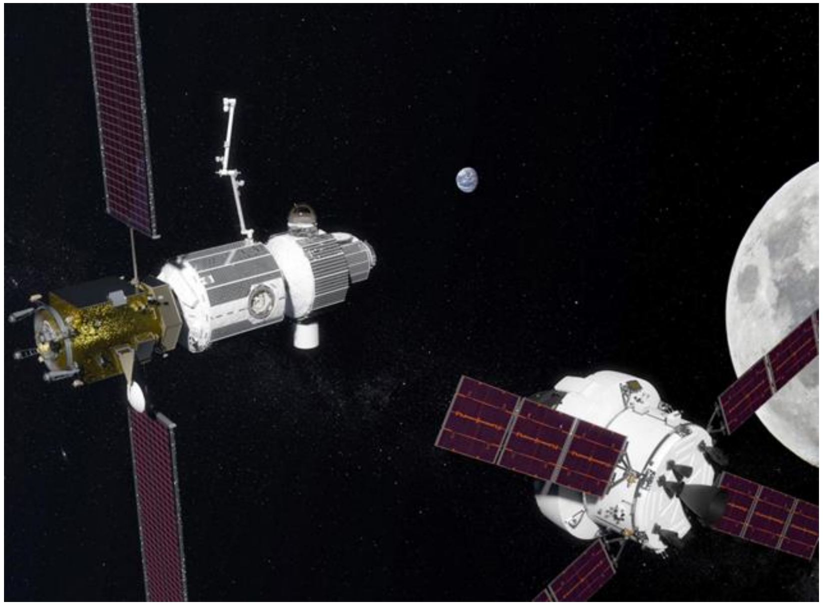
Number of satellites visible by altitude and receiver threshold

Potential Future Application: Lunar Orbital Platform—Gateway

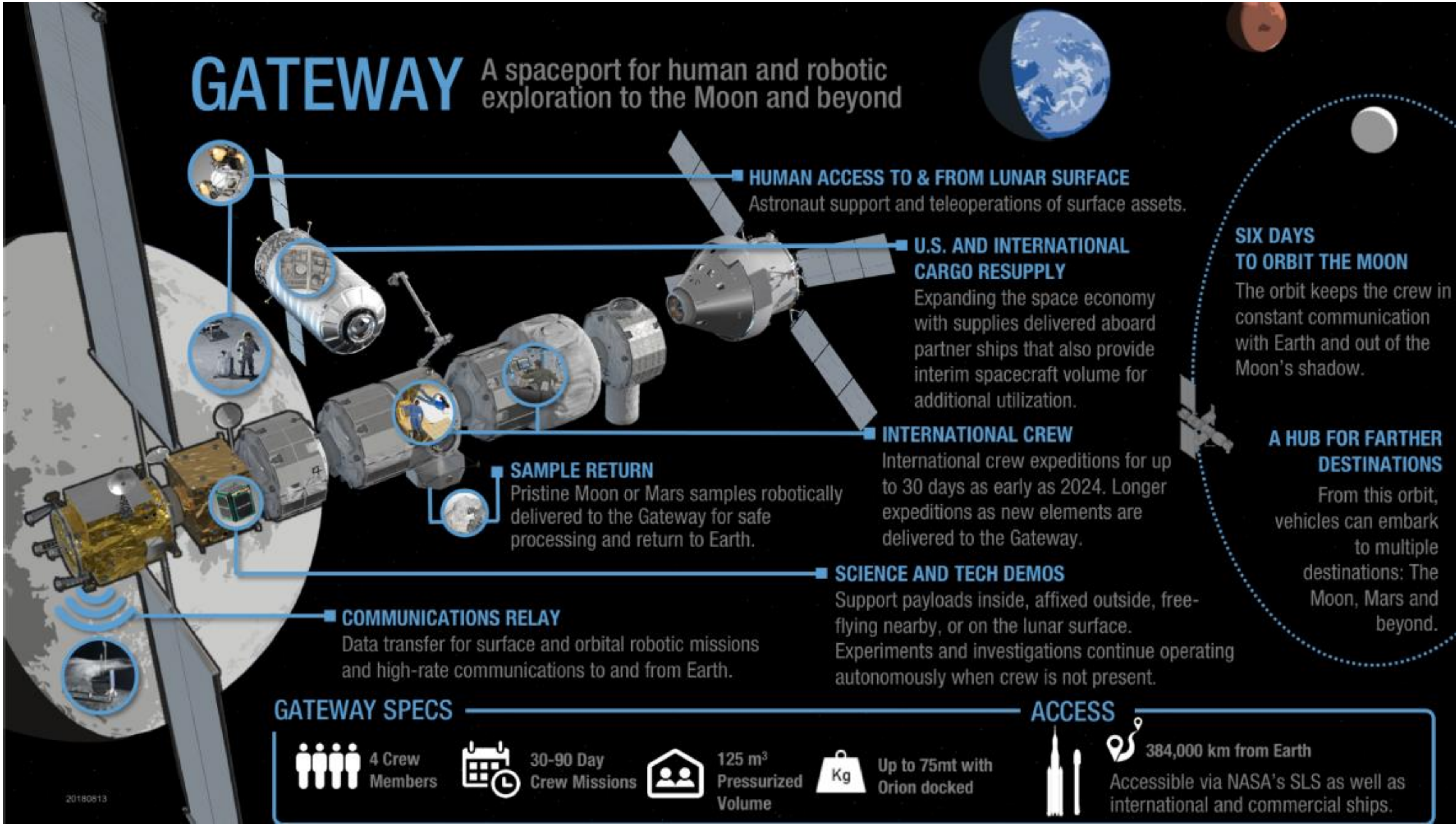
- NASA Exploration Campaign: Next step is deployment and operations of US-led Lunar Orbital Platform—Gateway (previously known as Deep Space Gateway)
- Step-off point for human cislunar operations, lunar surface access, missions to Mars
- Features include:
  - Power and propulsion element (PPE) – targeted for 2022
  - Human habitation capability
  - Docking/rendezvous capability
  - Extended uncrewed operations (not continuously crewed)
  - Lunar near-rectilinear halo orbit (NRHO)
- Gateway conceptual studies are continuing with ISS partners
  - Requirements to be baselined in 2018
  - To be followed by Broad Agency Announcement for partnerships
- **Gateway represents a potential application for on-board GNSS navigation**
- NASA will continue providing updates to WG-B as plans develop.

https://www.nasa.gov/feature/nasa-s-lunar-outpost-will-extend-human-presence-in-deep-space





Potential Future Application: Lunar Orbital Platform—Gateway



The Global Exploration Roadmap

10+ international lunar exploration missions planned for next 10 years;
many opportunities for demonstration of lunar GNSS capabilities

NASA Recent GNSS Technology Development Activities

USAF–NASA Collaboration on GPS SSV

- **Oct 13 2017: Joint NASA-USAF Memorandum of Understanding signed on GPS civil Space Service Volume (SSV) requirements**
  - Scope is relevant to future GPS III SV11+ (GPS IIIF) satellites
  - As US civil space representative, provides NASA insight into procurement, design and production of new satellites from an SSV capability perspective
  - Intent is to ensure SSV signal continuity for future space users, such as GOES-S–U
- **2018+: NASA participation in GPS IIIF procurement & design phases**

Automatic Flight Termination System (AFTS)

- Independent, self-contained subsystem mounted onboard a launch vehicle
- Flight termination / destruct decisions made autonomously via redundant Global Positioning System (GPS)/Inertial Measurement Unit (IMU) sensors
- Primary FTS for unmanned Range Safety Operations and being considered as Primary FTS for human space flight (Commercial Crew and SLS)
- Advantages:
  - Reduced cost—decreased need for ground-based assets
  - Global coverage (vehicle doesn't have to be launched from a range)
  - Increased launch responsiveness
  - Boundary limits increase due to 3-5 second gain from not having Mission Flight Control Officer (MFCO)
  - Support multiple vehicles simultaneously (such as flyback boosters)

April 2006: WSMR Sounding Rocket

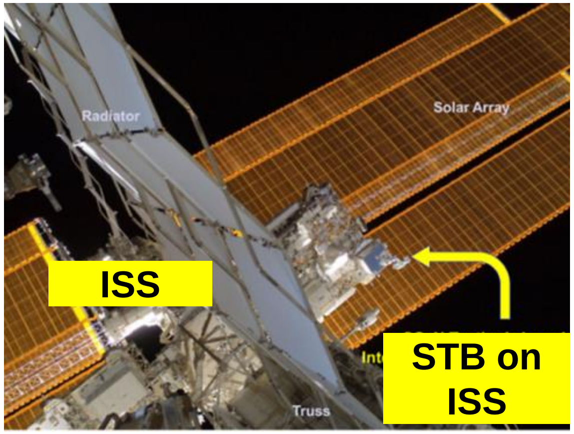
Mar 2007: SpaceX F1

Sept 2010: WFF Sounding Rocket

Enabling low cost, responsive, reliable access to space for all users

GAlileo **R**eceiver 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)

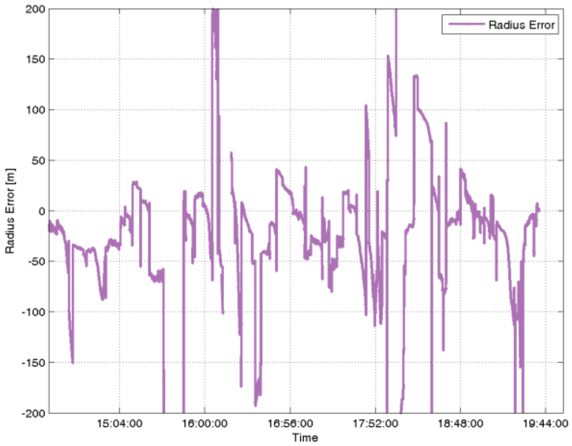


GARISS waveform development is an element of NASA/ESA cooperation involving multiple centers, Qascom

On-orbit waveform integration and testing

- **Moved integration and testing to on-orbit operations April 2018**
- **Successful on-orbit acquisition, track and PVT solution**
- **Full function for GPS and Galileo processing established at qualification review (May 2018) :**
  - Acquisition and Time to First Fix (TTFF) requirements are met for Galileo and for combined GPS/Galileo
  - GPS-only on-orbit PVT availability > 20%
  - Galileo -only on-orbit PVT availability > 40%

- **Achieved Combined Galileo/GPS PVT availability greater than 90%**
- **~64m RMS positional error (3D)**
- **First-ever on-orbit direct acquisition of L5/E5a (no L1 aiding)**



Real-Time Monitoring of GPS, GLONASS, BeiDou, Galileo, and QZSS by the GDGPS System

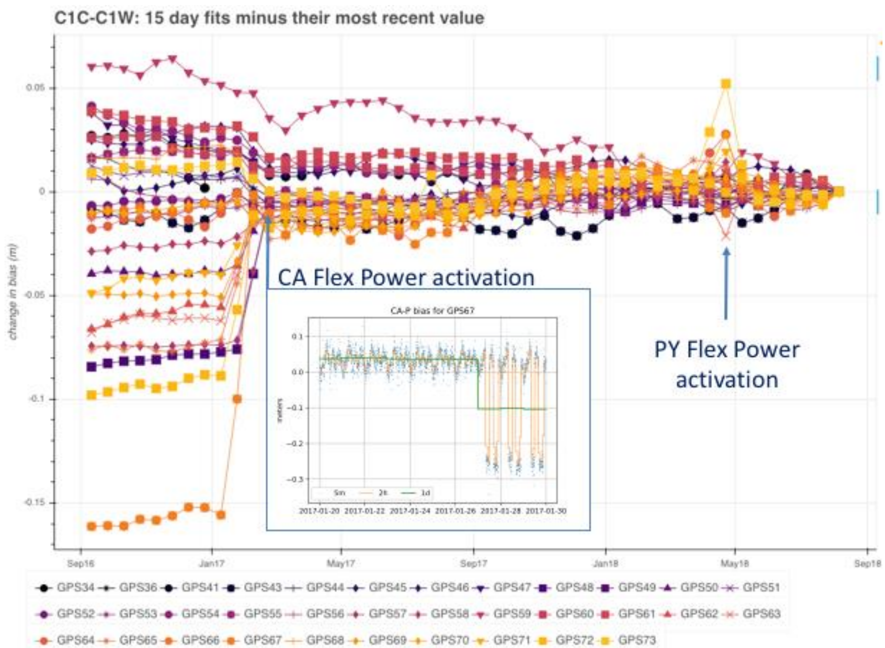
28 BDS in view (61 sites reporting)

Page generated on Sat Oct 20 22:01:21 2018 (UTC)
Data Epoch: 21 seconds prior to page generation, Sat Oct 20 22:01:00 2018 (UTC)

BDS Integrity Monitor: Table sorted by SVN
without auto-update *(Go to version with 30-sec auto-update)*

				Performance metrics				Orbit/Clock error metrics					Link Statistics							
SVN (?)	PRN (?)	Orbit (?)	Block (?)	URE (plot,?)	FORD (plot,?)	URA (plot,?)	URE/URA (plot,?)	UREE (plot,?)	CLK (plot,?)	RSS (plot,?)	RAC (plot,?)	SIGMA (plot,?)	Total (plot,?)	Good (plot,?)	Bad (plot,?)	Missing (plot,?)	BCE (plot,?)	AOD (plot,?)	Health (plot,?)	SVN (?)
101	1	GEO-2		8.08	9.57	4.00	2.02	1.24	-9.30	1.99	plot	0.00	20	20	0	0	11	1.0	0	101
103	3	GEO-2		-	-	-	-	-	-	-	plot	-	21	19	0	2	18	1.0	0	103
104	4	GEO-2		4.72	1.57	4.00	1.18	1.29	-5.76	4.97	plot	0.00	20	18	0	2	10	1.0	0	104
105	5	GEO-2		9.71	3.15	4.00	2.43	0.92	-10.39	4.40	plot	0.00	27	23	0	4	19	1.0	0	105
106	2	GEO-2		4.53	2.42	4.00	1.13	0.86	-4.34	6.20	plot	0.00	24	22	0	2	18	1.0	0	106
201	6	IGSO-2		0.74	2.41	4.00	0.19	0.78	0.05	3.03	plot	0.00	22	19	0	3	-1	4.0	0	201
202	7	IGSO-2		5.22	5.32	4.00	1.31	0.59	-5.12	4.19	plot	0.00	21	20	0	1	-1	1.0	0	202
203	8	IGSO-2		5.21	4.43	4.00	1.30	0.60	-4.65	1.57	plot	0.00	24	20	0	4	-1	1.0	0	203
204	9	IGSO-2		1.78	2.41	4.00	0.45	0.88	2.60	2.11	plot	0.00	26	24	0	2	-1	3.0	0	204
205	10	IGSO-2		0.61	2.42	4.00	0.15	0.65	0.06	3.24	plot	0.00	19	16	0	3	-1	1.0	0	205

- Real-time (6 sec latency) orbit determination operations
- Additional hourly precise orbit determination operations
- Real time environmental monitoring: earthquakes, space weather, tsunamis

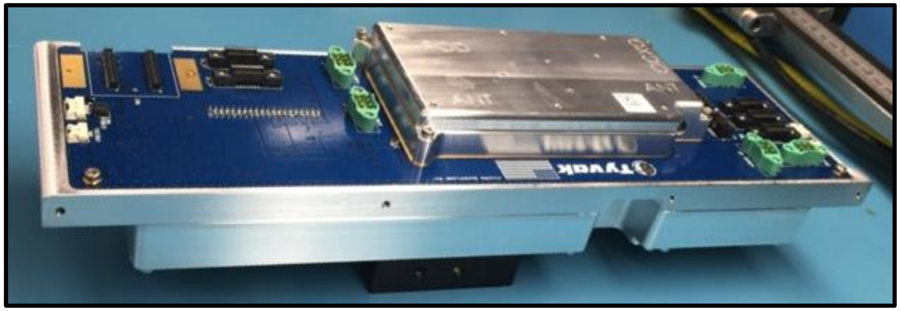


- Differential Code Bias Monitoring for all GNSS signals at high rate (especially needed to monitor GPS Flex Power)

Cion – NASA's new Software-Defined GNSS Radio Science Instruments for Cubesats

Low cost, low power, high performance space GNSS receiver for POD and radio occultations (RO)

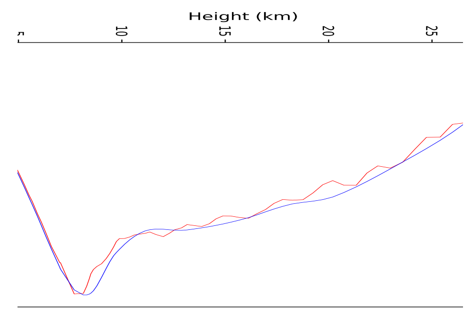
- Designed by JPL and built by Tyvak for initial use on GeoOptics' CICERO RO Constellation
- Based on the PicoZed off the shelf OEM computer and JPL's TriG GPS receiver design
- A NASA Class D version of this design has recently been completed



Tyvak-Built Cion Reciever

Key Cion Features:

- 3 antenna inputs with 4 down converters each
- 1.2 GHz Dual Core Arm processor
- 30cm X 10cm X 6cm
- 1 kg
- ~10 watts at 12 VDC
- Can be coupled with an external receiver to increase number of channels available for radio science



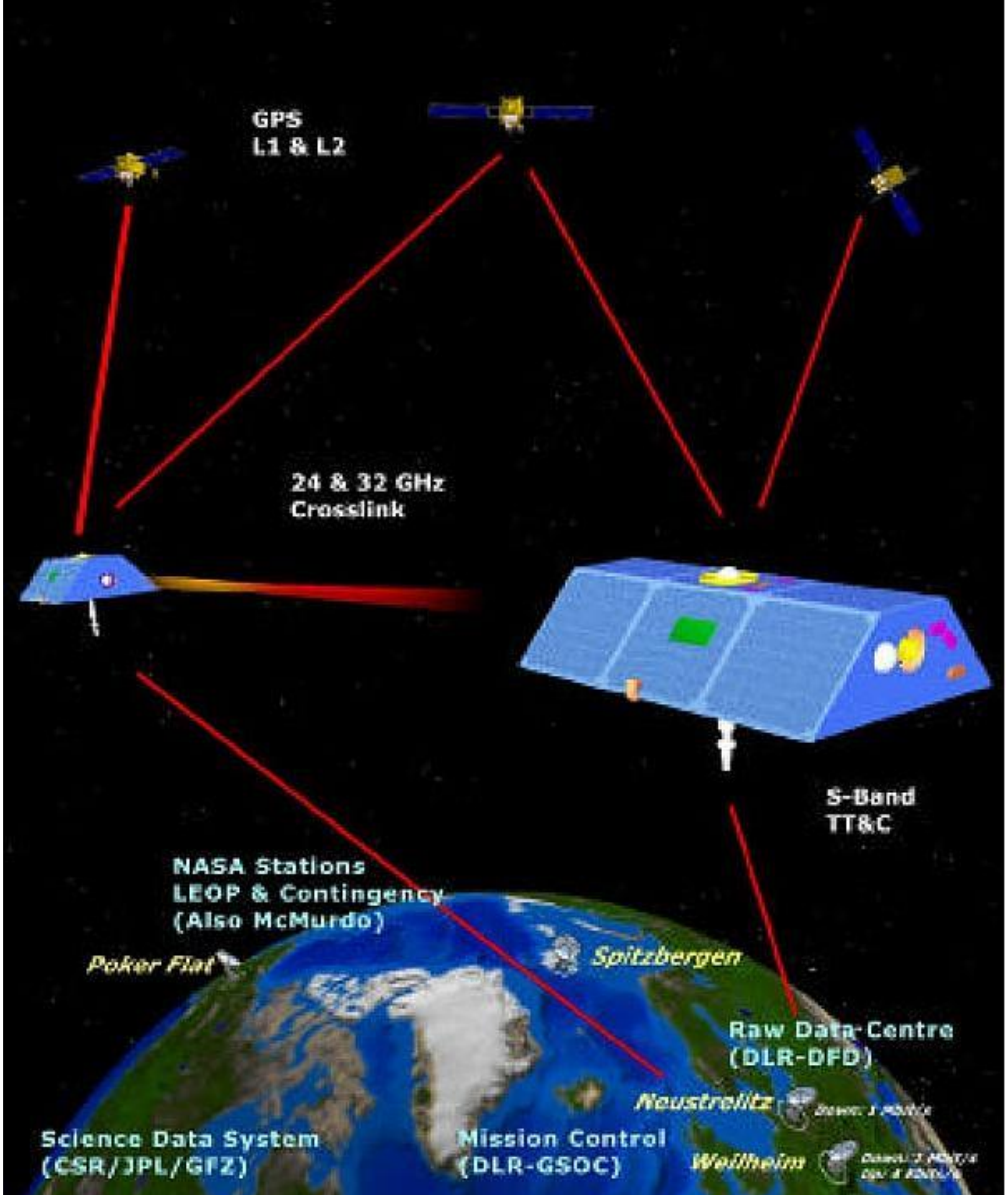
Successful operations on CICERO in orbit since March 2018, providing GPS and GLONASS radio occultation data

- Coupled with a Novatel GPS+GLONASS POD receiver
- Launch of additional CICERO satellites anticipated in 2018

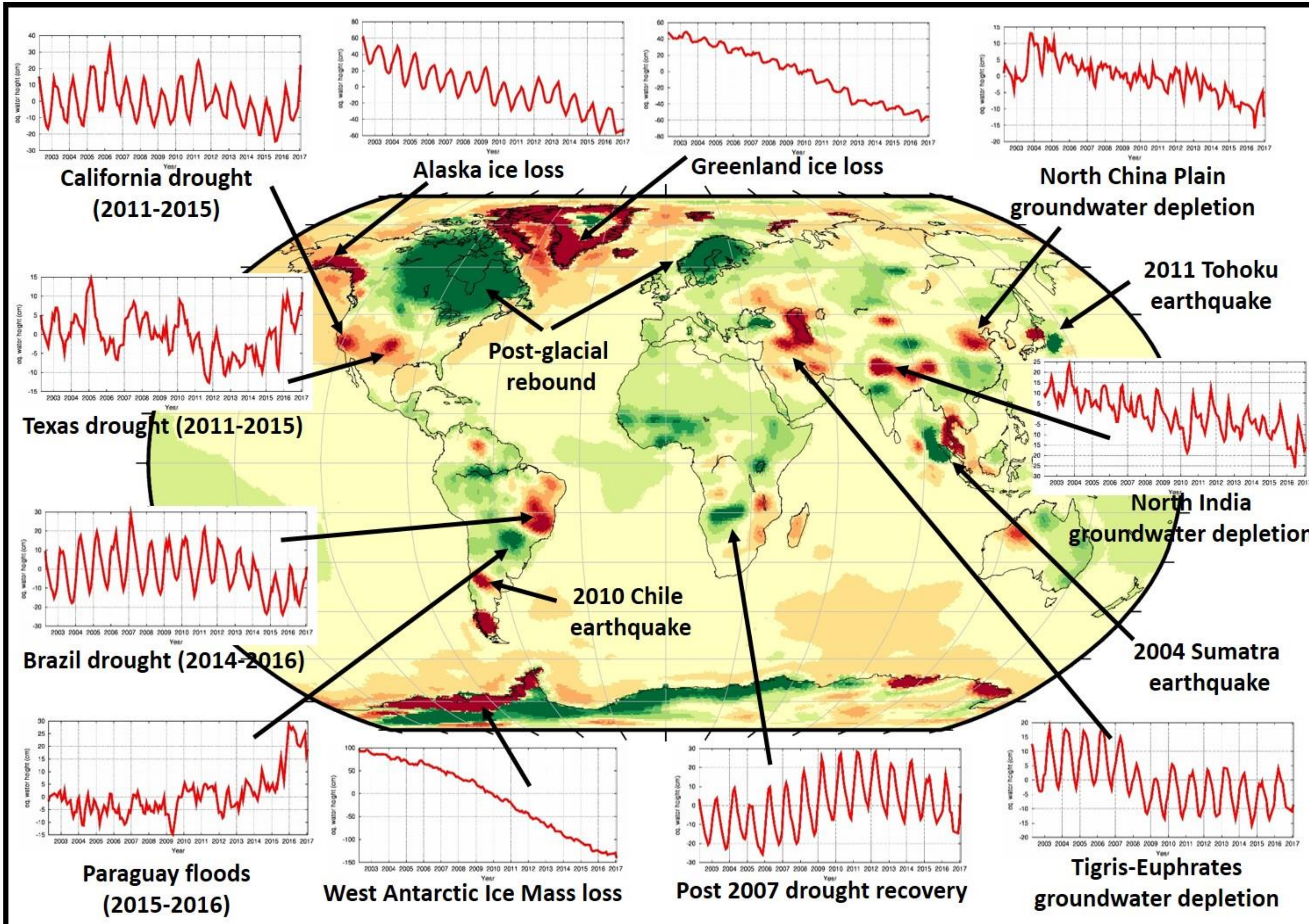
Summary

- **NASA is engaged** in numerous space-based GNSS initiatives that are bearing great fruit for science and future mission development
- The **NASA civil GNSS space user fleet** is growing and expanding into new regimes
  - GRACE retired after 15 years of groundbreaking science
  - Space Launch System (SLS) has five upcoming cislunar exploration flights with GPS onboard
  - Restore-L and PACE will add to NASA's extensive use of GPS in LEO
- **NASA studies on cislunar use of GPS** show high level of potential performance in lunar orbit with modest investments in receiver system capabilities.
  - The int'l Gateway project and the Global Exploration Roadmap provide numerous opportunities for in-depth study and inflight demonstrations.
- NASA's **GPS Antenna Characterization Experiment** (ACE) has gathered and published the most extensive dataset on GPS antenna patterns for space users to-date, enabling a new series of high-fidelity mission simulations in the SSV.
- **NASA technology developments** have achieved numerous milestones:
  - Automatic Flight Termination System (AFTS) is providing operational GPS-based range safety since 2017
  - GARISS achieved the first direct acquisition of L5/E5a in space, and is exceeding its performance requirements in initial flight tests
  - JPL GDGPS system is providing real-time monitoring of GPS, GLONASS, Galileo, BDS, QZSS
  - New JPL Cion GNSS receiver for CubeSats is operational on-orbit
- **We encourage** GNSS providers to report on their activities to support the global space user community and enhance the utility of interoperable GNSS in space

Backup Slides

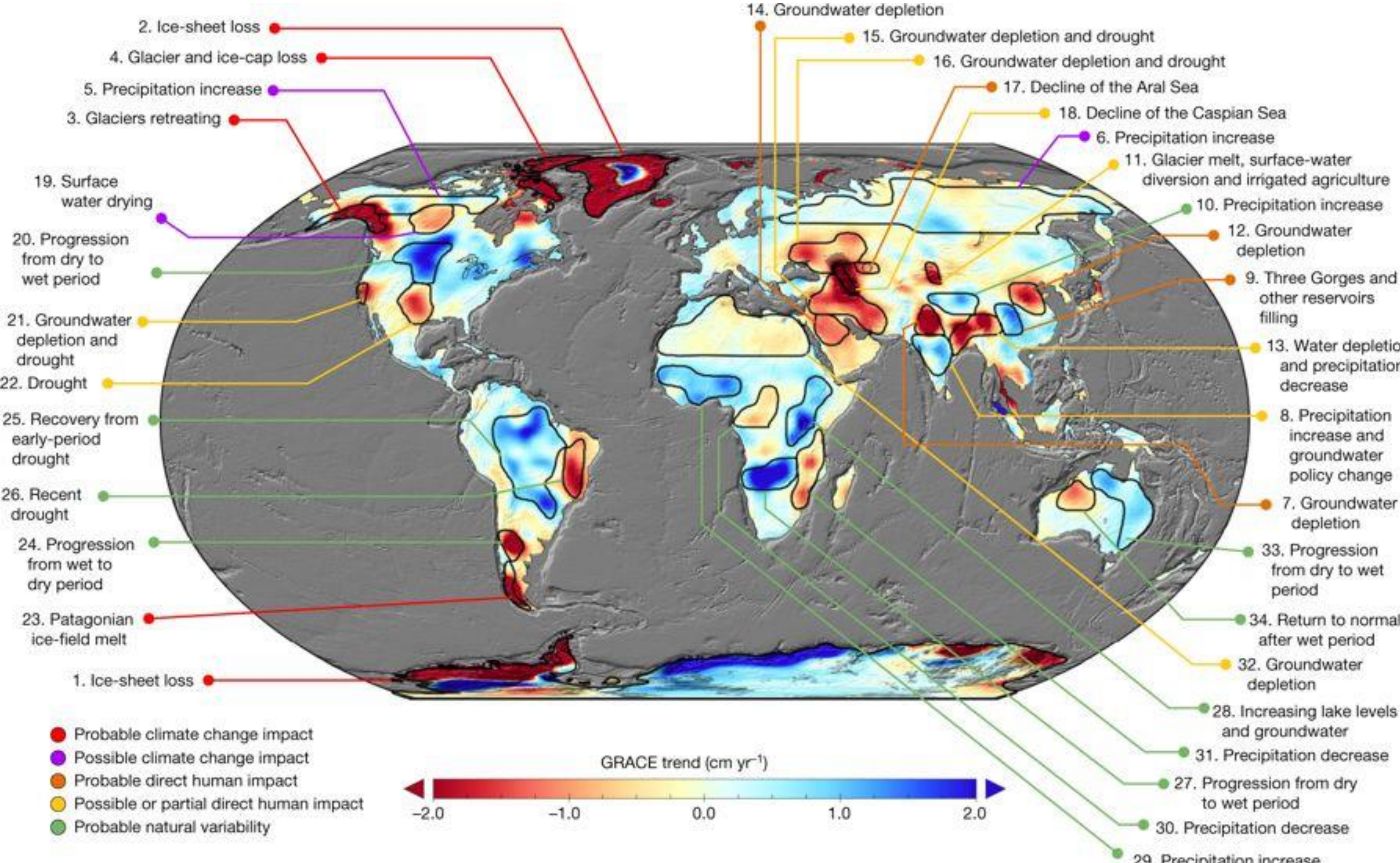


(image credit: NASA, UTA/CSR)



Trend signals in GRACE data from April 2002- Jan 2017

M. Rodell, J. S. Famiglietti, D. N. Wiese, J. T. Reager, H. K. Beaudoing, F. W. Landerer, M.-H. Lo. **Emerging trends in global freshwater availability**. *Nature*, 2018; DOI: 10.1038/s41586-018-0123-1



Trends in TWS (in centimetres per year) obtained on the basis of GRACE observations from April 2002 to March 2016. The cause of the trend in each outlined study region is briefly explained and colour-coded by category. The trend map was smoothed with a 150-km-radius Gaussian filter for the purpose of visualization; however, all calculations were performed at the native 3° resolution of the data product.

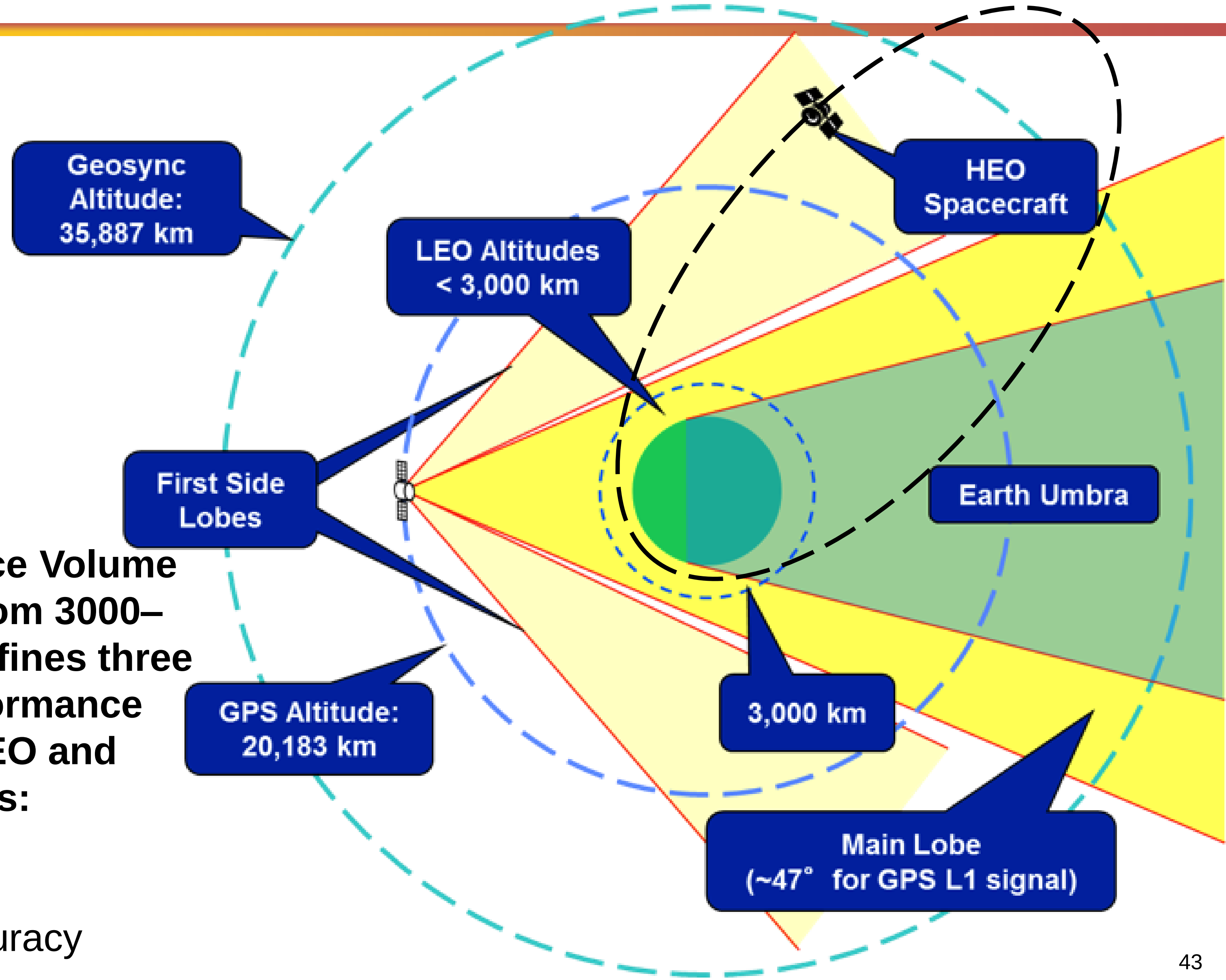
US Civil SSV Users

Mission	Purpose	Orbit Regime	Launch Date
AMSAT-OSCAR 40	Experimental	HEO (1,000×58,000 km)	November 2000
Magnetospheric Multiscale (MMS)	Heliophysics, formation flying	HEO (1,200×150,000 km)	March 2015
GOES-16	Terrestrial & space weather	GEO	November 2016
GOES-17	Terrestrial & space weather	GEO	March 2018
GOES-T	Terrestrial & space weather	GEO	2019
Exploration Mission 1 (EM-1)	Lunar technology demonstration	Lunar	2020
EM-2	Human exploration	Lunar	2021
EM-3	Human exploration	Lunar	2022
EM-4	Human exploration	Lunar	2023
EM-5	Human exploration	Lunar	2024
GOES-U	Terrestrial & space weather	GEO	2024

Historical **Active** **Future**

42

Reception Geometry for GPS Signals in Space Service Volume (SSV)



The Space Service Volume (SSV) extends from 3000–36000 km and defines three interrelated performance metrics in the MEO and HEO/GEO regions:

Availability

Received power

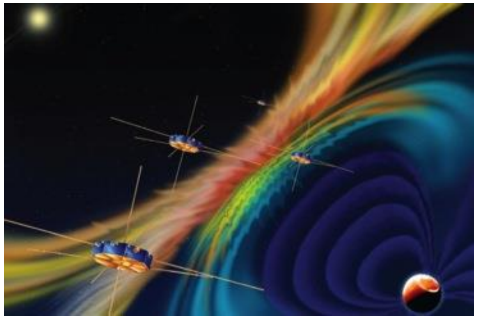
Pseudorange accuracy

The Promise of GNSS for Real-Time Navigation in the SSV

<u>Benefits of GNSS use in SSV:</u>

- 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)
- 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) and Geosynchronous Earth Orbit (GEO) missions,** such as:

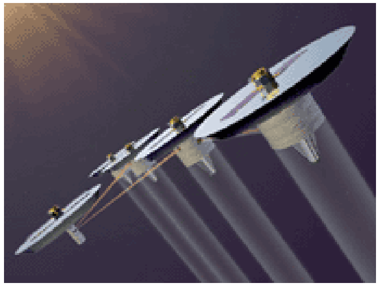
Earth Weather Prediction using Advanced Weather Satellites



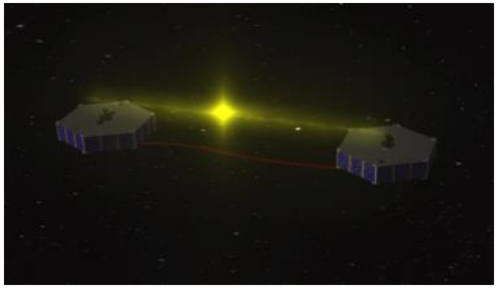
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



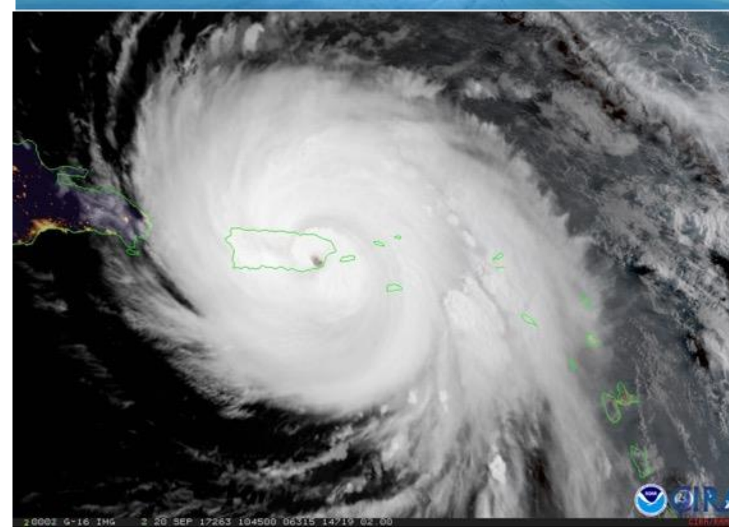
Formation Flying, Space Situational Awareness, Proximity Operations



Precise Position Knowledge and Control at GEO

GOES-R Series Weather Satellites

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- GOES-R/GOES-16 Launch: 19 Nov 2016
- 15 year life, series operational through mid-2030s
- Employs GPS at GEO to meet stringent navigation requirements
- Relies on beyond-spec GPS sidelobe signals to increase SSV performance
- Collaboration with the USAF (GPS) and ICG (GNSS) expected to ensure similar or better SSV performance in the future
- NOAA also identifies **EUMETSAT (EU) and Himawari (Japan) weather satellites** as reliant on increased GNSS signal availability in the SSV

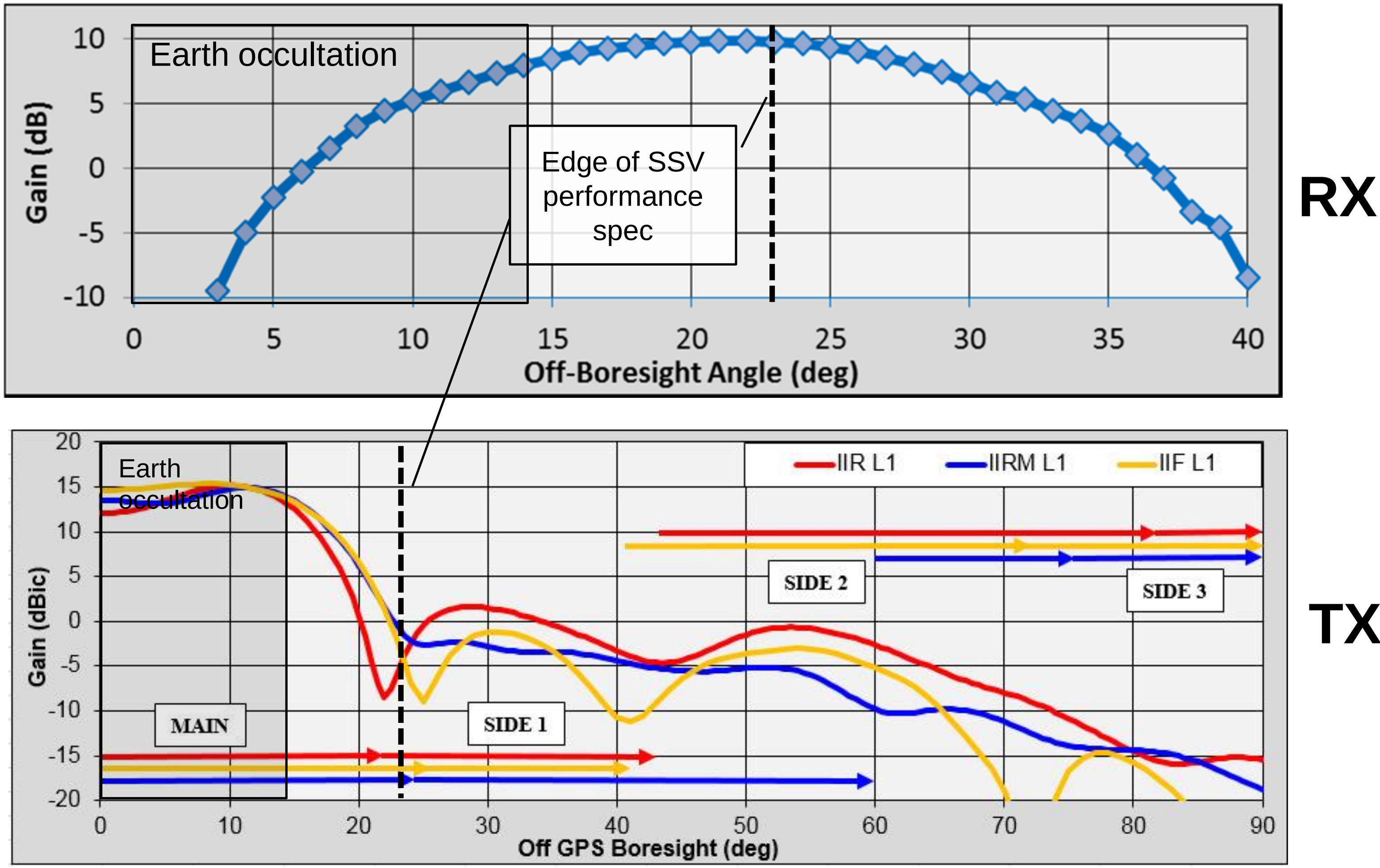


GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

GOES-R/GOES-16 Signal Reception

- GPS L1 C/A only
- Receive antenna optimized for above-the-constellation use
- Max gain @20 deg off-nadir angle
- Tuned to process main lobe spillover + first side lobe

Antenna patterns

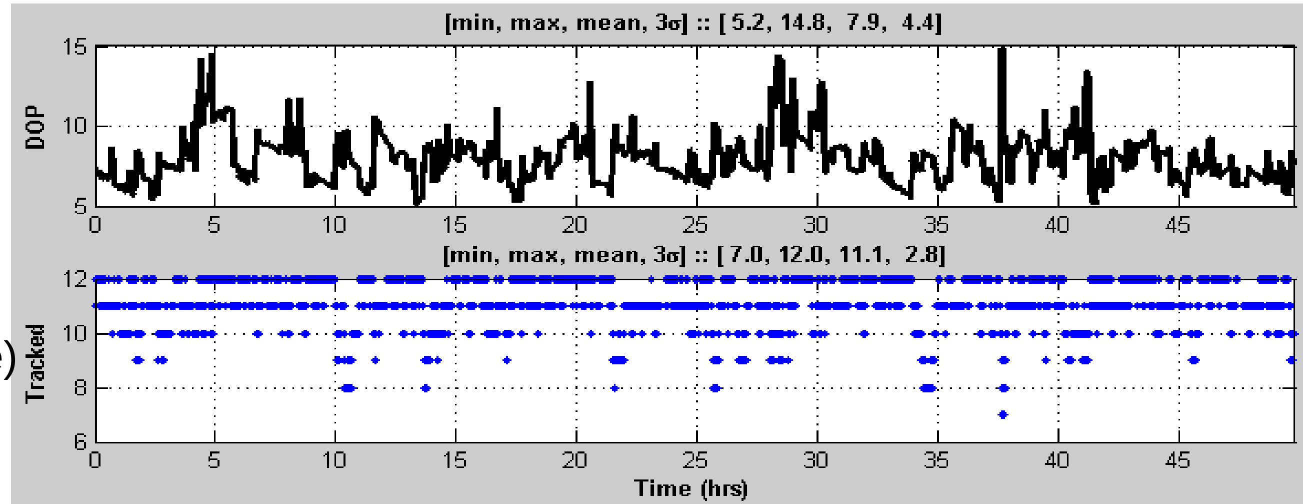


Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., “GPS Receiver On-Orbit Performance for the GOES-R Spacecraft,” ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

GOES-R/GOES-16 In-Flight Performance

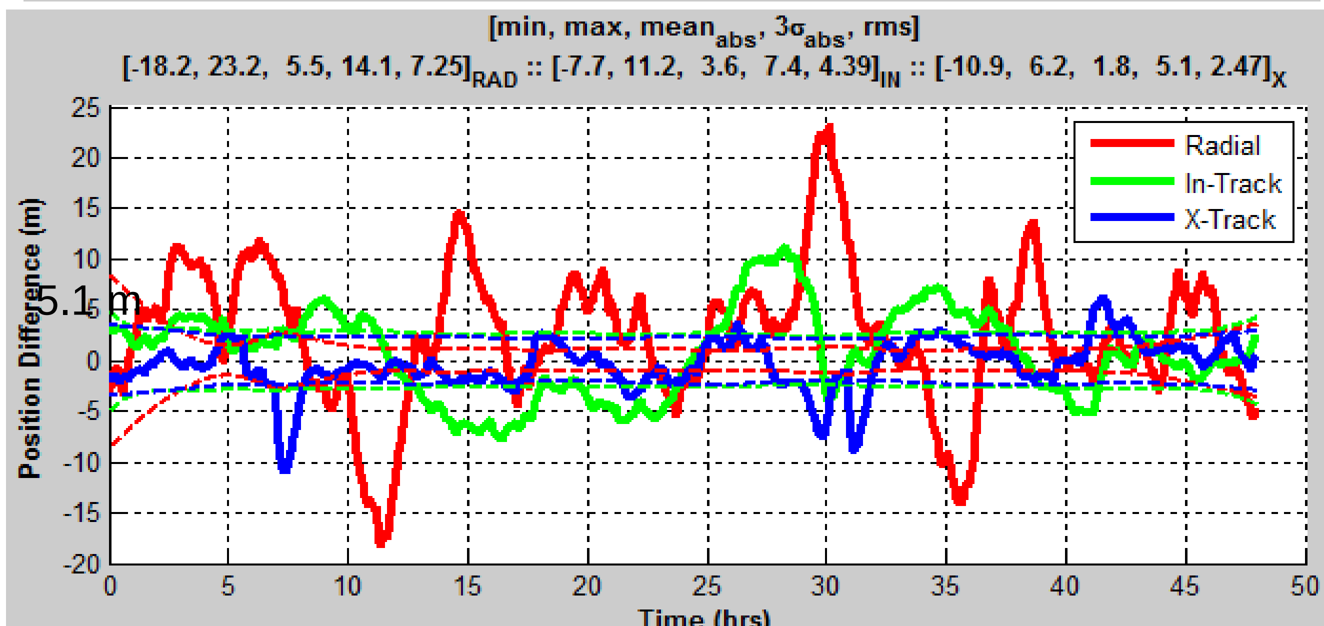
GPS Visibility

- Minimum SVs visible: 7
- DOP: 5–15
- Major improvement over guaranteed performance spec
  (4+ SVs visible 1% of time)



Navigation Performance

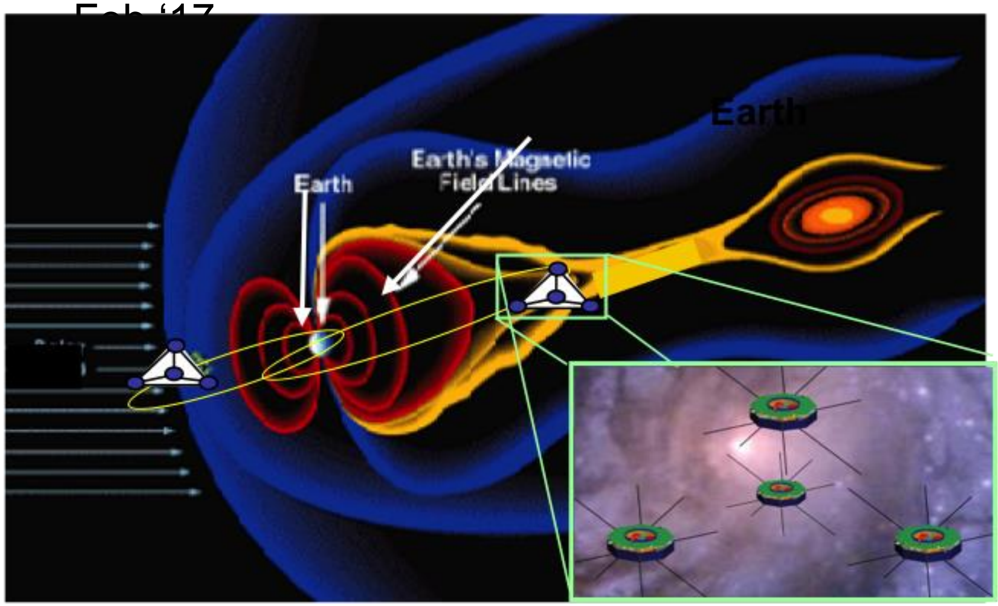
- 3σ position difference from smoothed ground solution (~3m variance):
  - Radial: 14.1 m
  - In-track: 7.4 m
  - Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m



Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

NASA's Magnetospheric MultiScale (MMS) Mission

- Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere.
- Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 10km
- Flying in two highly elliptic orbits in two mission phases
  - Phase 1 1.2x12 R_E (magnetopause) Mar '14-



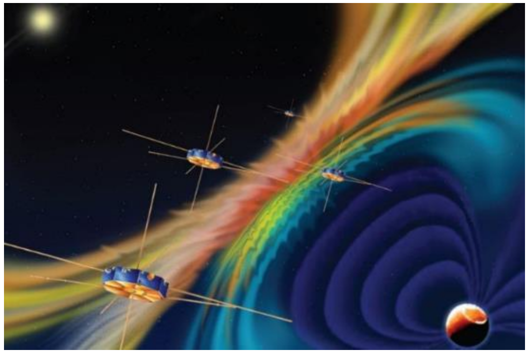
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

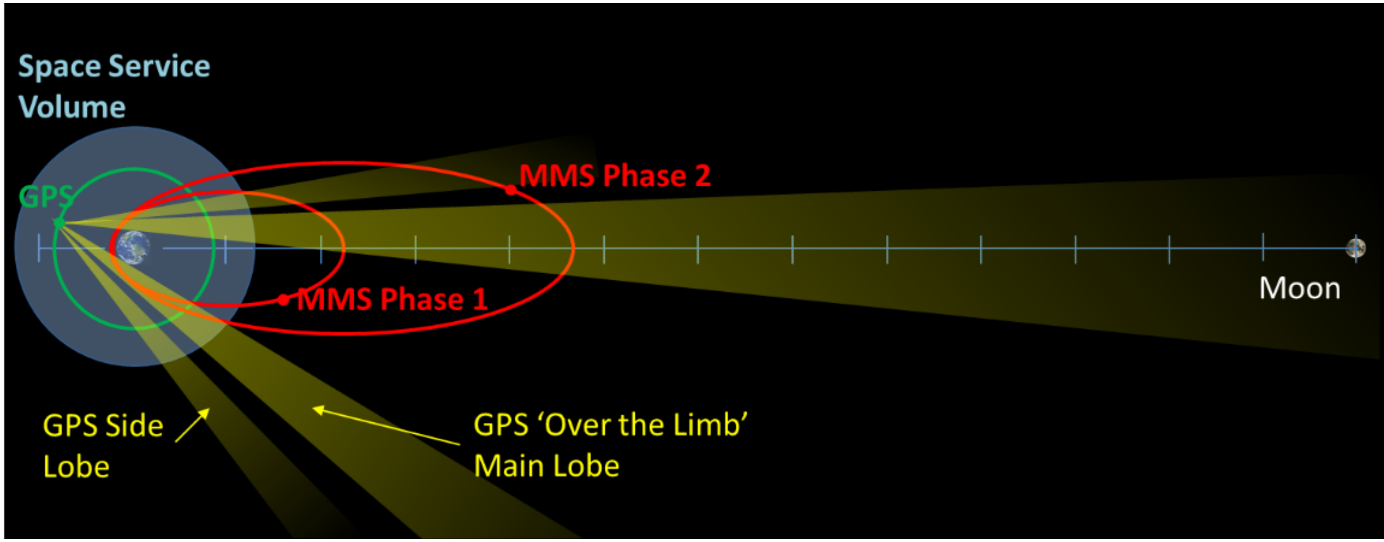
Magnetospheric Multi-Scale (MMS)

- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Phase 1: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - Phase 2B: Extends apogee to 25 Re (~150,000 km) **(40% of way to Moon!)**

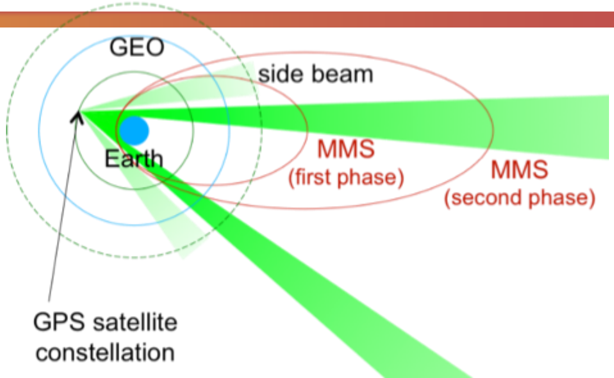
MMS Navigator System

- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set Guiness world record for the highest-ever reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guiness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h





MMS Navigation



- **MMS baselined GSFC Navigator + GEONS Orbit Determination (OD) filter software as sole means of navigation (mid 2000's)**
  - Original design included crosslink, later descoped
- **Trade vs. Ground OD (2005)**
  - Estimated >$2.4M lifecycle savings over ground-based OD
  - Enhanced flexibility wrt maneuver support
  - Quicker return to science after maneuvers
- **Main challenge #1: Sparse, weak, poorly characterized signal environment**
  - MMS Navigator acquires and tracks below 25dB-Hz (around -178dBW)
  - GEONS navigation filter runs embedded on the Navigator processor
  - Ultra stable crystal oscillator (Freq. Electronics, Inc.) supports filter propagation
- **Main challenge #2: Spacecraft are spin stabilized at 3 rpm with obstructions on top and bottom of spacecraft**
  - Four GPS antennas with independent front end electronics placed around perimeter achieve full sky coverage with low noise
  - Receiver designed to hand off from one antenna to next every 5s

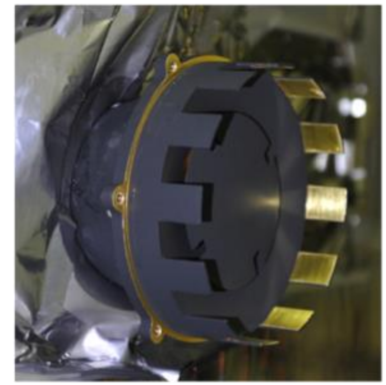
MMS Navigator GPS Hardware

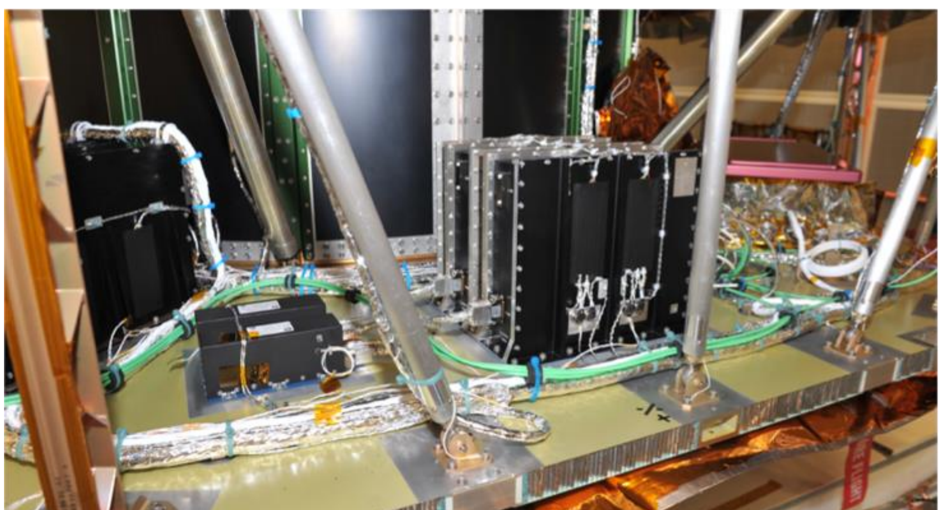
- GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends.

Ultra Stable Osc.

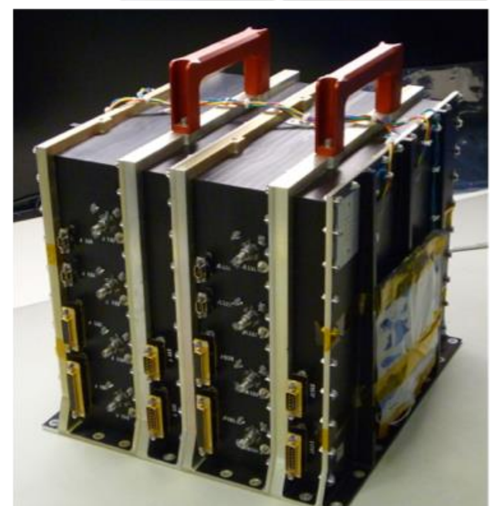
Front end electronics assembly

GPS antenna





Receiver and USO on spacecraft deck

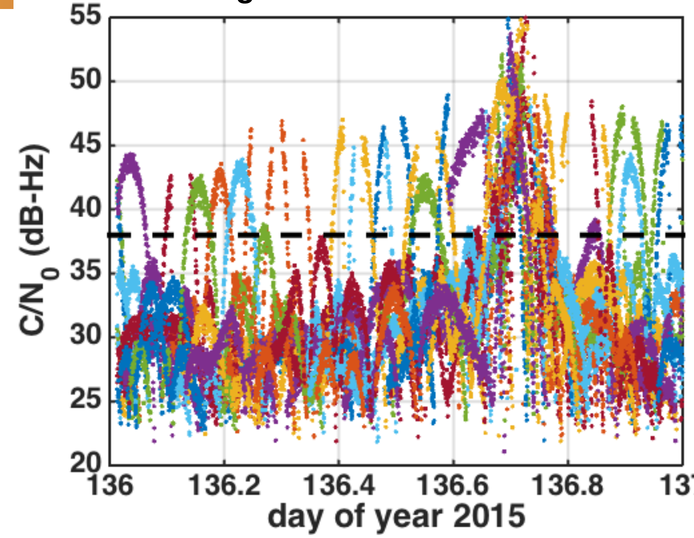


Redundant receiver electronics

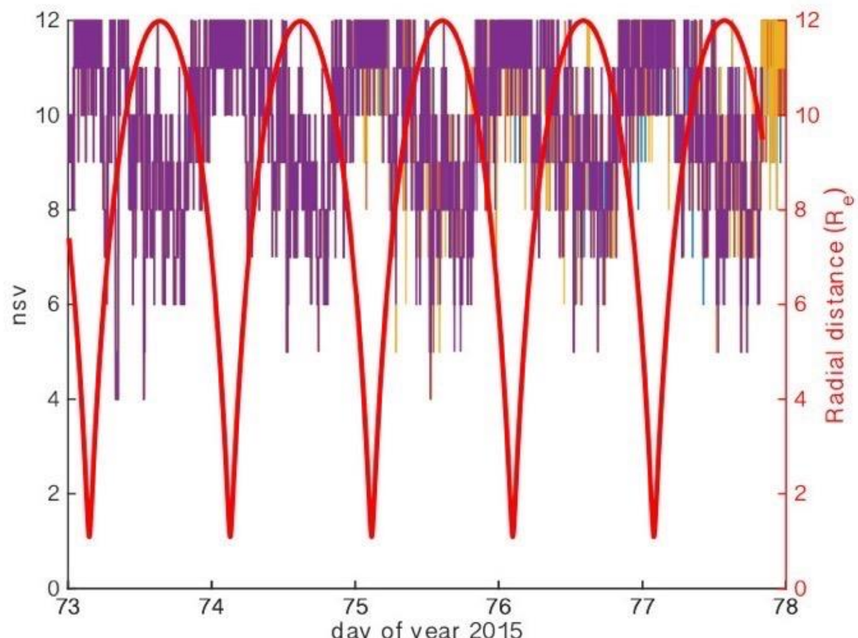
Phase 1 Performance: Signal Tracking

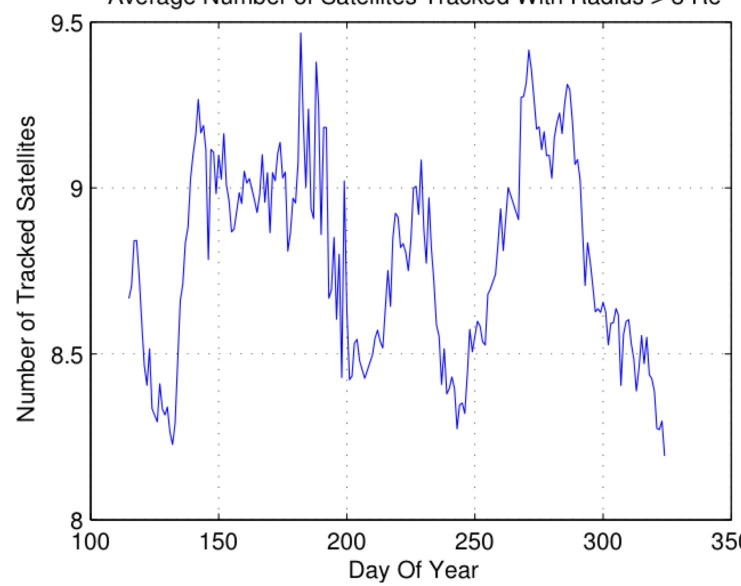
- Once powered, receiver began acquiring weak signals and forming point solutions
- Long term trend shows average of >8 signals tracked above $8R_E$
- Above GPS constellation, vast majority of these are sidelobe signals
- Visibility exceeded preflight expectations

Signal to noise vs. time



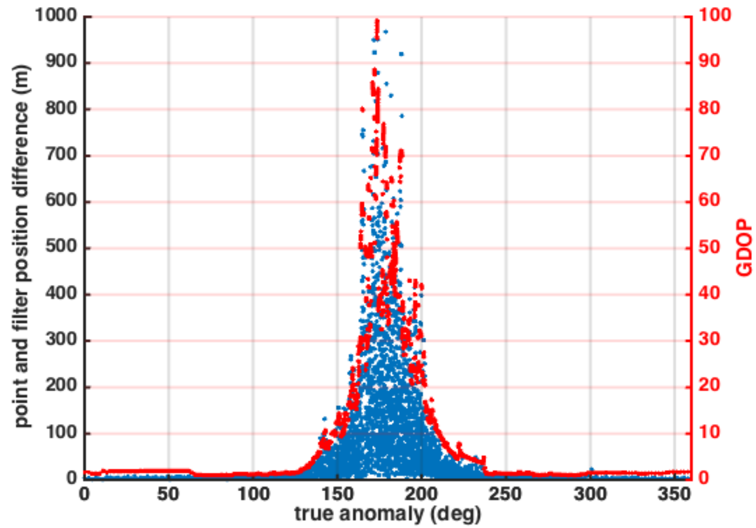
Signals tracked during first few orbits

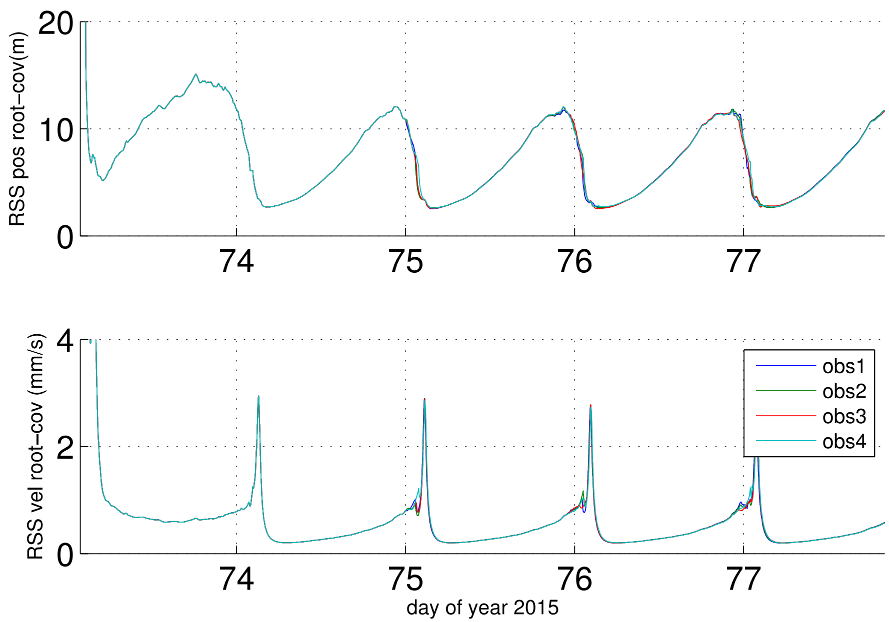


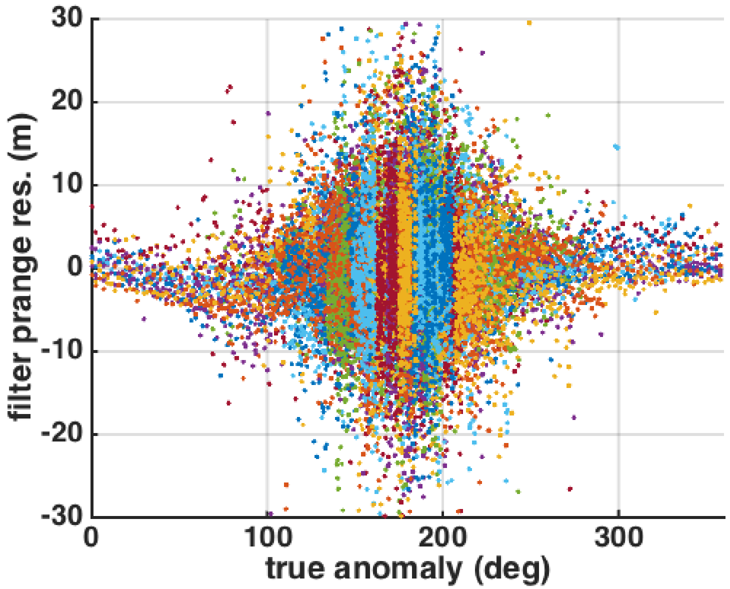


Phase 1 Results: Measurement and Navigation Performance

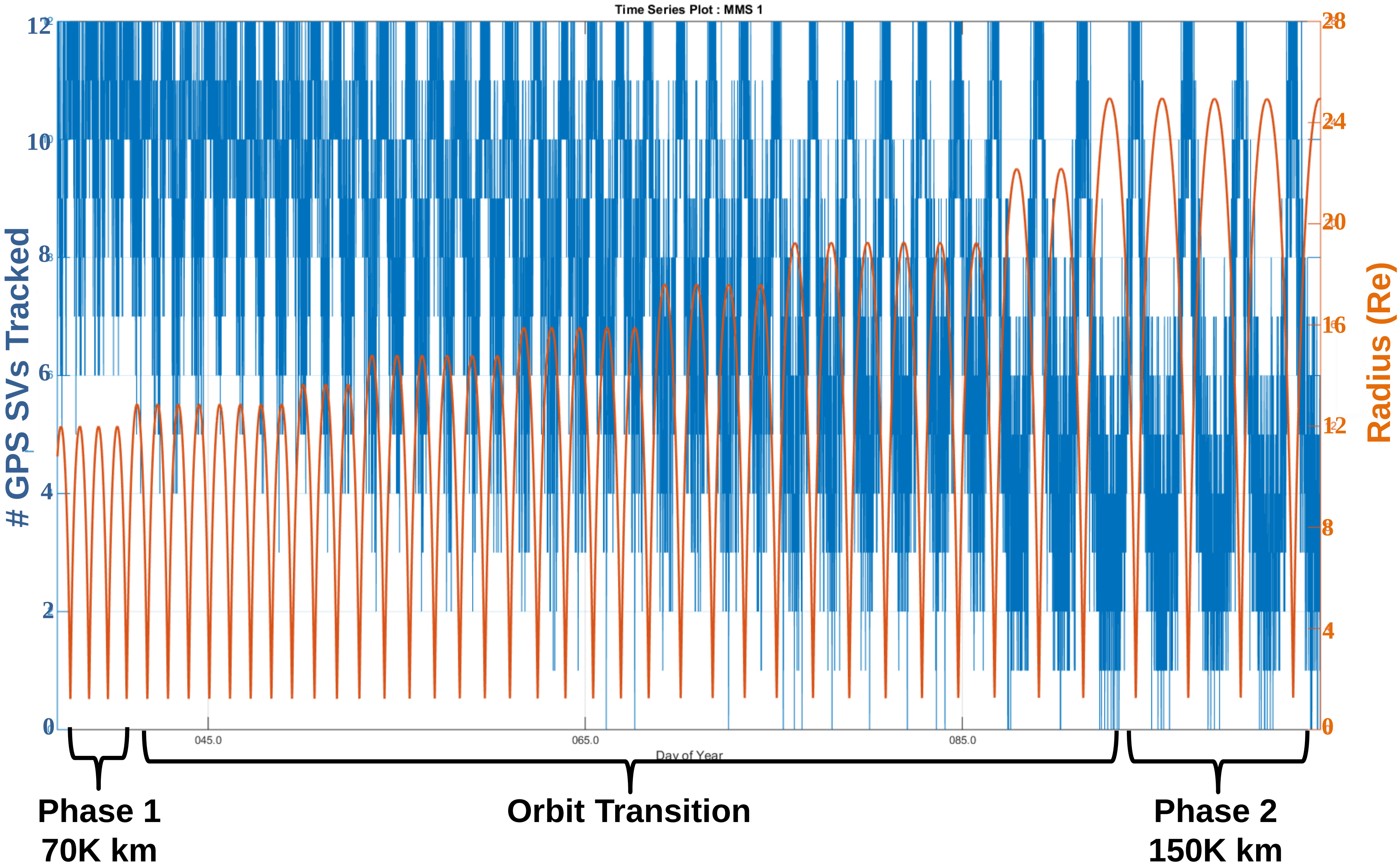
- GEONS filter RSS 1-sigma formal errors reach maximum of 12m and 3mm/s (typically <1mm/s)
- Although geometry becomes seriously degraded at apogee, point solutions almost continuously available
- Measurement residuals are zero mean, of expected variation. Suggests sidelobe



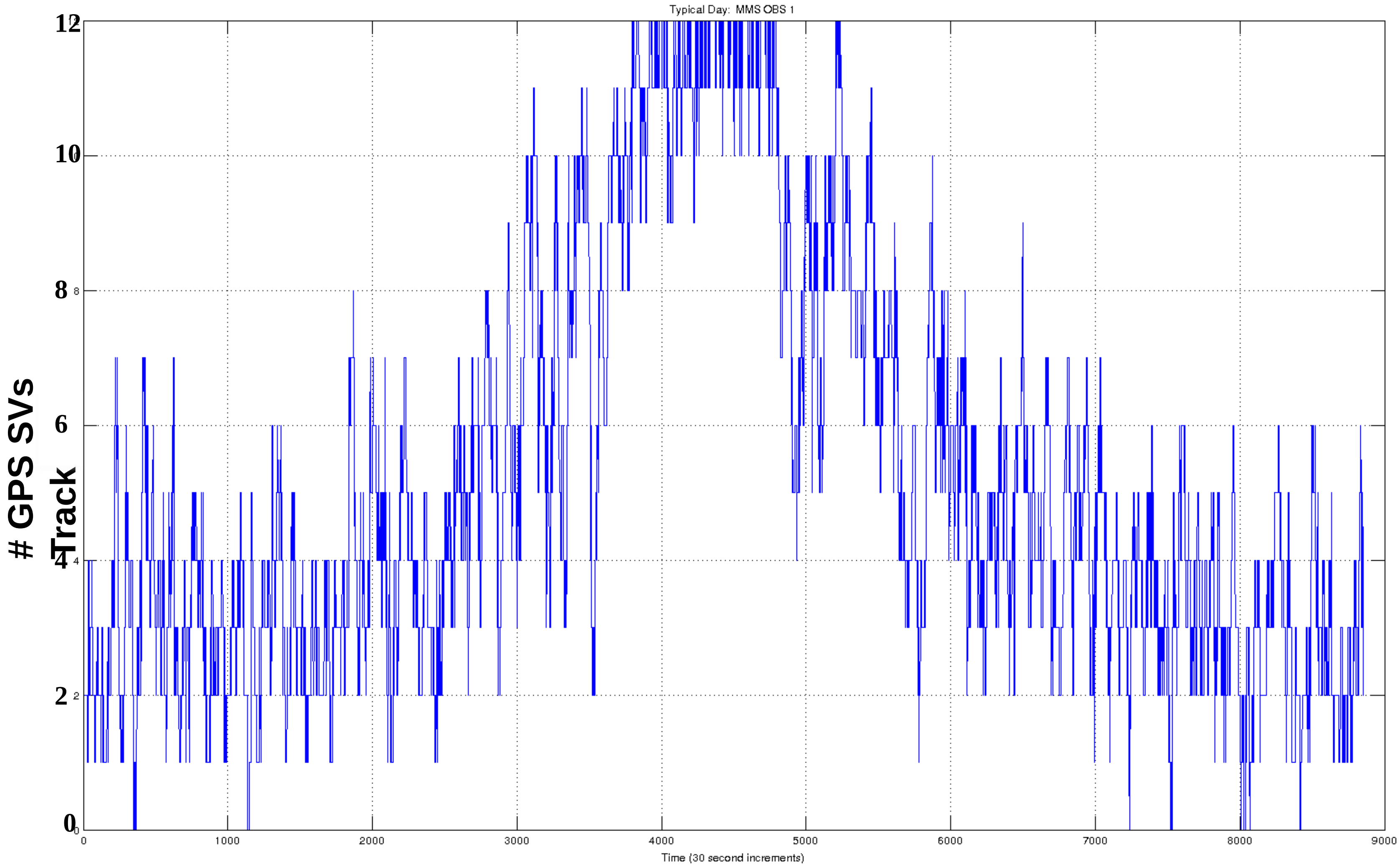




Signal Tracking Performance During Phase 1 to Phase 2 Apogee Raising (70K km to 150K km)



Signal Tracking Performance
Single Phase 2B Orbit (150K km Apogee)



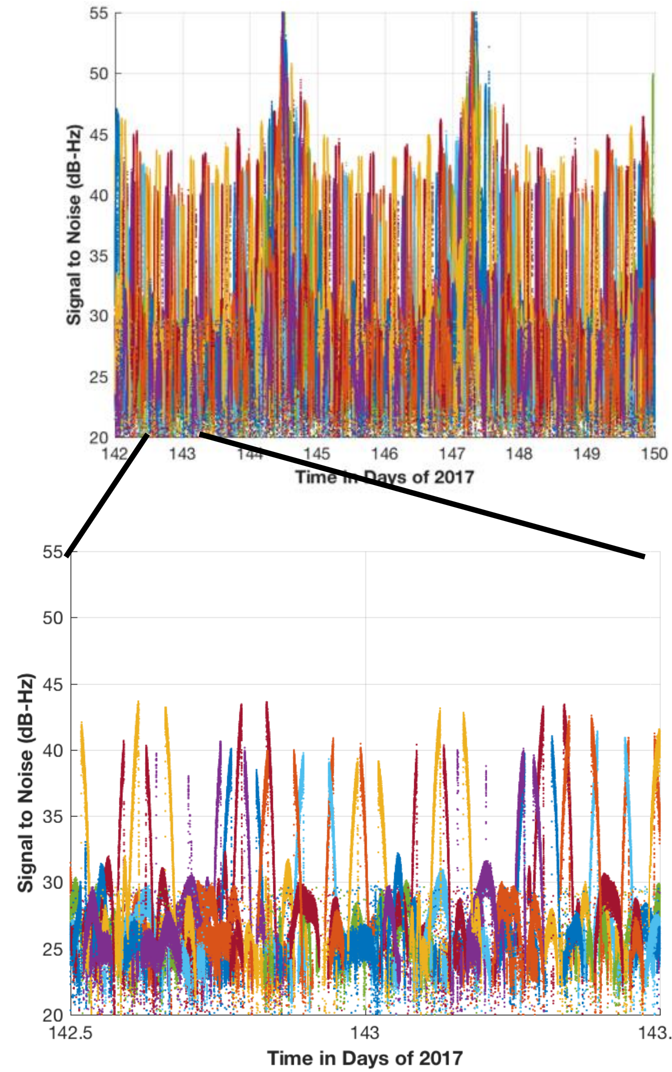
Average Outage: 2.8 mins; Cumulative outage: 22 min over 67 hour orbit (0.5%)

Note: Actual performance is orbit sensitive

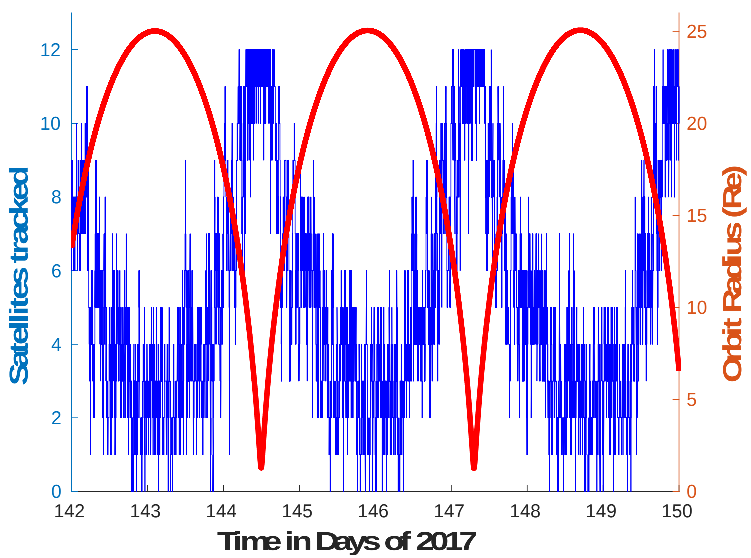
MMS on-orbit Phase 2B results: signal tracking

- Consider 8-day period early in Phase 2B
- Above GPS constellation, majority of signals are still sidelobes
- Long term trend shows average of ~3 signals tracked near apogee, with up to 8 observed.
- Visibility exceeds preflight expectations significantly

C/N_0 vs. time, near apogee

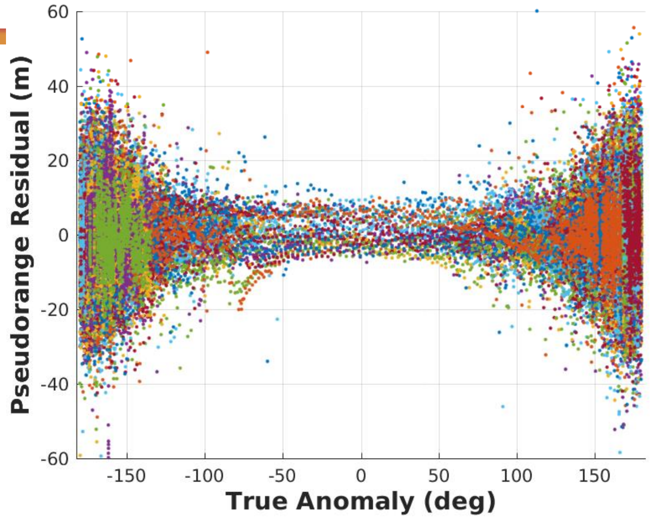


Signals tracked

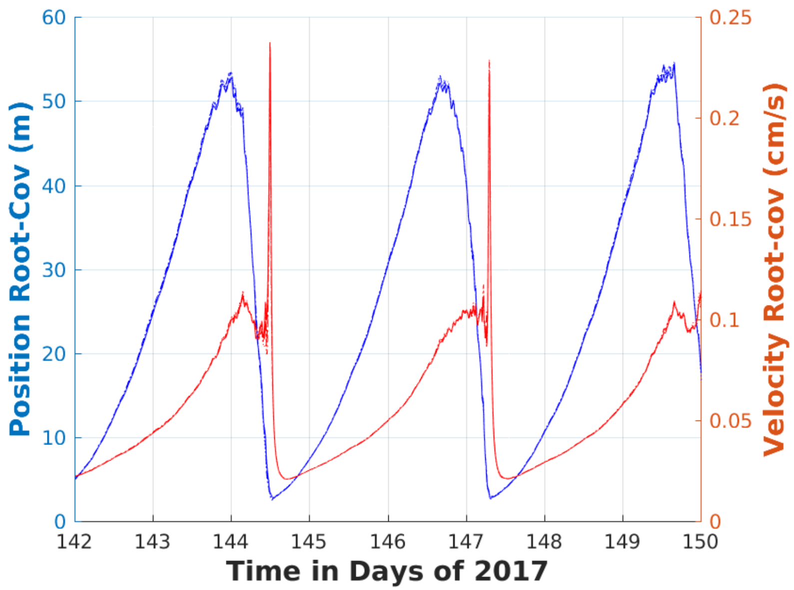


MMS on-orbit Phase 2B results: measurement and navigation performance

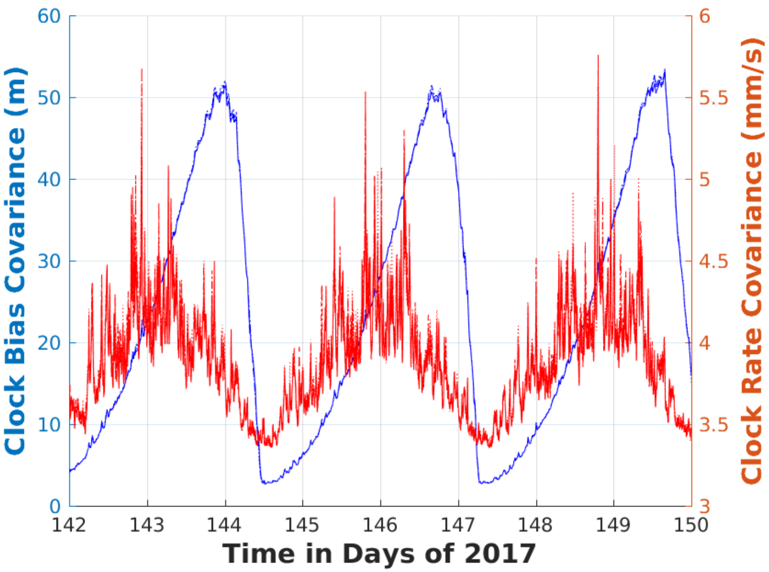
- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
  - Suggests sidelobe measurements are of high quality.



Filter formal pos/vel errors (1σ root cov)



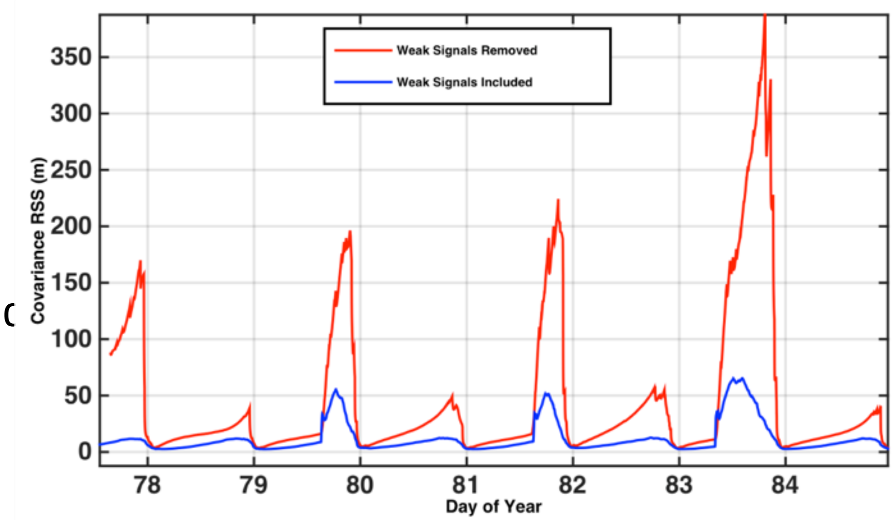
Filter formal clock errors (1σ root cov)



57

GOES-16 & MMS SSV Lessons Learned

- Flight data presents real-world snapshot of current GPS SSV performance, especially the substantial enhancements afforded by side-lobe signals
- Side-lobe signals:
  - Shown to significantly improve availability and GDOP out to cis-Lunar space
  - Substantial enhancement of maneuver recovery for vehicles in SSV (graphic)
  - Integrity of signals sufficient enough to enable outstanding, real-time navigation out to cis-Lunar distances
- Operational use of side-lobe signals is an increasing area of interest & multiple operational examples are on-orbit and in development
- WG-B team should consider whether beyond main-lobe (aggregate) signals should be documented and protected to optimize the utility of the SSV



MMS response to apogee maneuvers with side-lobe signals (blue) and without (red)

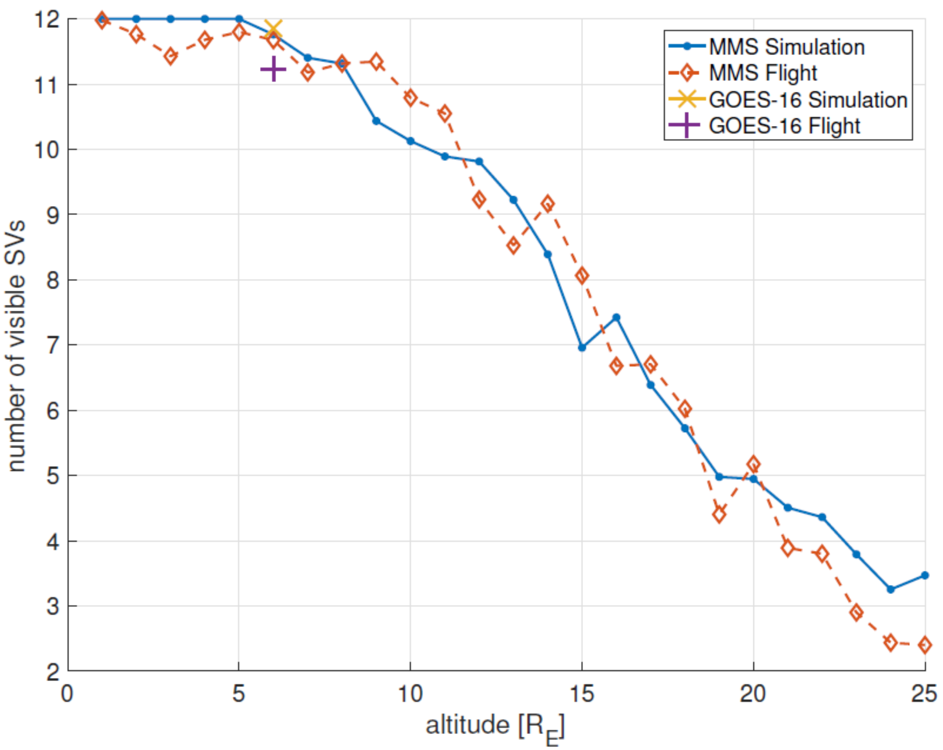
Notes:

1) Blue—flight data
2) Red—simulated data based on flight signal availability
3) MMS Phase 1 (70,000 km apogee)

Lunar GPS Visibility Simulation

- GPS constellation modeled as accurately as possible, validated with GOES-16 and MMS flight data
  - GPS sidelobes included
  - 31 GPS SVs with block composition consistent with validation flight data (spring 2017)
  - Transmitter antenna patterns: IIR/IIR-M public patterns (gps.gov), IIA averaged pattern used for similar IIF
- GPS signals visible if 1) line of sight is unobstructed and 2) carrier-to-noise spectral density (C/N0) exceeds receiver acquisition/tracking threshold
- Validation shows broad agreement between simulation and flight data, allowing application to near-rectilinear halo orbit (NRHO) under consideration for US future human exploration

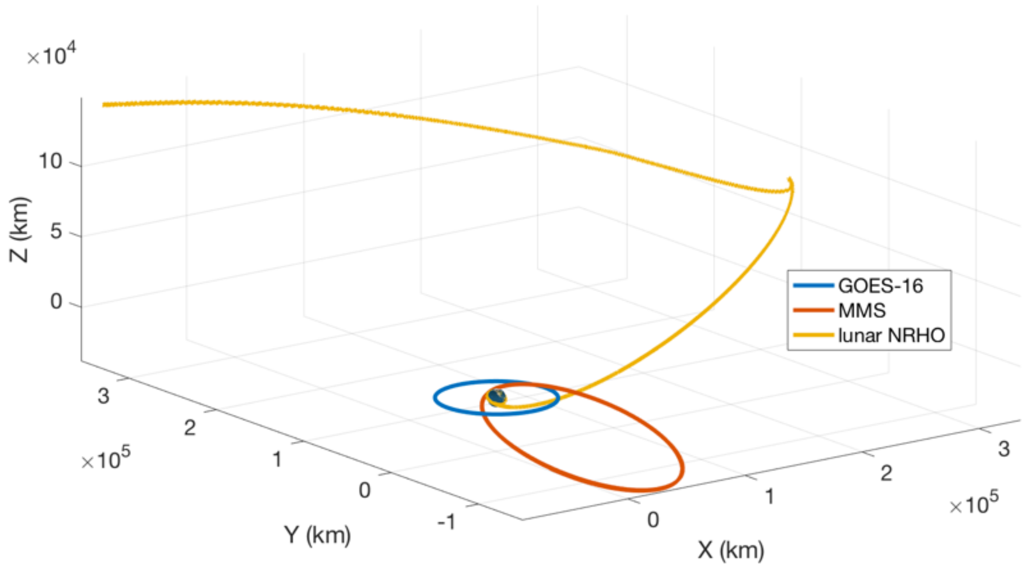
Simulation validation with MMS and GOES-16 flight data: number of SVs visible over altitude



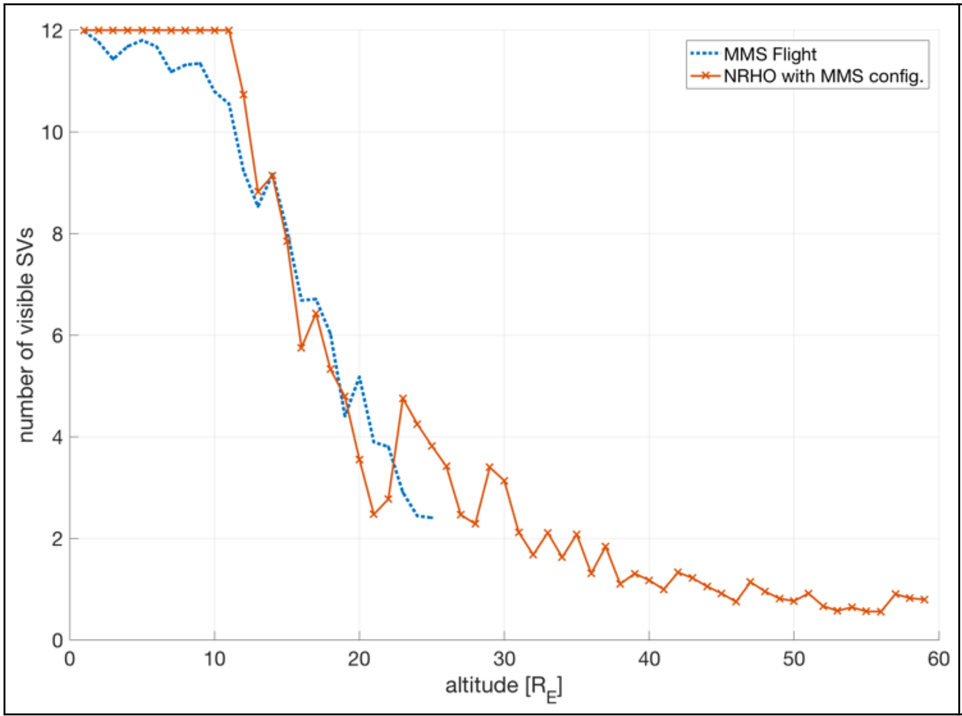
59

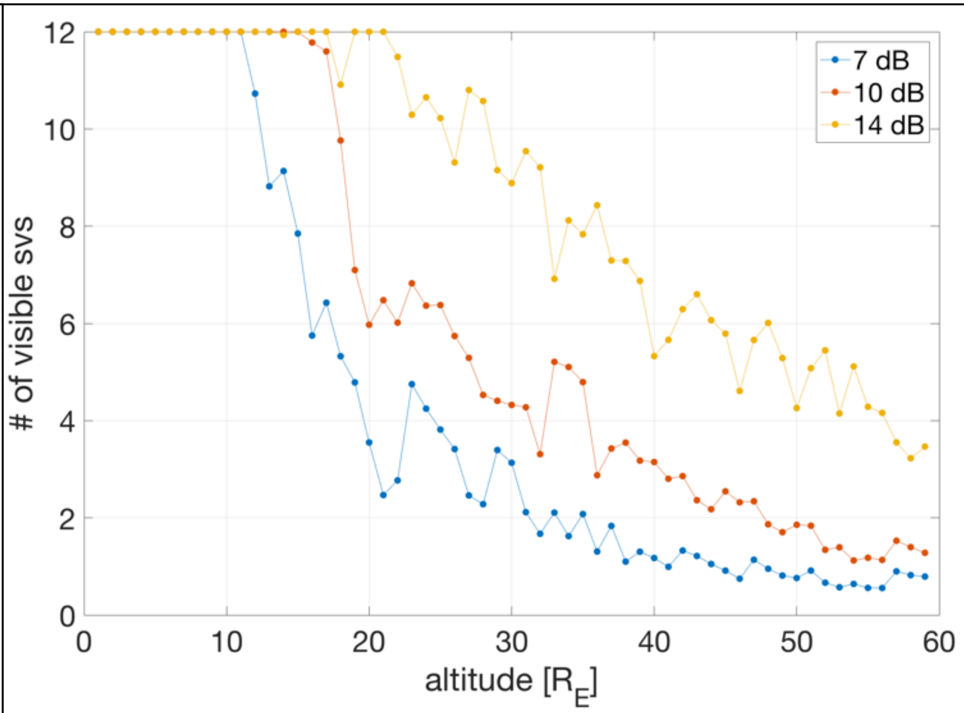
Lunar GPS Visibility Simulation

- US plans to return to human exploration of the Moon and cislunar space with EM-1 and EM-2; one long-term objective is the Lunar Orbital Platform - Gateway, an international, permanent way-station in the vicinity of the moon
- Near Rectilinear Halo Orbit (NRHO) is one proposed orbit; this is used here for the lunar simulation with only the outbound cruise
- **Three mission configurations**:
  - **Validation** – same antenna gain (7 dB peak), pointing, and receiver acq/trk thresholds as MMS (22 dB-Hz)
  - **High gain antenna** – 10 and 14 dB peak gain, same 22 dB-Hz receiver acq/trk thresholds
  - **Receiver design baseline** – 10 dB peak gain antenna, but 1 dB-Hz receiver thresholds



Lunar GPS Visibility Simulation



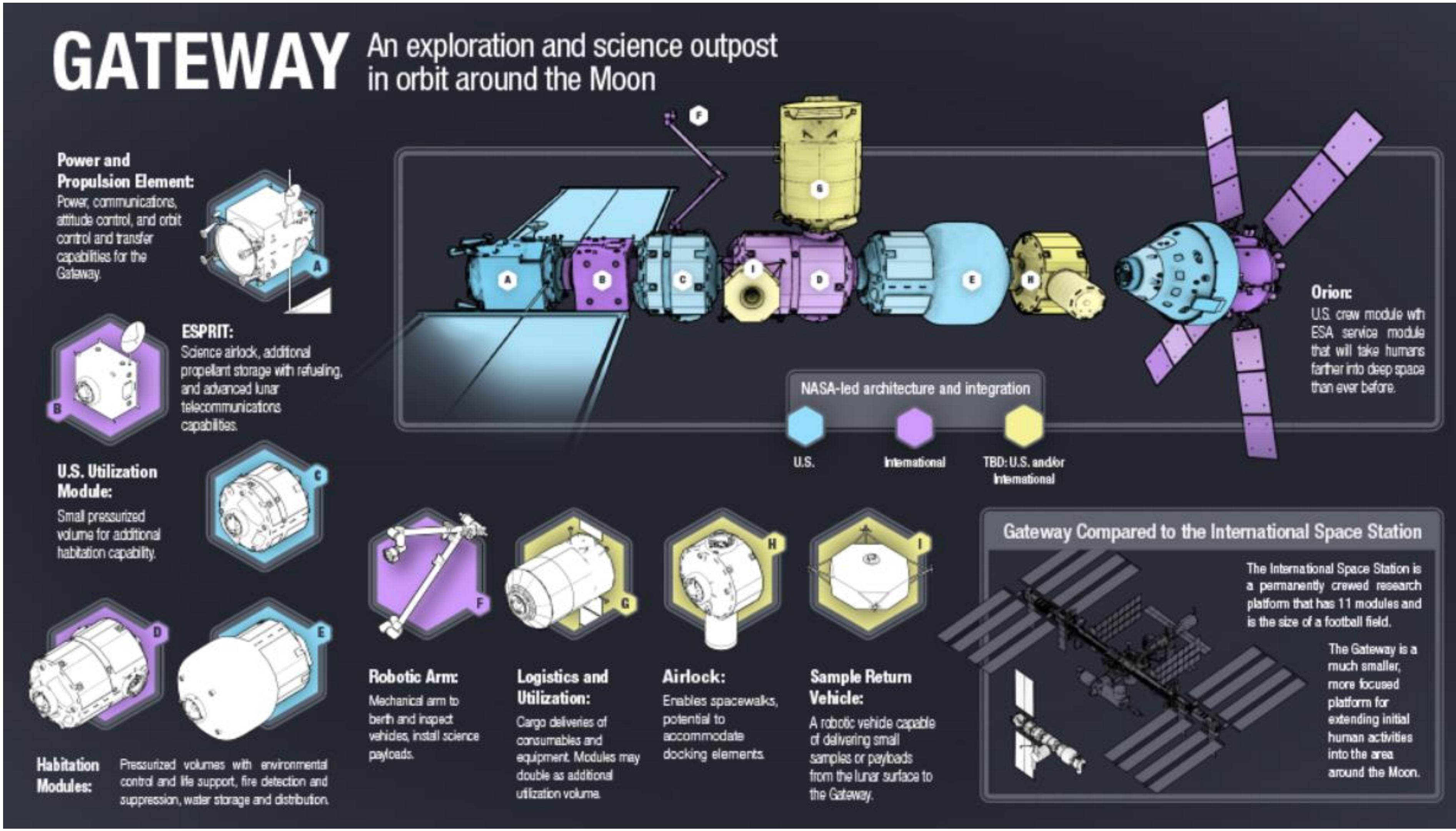


Lunar trajectory: number of SVs visible by altitude

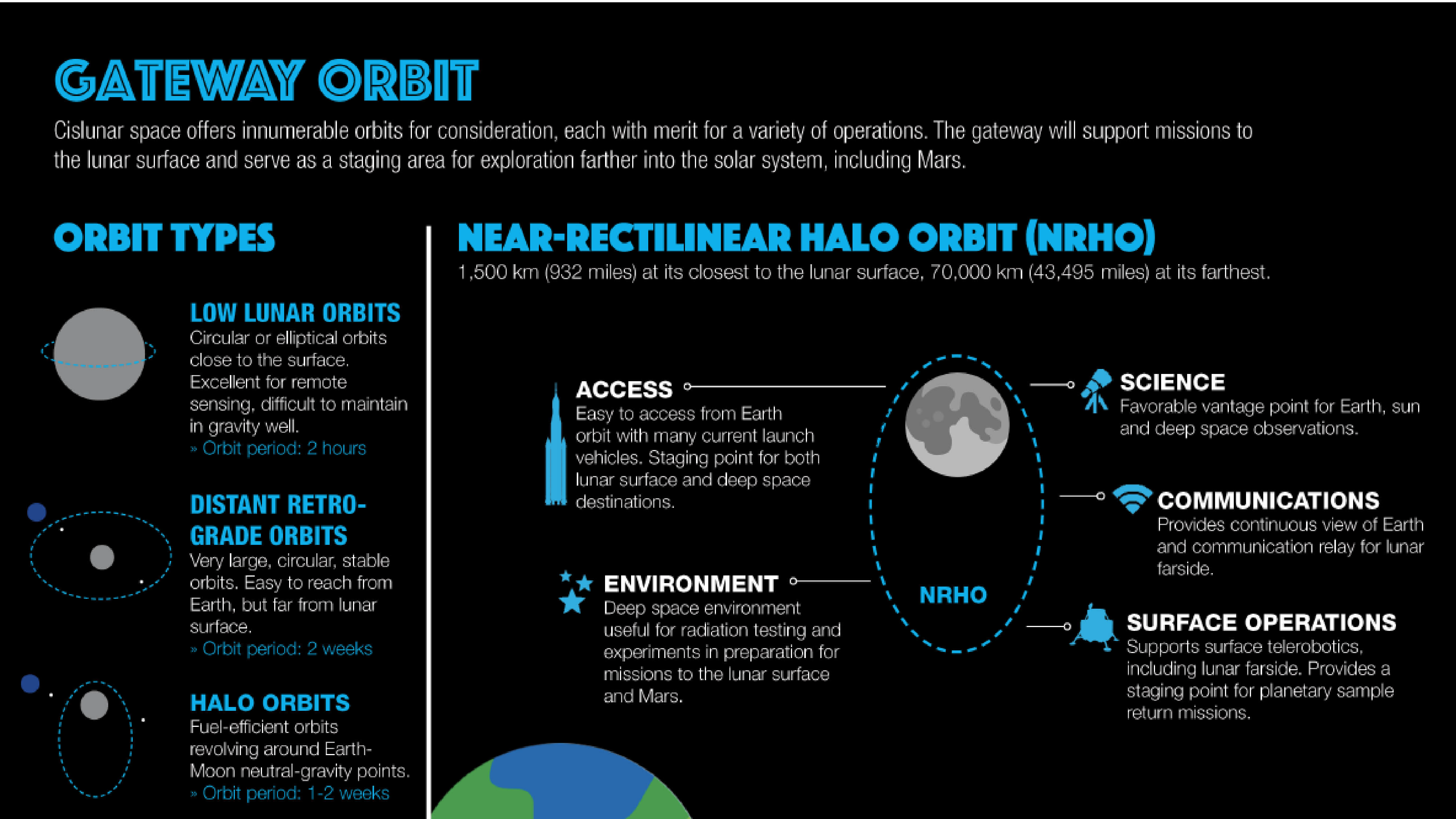
Validation of results vs. MMS flight data

Number of satellites visible by altitude for different antenna gains

Potential Future Application: Lunar Orbital Platform—Gateway



Potential Future Application: Lunar Orbital Platform—Gateway



Conclusions: Beyond-SSV Applications

- **ICG SSV Booklet** showed potential application of GNSS mainlobe signals to cislunar navigation
- **Kyoto recommendation** called for further study into potential performance levels and applications in cislunar space and beyond
- Recent **US GPS-only studies** show even greater levels of availability and navigation performance when sidelobe signals are included and high-fidelity models are used.
- **3rd Global Exploration Roadmap** lists 10+ upcoming global cislunar exploration missions in the next 10 years
- **WG-B has an opportunity** to take a leading role in future utilization of GNSS for cislunar exploration, via advocacy for, and collaboration on:
  - Mission-specific multi-GNSS analyses
  - Cislunar flight demonstrations

NASA Proposed Path Forward to Realization of Recommendation

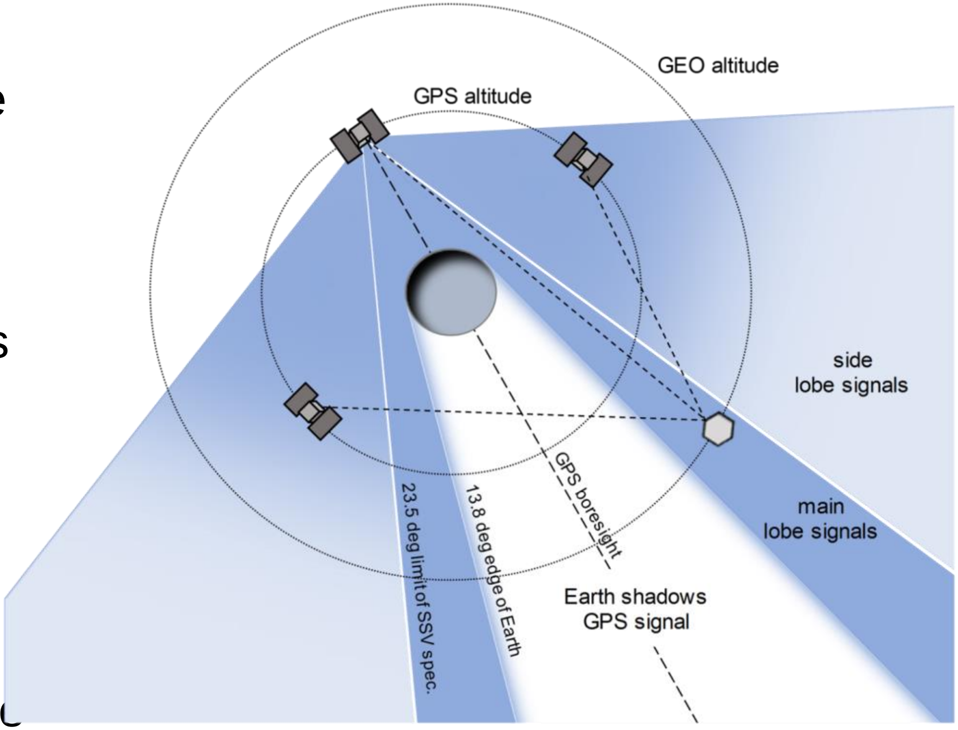
- **Goal: Conduct a WG-B-led trade study on options for future SSV concepts to support exploration needs in cislunar space and beyond.**
- Study would be follow-on to SSV Booklet, which establishes baseline for GNSS SSV.
- **Scoping activity**:
  - How far is “beyond”?
  - What regimes are included? Cislunar? Sun-Earth Lagrange points? Interplanetary?
  - Does scope extend beyond GNSS to complementary PNT services?
- **Study Objectives**:
  - Develop a PNT architecture, focusing on GNSS capabilities that will support missions within and around cislunar space, Lagrange points, Mars vicinity (subject to agreed-upon scoping)
  - As part of architecture trades, define minimal set of GNSS augmentations that will support these mission scenarios
  - Look at other PNT capabilities and augmentations that can support these mission scenarios in conjunction with GNSS; (e.g. X-ray Pulsar Navigation, Celestial Navigation, OpNav, Deep Space Atomic Clock timing, Mars orbiter hosted payloads)
- Proposal is for **two meetings** within the next year:
  1. **Internal planning meeting** focused on trade study planning/scoping
  2. **Public workshop** to collect baseline inputs on concepts, use cases, roadmaps

US Proposal: Workshop on Future Directions for the SSV

- **Workshop Goals:** Collect international inputs on future directions for the Multi-GNSS SSV in cislunar space and beyond
  - What are the major use cases? What are the agencies' roadmaps for exploration?
  - What threshold performance is needed? What is achievable?
  - What future SSV plans are in progress by the providers?
- **Time horizon:** 20–30 years (2040–2050)
- **Participants:** Providers, Space Agencies, and Research Institutions
- **Workshop venue options (proposed):**
  - ICG-13, Xi'an, China, Nov 2018 – venue for planning meeting?
  - NASA HQ, Washington, DC, Jan/Feb 2018 (alongside ION ITM)
  - Munich Satellite Navigation Summit, Munich, Germany, March 2018
- **Discussion to be held in WG-B intercessional meeting:**
  - Is this path forward agreeable for addressing ICG-12 Recommendation?
  - Is there interest by WG-B members in participating in this discussion?
  - What are preferred options for workshop planning?

GPS Antenna Characterization Experiment

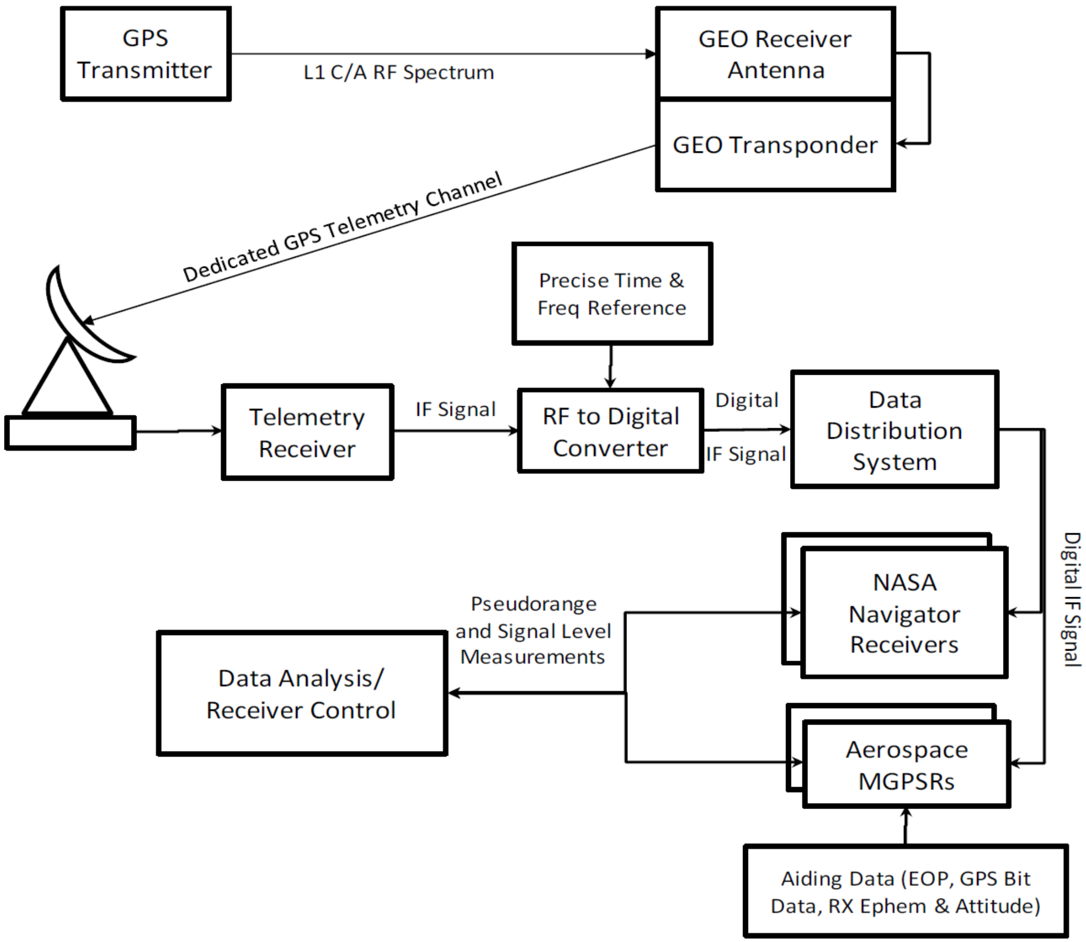
- **Problem Statement**
  - Vehicles operating in Space Service Volume (SSV, 3000-36,0000 km alt) have very limited visibility of GPS main beam
  - Expanding GPS usage to side lobes greatly enhances availability and accuracy of GPS solution
  - Side lobes are poorly characterized
  - Unknown side lobe performance results in lack of confidence in usage



- **GPS ACE Contribution**
  - GPS L1 C/A signals from GEO are available at a ground station through a "bent-pipe" architecture
  - Map side lobes by inserting advanced, weak-signal tracking GPS receivers at ground station to record observations from GEO

GPS ACE Implementation

- GEO vehicle transponds GPS L1 spectrum to ground
- Digitized data is sent over network to GPS receivers
- Two versions of receivers installed:
  - NASA Navigator receiver
    - Real-time space receiver for high altitude
  - Aerospace Mariposa GPS receiver
    - Ground based bit aided weak signal receiver
- Record GPS pseudorange and signal level observations
- Gather daily measurement files over time for batch processing
  - Full transmit gain patterns
  - Pseudorange residual assessment

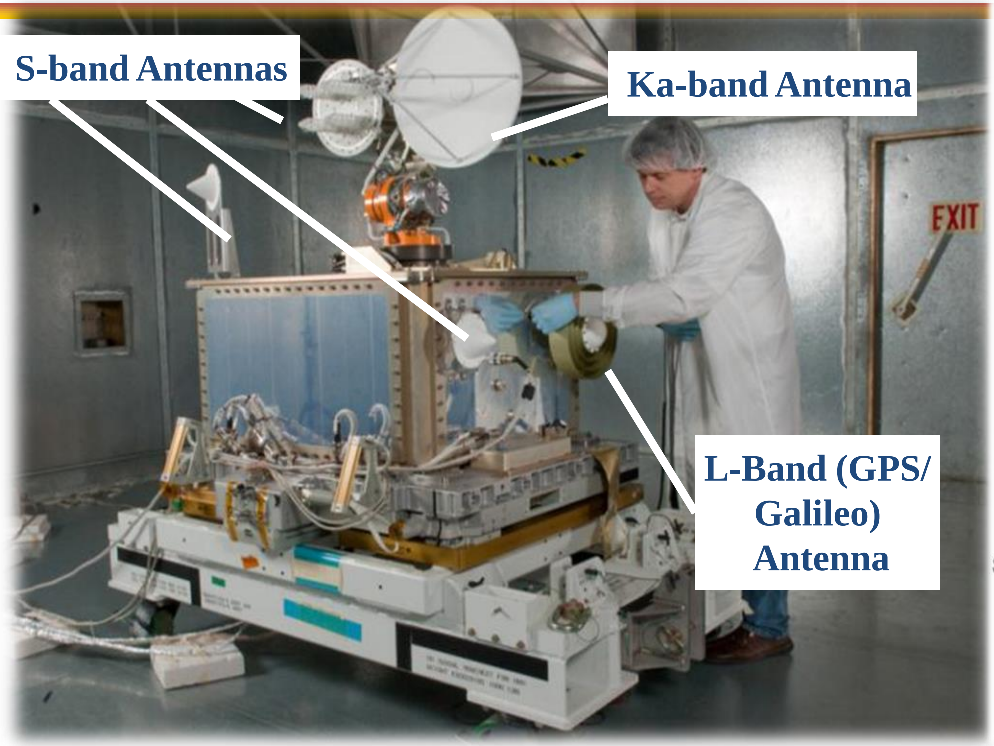


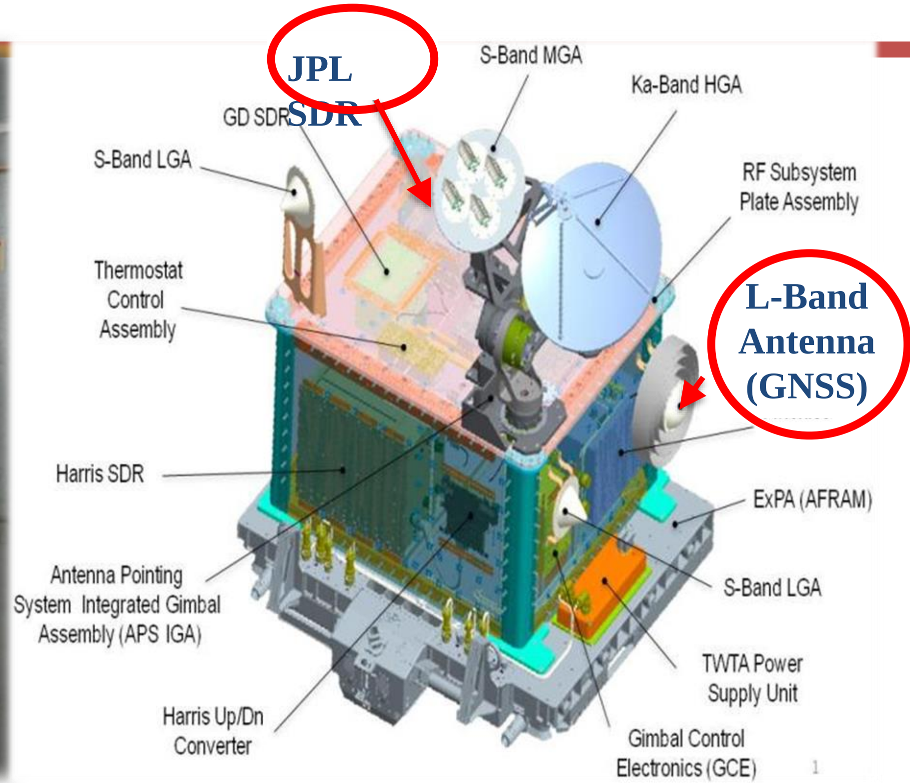
Automatic Flight Termination System Operational Use

- In work over 17 years with many flight demonstrations
- Independent Verification and Validation (IV&V) completed June 2015
- Prototype AFTS units were flown on 13 SpaceX launches since April 2015
- First Operational Launch of AFTS on SpaceX CRS-10 launch, Feb 20, 2017
- Five (5) additional successful operational launches to-date (as of June 2017)

AFTS Fully Operational & Demonstrating its Critical Role of Protecting People & Property and Enabling Quicker Cadence of Launch Ranges

NASA's SCaN Testbed





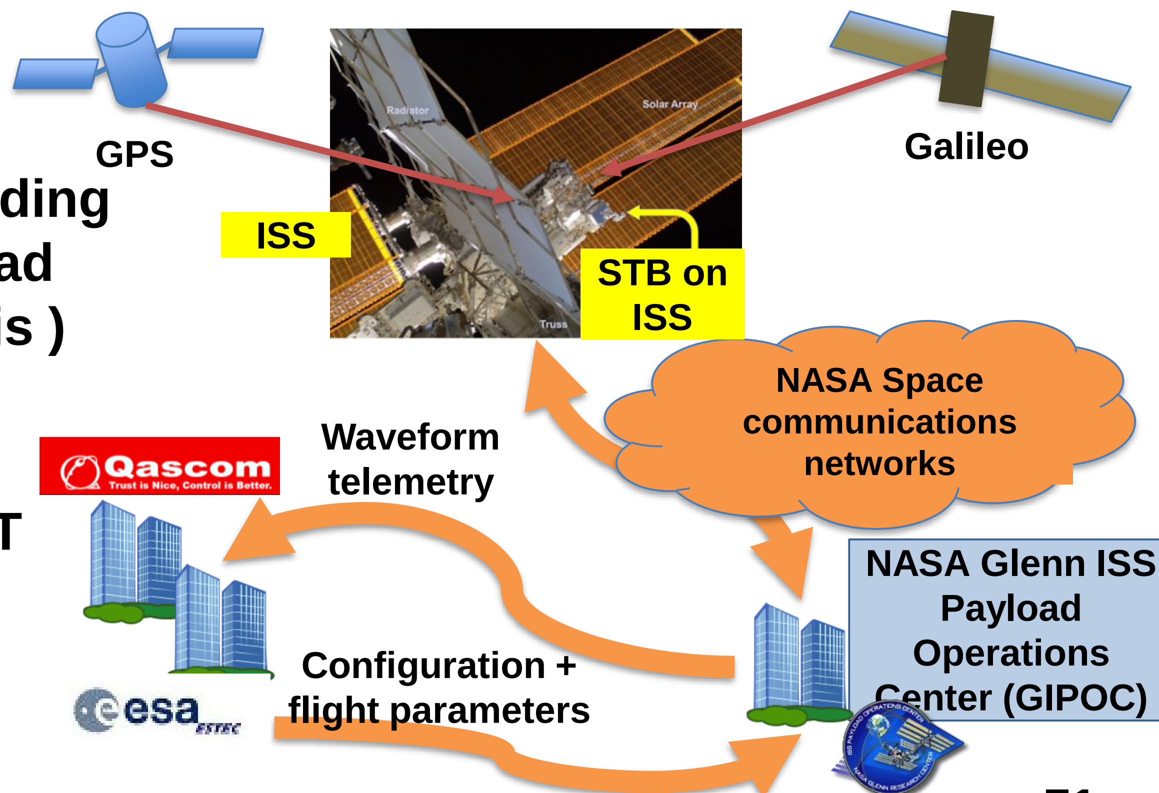
<u>Space Communication and Navigation (SCaN) Testbed</u>

Installed on the International Space Station (ISS) in July 2012

Fully reprogrammable Software Defined Radio capability at L-band

On-orbit Operational/Experiment Concepts

- **Concept of operation:**
  - **Transfer waveform from ground support equipment to STB**
  - **Operate waveform per ISS and STB operations schedule**
  - **Collect/process log data**
- **Warm start acquisition aiding from ground via file upload (GGTO, SV, ISS ephemeris)**
- **Assess acquisition and tracking performance, pseudo-range errors, PVT performance, etc.**



GARISS Conclusions

<u>Conclusions</u>

- GARISS waveform development is an element of NASA/ESA cooperation involving multiple centers, Qascom
- GARISS leverages SCAN testbed, STRS development framework
- Demonstrates use of SDR waveform upload to install radio capabilities post-launch
- Demonstrated effectiveness of multi-constellation/GNSS solutions
- First-ever on-orbit direct acquisition of L5/E5a (no L1 aiding)

Aggregate Table of IOAG Missions Using GNSS

See attachment:

Microsoft Excel
Worksheet