Keeping the universe connected.

NASA GNSS Activities

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

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www.nasa.gov

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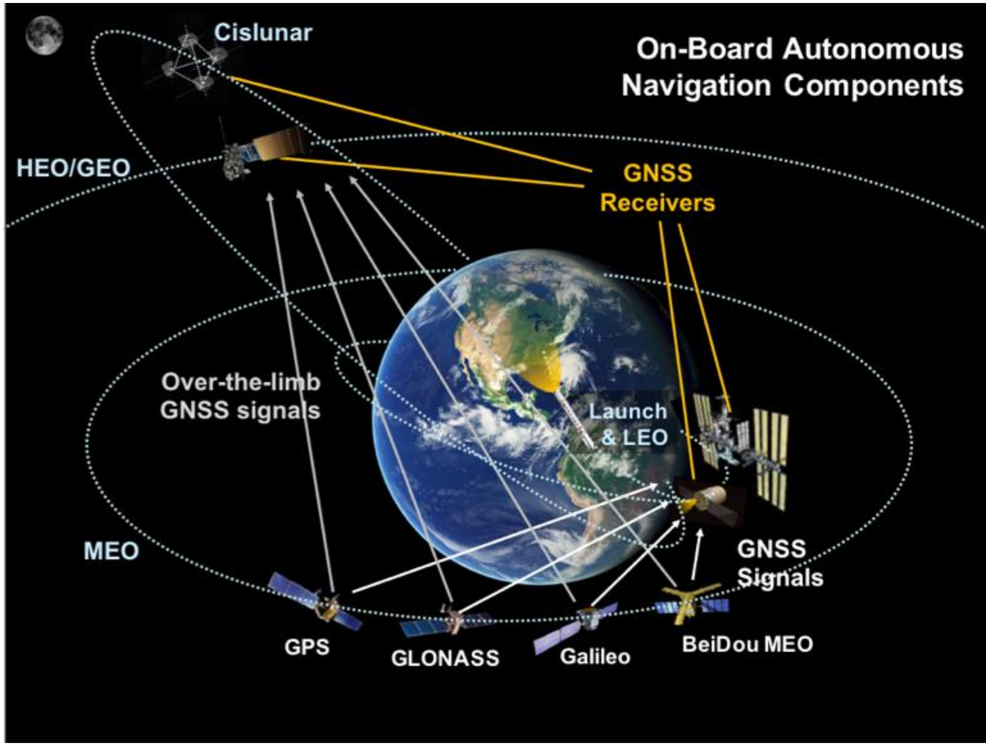
Space Uses of Global Navigation Satellite Systems (GNSS)

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

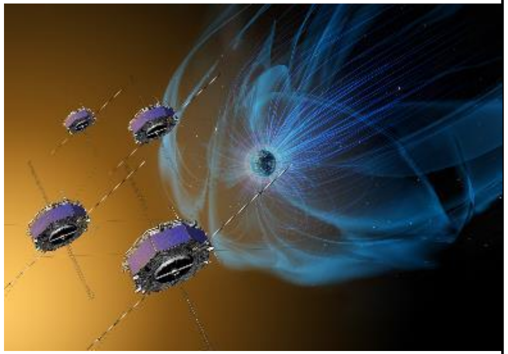


GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

U.S. Initiatives & Contributions to Develop & Grow an Interoperable GNSS SSV Capability for Space Users

Operational Users

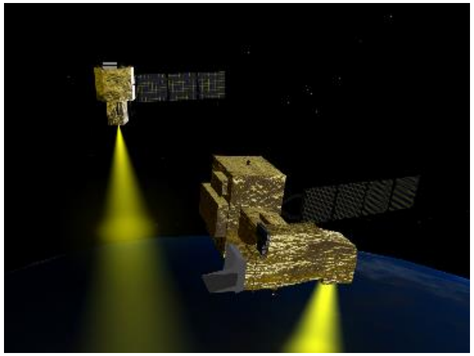
- MMS
- GOES-R, S, T, U
- EM-1 (Lunar en-route)
- Satellite Servicing



Operational Use Demonstrates Future Need

Space Flight Experiments

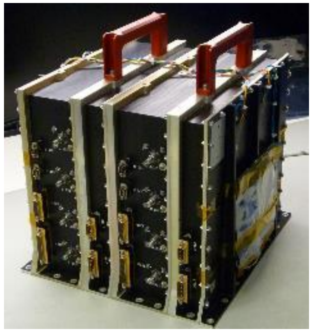
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)



Breakthroughs in Understanding; Supports Policy Changes; Enables Operational Missions

SSV Receivers, Software & Algorithms

- GEONS (SW)
- GSFC Navigator
- General Dynamics
- Navigator commercial variants (Moog, Honeywell)



Develop & Nurture Robust GNSS Pipeline

SSV Policy & Specifications

- SSV definition (GPS IIF)
- SSV specification (GPS III)
- ICG Multi-GNSS SSV common definitions & analyses

Operational Guarantees Through Definition & Specification

From 1990's to Today, U.S. Provides Leadership & Guidance Enabling Breakthrough, Game-changing Missions through use of GNSS in the SSV

NASA GNSS User Segment

Status Update

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 November 14, 2017 (IOAG-21)
- 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	12
ESA	European Space Agency	17
JAXA	Japan Aerospace Exploration Agency	12
NASA	National Aeronautics and Space Administration	38

NASA GNSS User Update

Mission status updates and modifications:

Agency	Mission	GNSS Used	GNSS Signals Used	GNSS Application	Orbit	Launch	Notes
NASA	SCaN Test-Bed on ISS	GPS, Galileo	L1 C/A, L2C, L5, Galileo E1 and E5A	Demo of software defined radio	LEO	2012	Blackjack-based SDR. Monitoring of GPS CNAV testing began in June 2013. Development of Galileo E5a/GPS L5 waveform through agreement with ESA began in October 2016
NSPO/ USAF/ NASA	COSMIC IIA (6 satellites)	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2018	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	2018	TriG lite receiver
NASA	GOES-16	GPS	L1 C/A	Orbit	GEO	2016	General Dynamics Viceroy-4

Removed: COSMIC IIB (cancelled)

Updates from Nov 2016 database, as of Nov 2017; 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	GRASP	GPS, GLONASS FDMA, Beidou, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination	LEO	2020	Trig receiver (proposed)
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	2015 & 2020	TriG receiver with 1553
NASA/ ISRO	(not available)	GPS, IRNSS	L1 C/A, L2C, semi-codeless P2, L5, IRNSS	Precise Orbit Determination, Occultation, Reflections (Scatterometry)	LEO	2020	TriG receiver

Updates from Nov 2016 database, as of Nov 2017; full database in backup

NASA GNSS User Update

Newly-added NASA missions:

Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch	Notes
NASA	GOES-S	GPS	L1 C/A	Orbit	GEO	2018	General Dynamics Viceroy-4
NASA	GOES-T	GPS	L1 C/A	Orbit	GEO	2019	General Dynamics Viceroy-4
NASA	GOES-U	GPS	L1 C/A	Orbit	GEO	2024	General Dynamics Viceroy-4
NASA	Fermi Gamma-ray Space Telescope (GLAST)	GPS	L1 C/A	Orbit	LEO	2008	General Dynamics Viceroy

Updates from Nov 2016 database, as of Nov 2017; full database in backup

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-S		GEO	March 2018
Exploration Mission 1 (EM-1)	Lunar technology demonstration	Lunar	September 2018
GOES-T		GEO	2019
GOES-U		GEO	2024

Historical

On-orbit

Future

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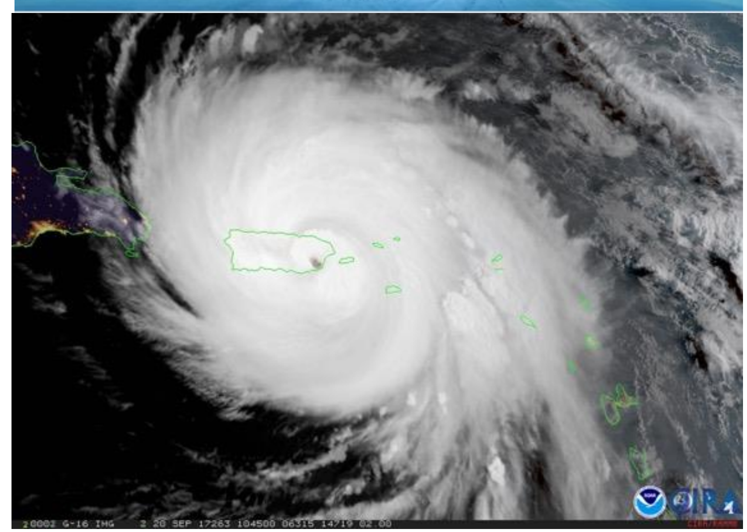
Historical

On-orbit

Future

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

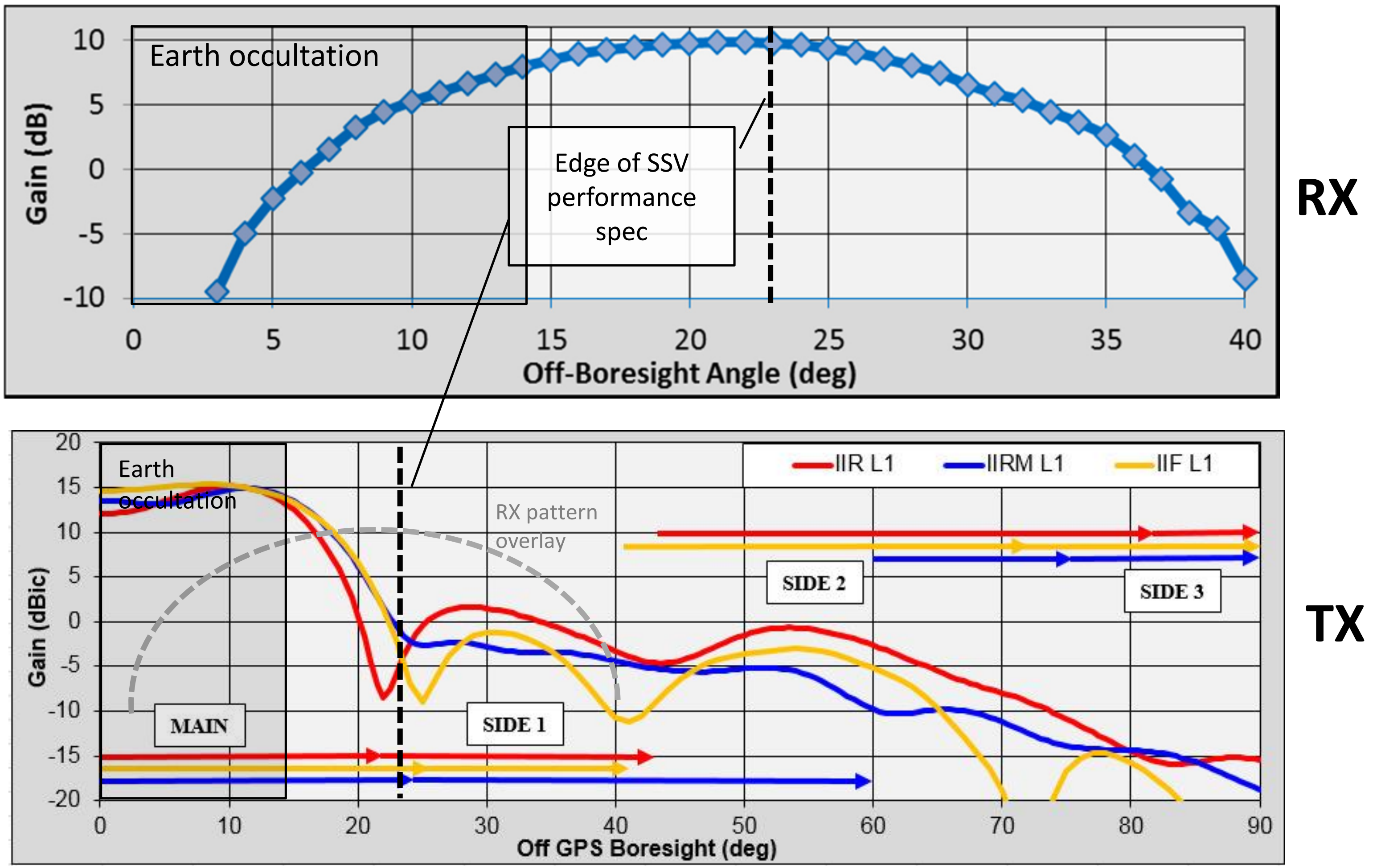


GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

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

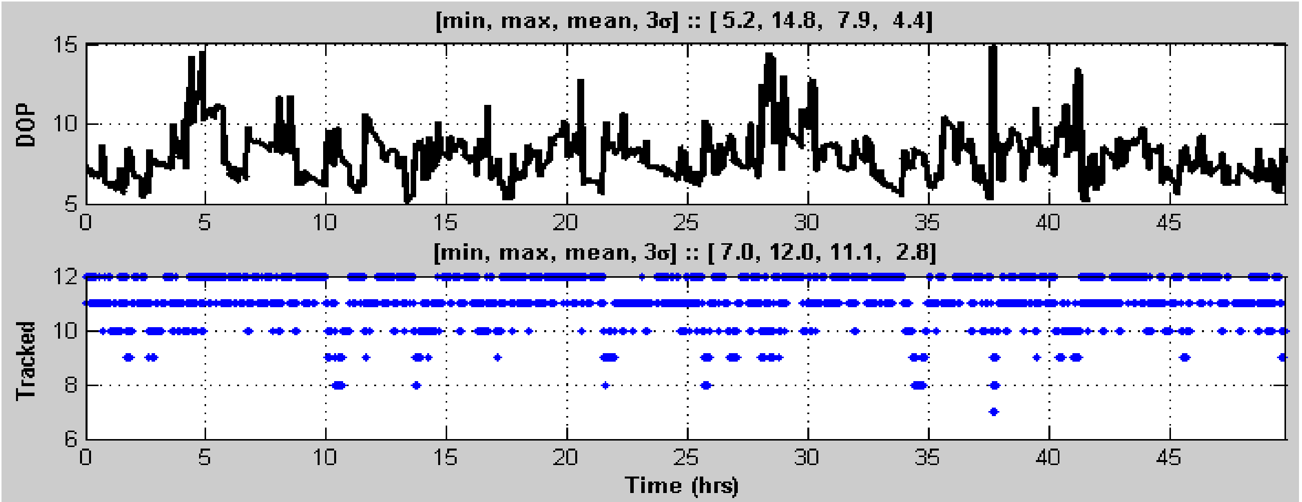


Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

GOES-R/GOES-16 In-Flight Performance

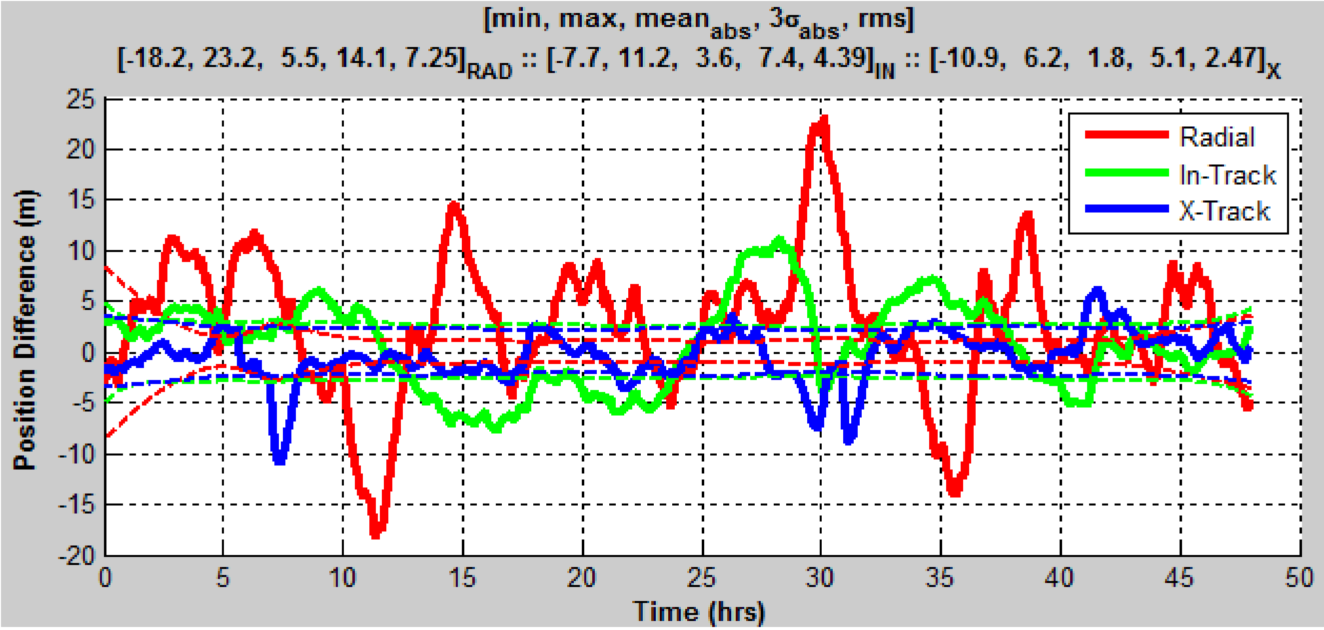
GPS Visibility

- 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



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GOES-U		GEO	2024

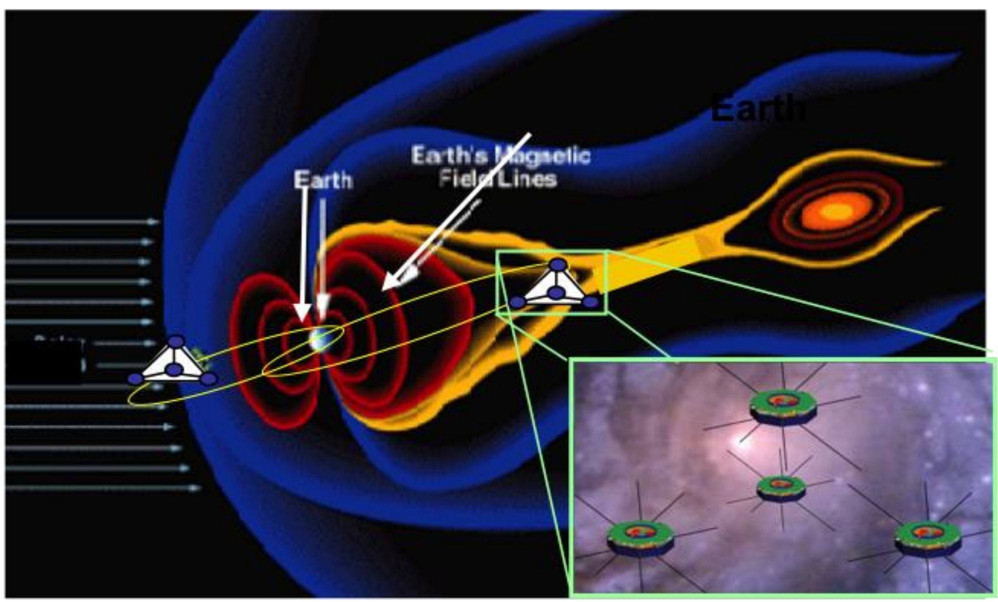
Historical

On-orbit

Future

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-Feb '17
  - Phase 2B 1.2x25 R_E (magnetotail) May '17-present



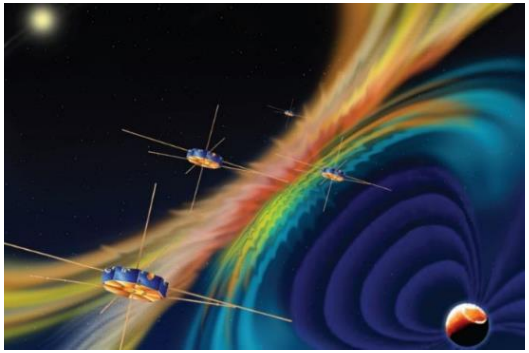
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

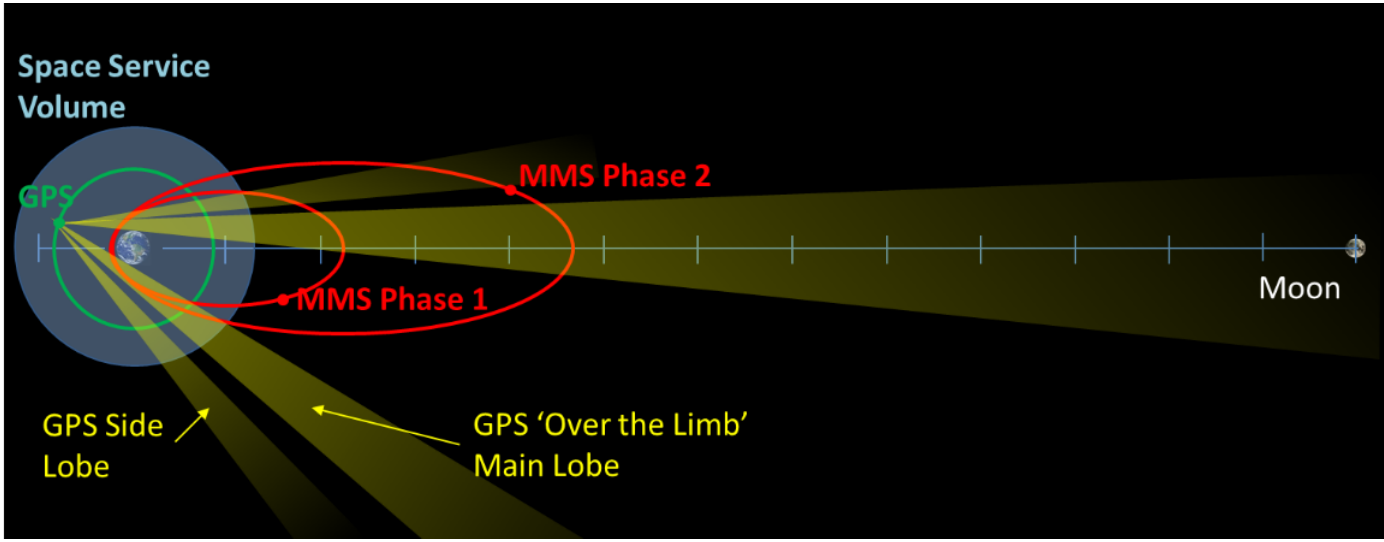
Magnetospheric Multi-Scale (MMS)

- 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!)**

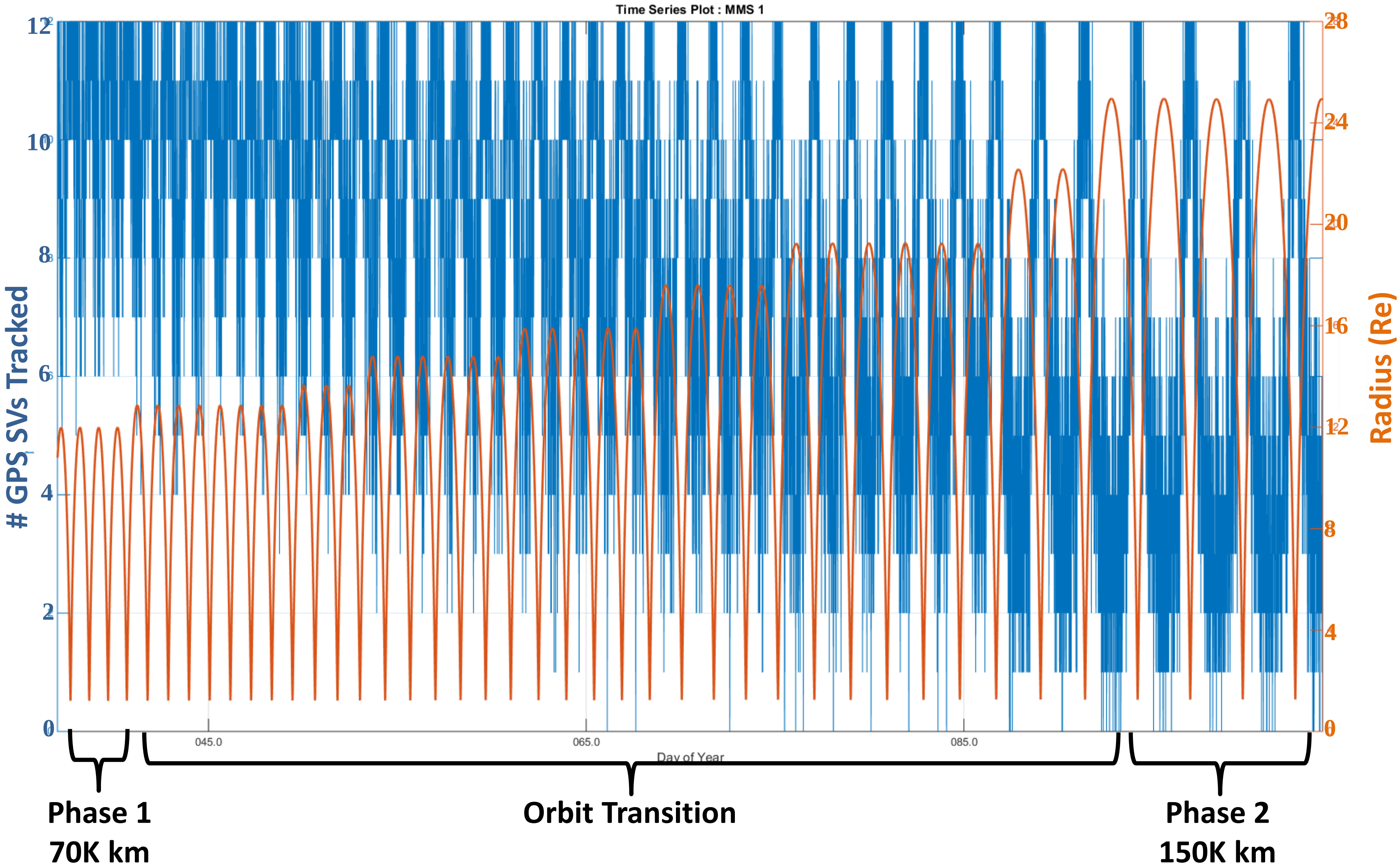
MMS Navigator System

- 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

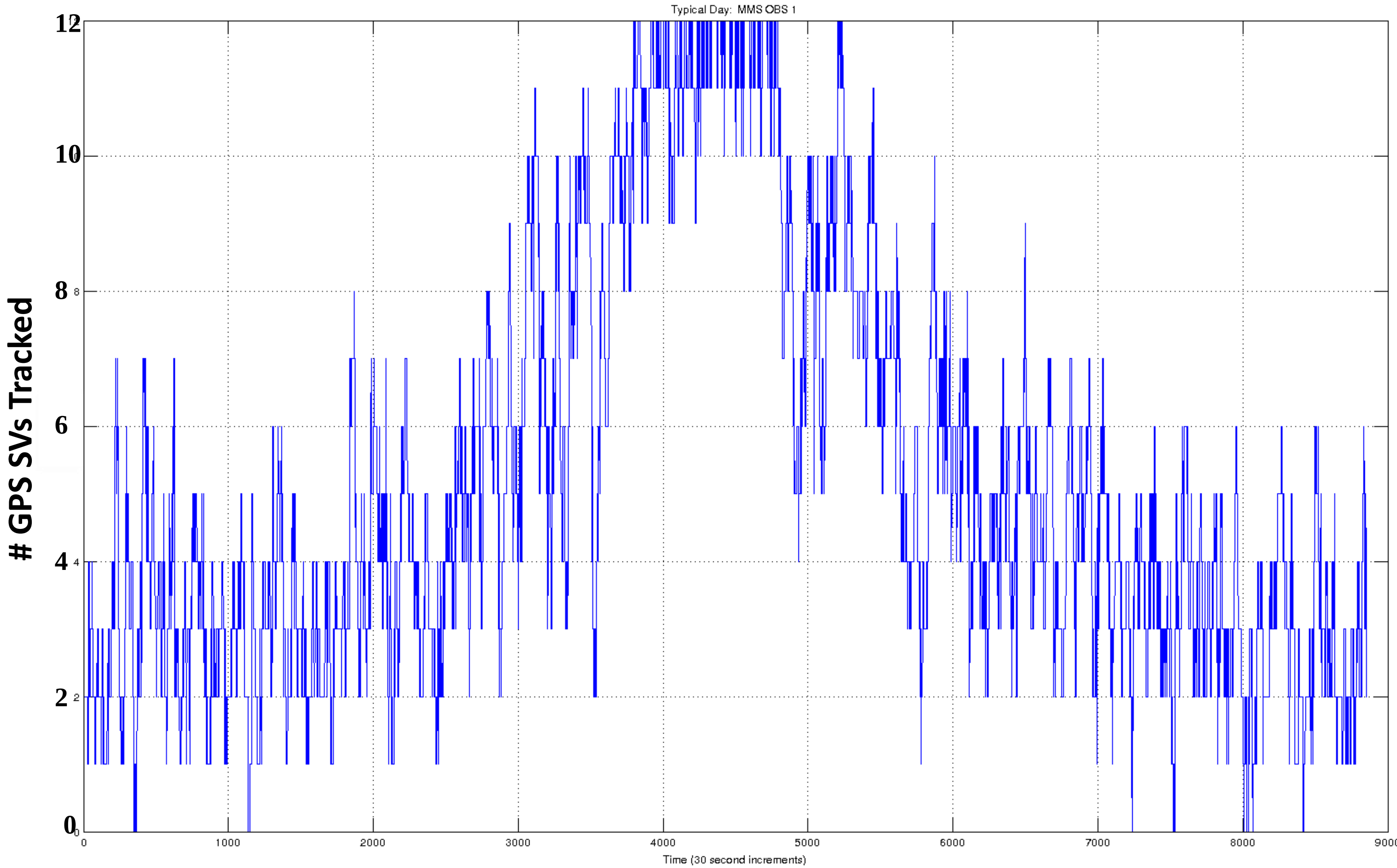




Signal Tracking Performance During Phase 1 to Phase 2 Apogee Raising (70K km to 150K km)



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



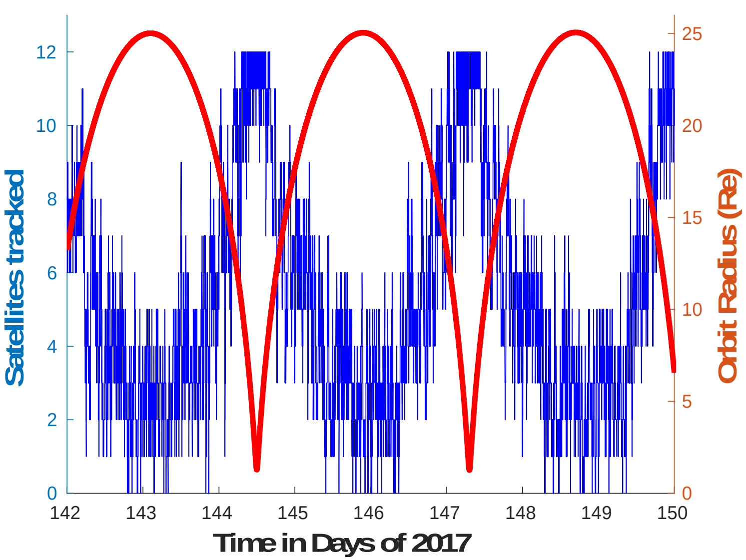
Average Outage: 2.8 mins; Cumulative outage: 22 min over 67 hour orbit (0.5%)

Note: Actual performance is orbit sensitive

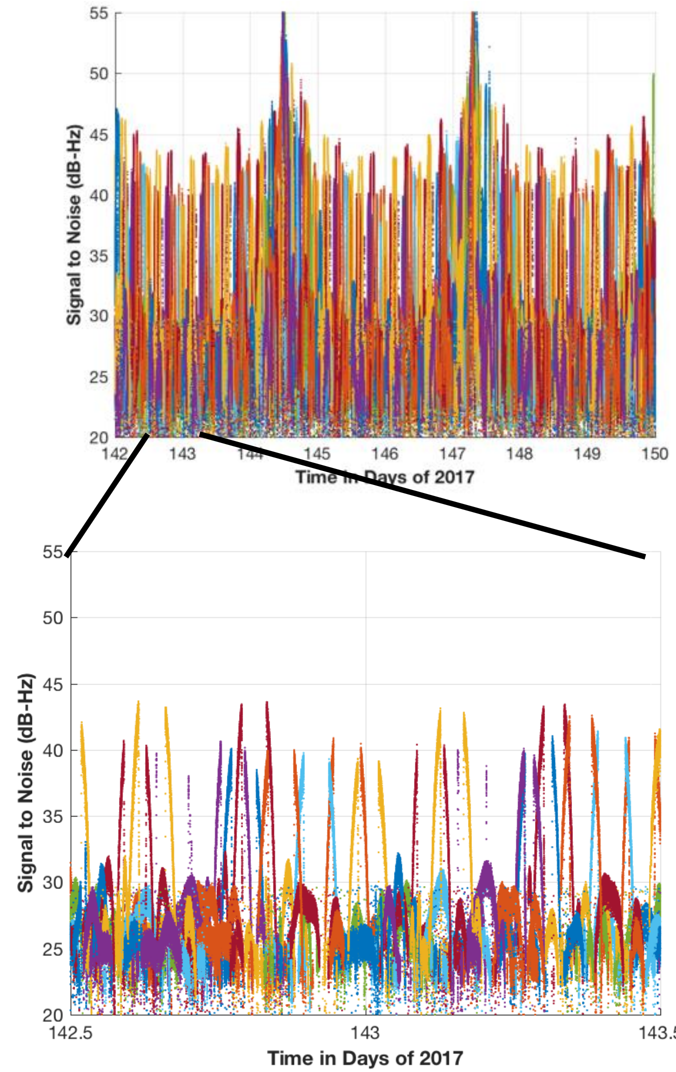
MMS on-orbit Phase 2B results: signal tracking

- 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

Signals tracked

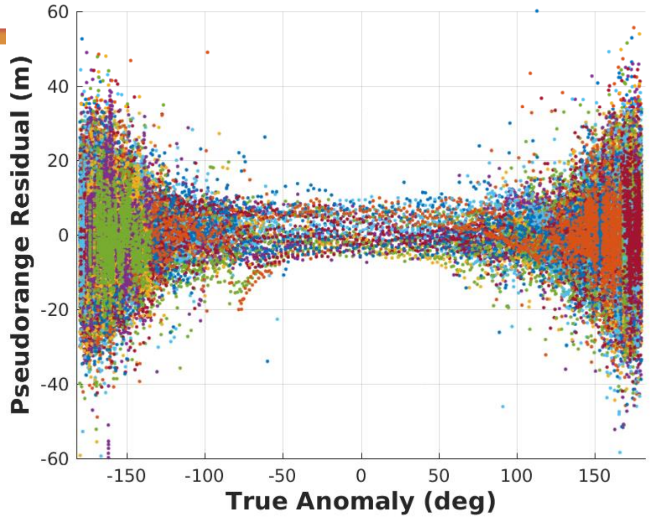


C/N_0 vs. time, near apogee

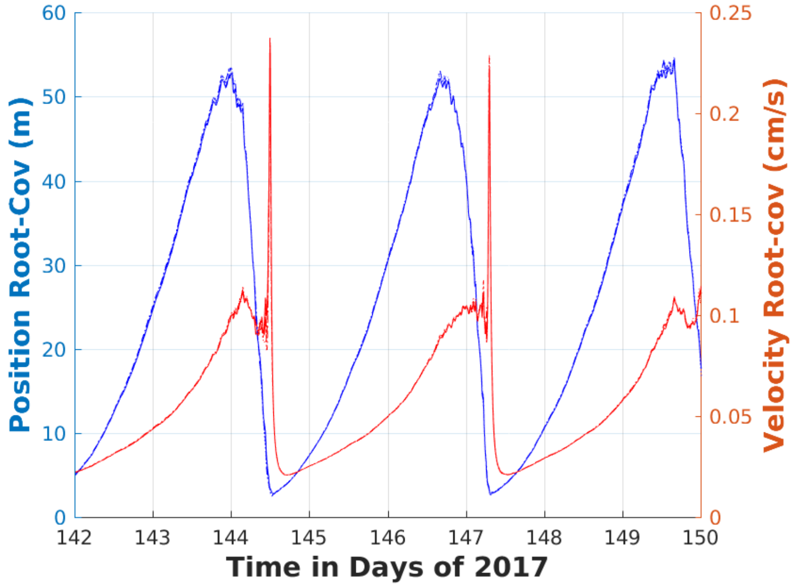


MMS on-orbit Phase 2B results: measurement and navigation performance

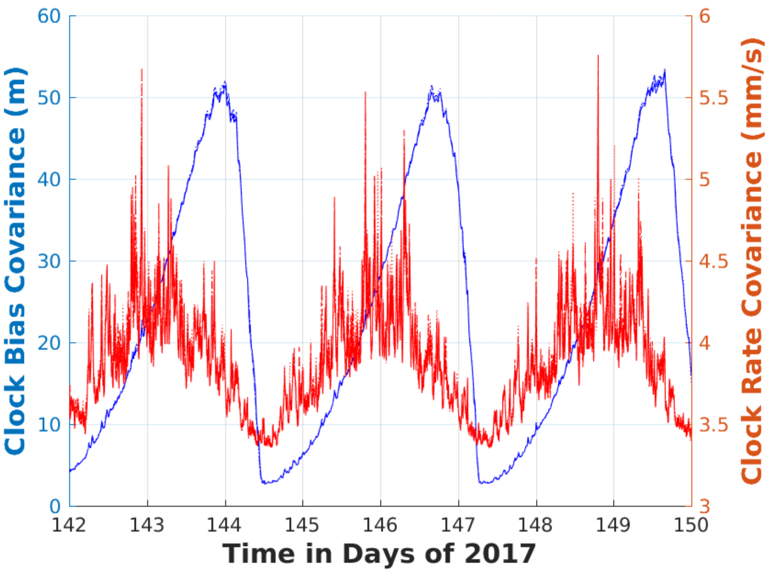
- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
  - Suggests sidelobe measurements are of high quality.



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



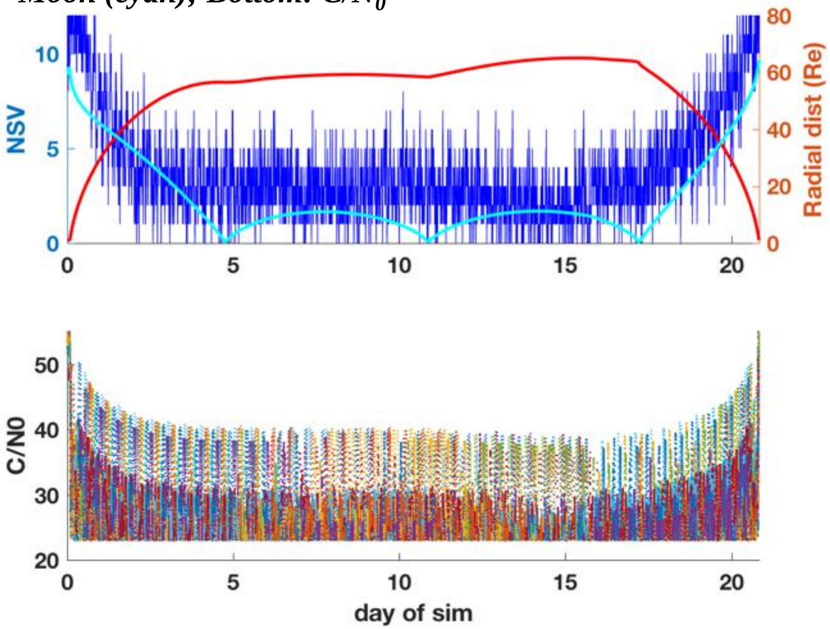
Filter formal clock errors (1σ root cov)



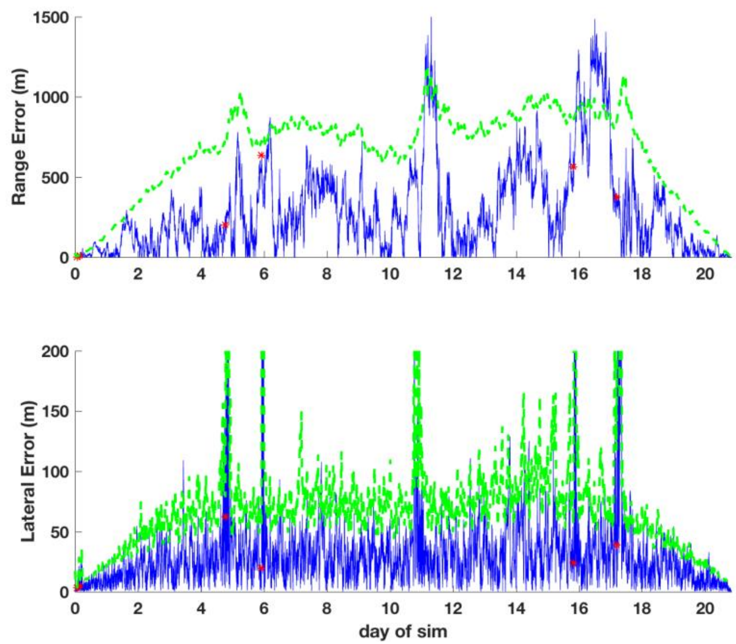
MMS study: Concept Lunar mission

- **Study: How will MMS receiver perform if used on a conceptual Lunar mission with 14dBi high-gain antenna?**
- **Concept lunar trajectory similar to EM-1: LEO -> translunar -> Lunar (libration) orbit -> return**
- **GPS measurements simulated & processed using GEONS filter.**
- **Visibility similar to MMS2B, 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

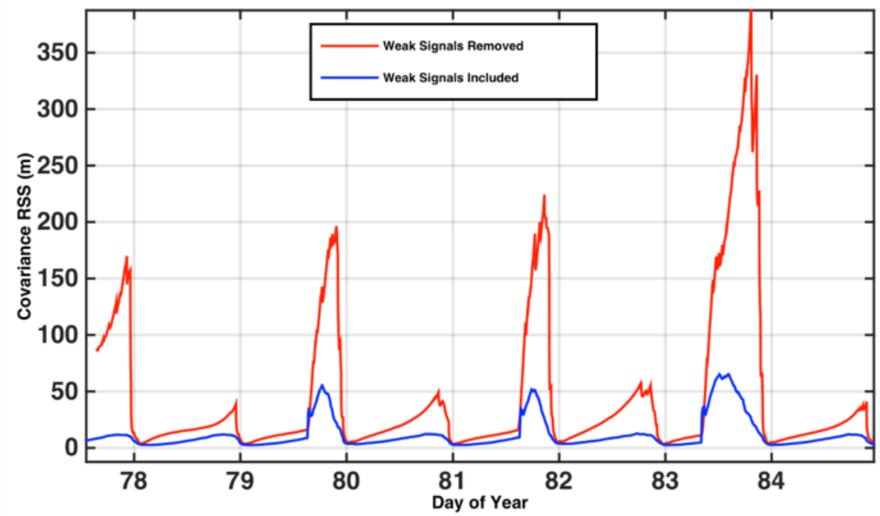


Filter position formal (3σ) and actual errors



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)

NASA Recent GNSS Activities

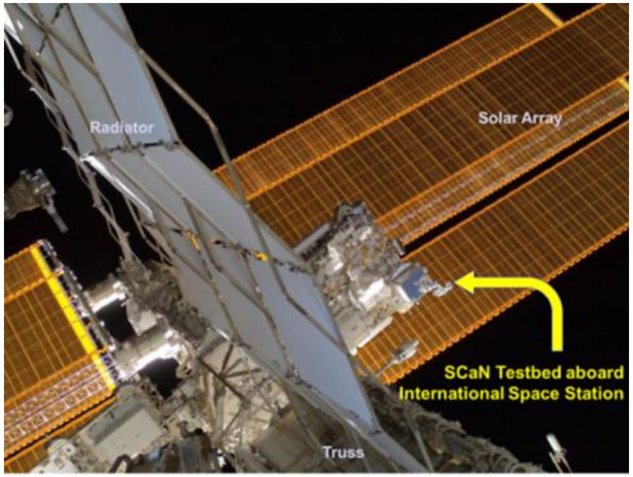
Selected Highlights and Developments

USAF–NASA Collaboration on GPS SSV

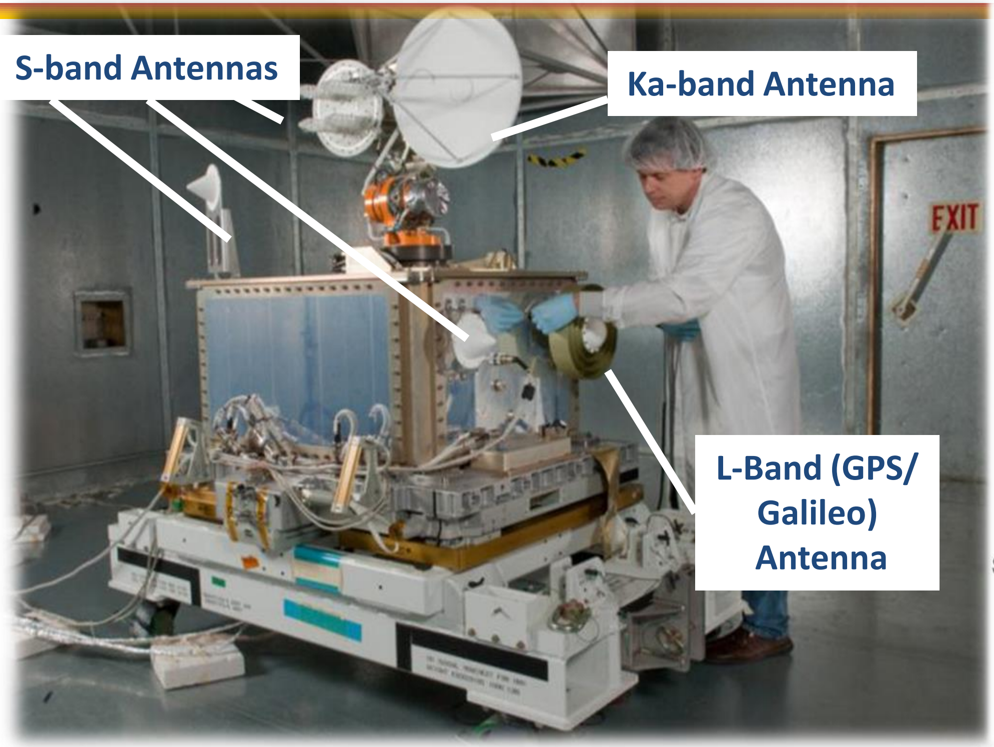
- **Oct 13: Joint NASA-USAF Memorandum of Understanding signed on GPS civil Space Service Volume (SSV) requirements**
  - Scope is relevant to future GPS III SV11+ (GPS IIIF) satellites
  - As US civil space representative, provides NASA insight into procurement, design and production of new satellites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

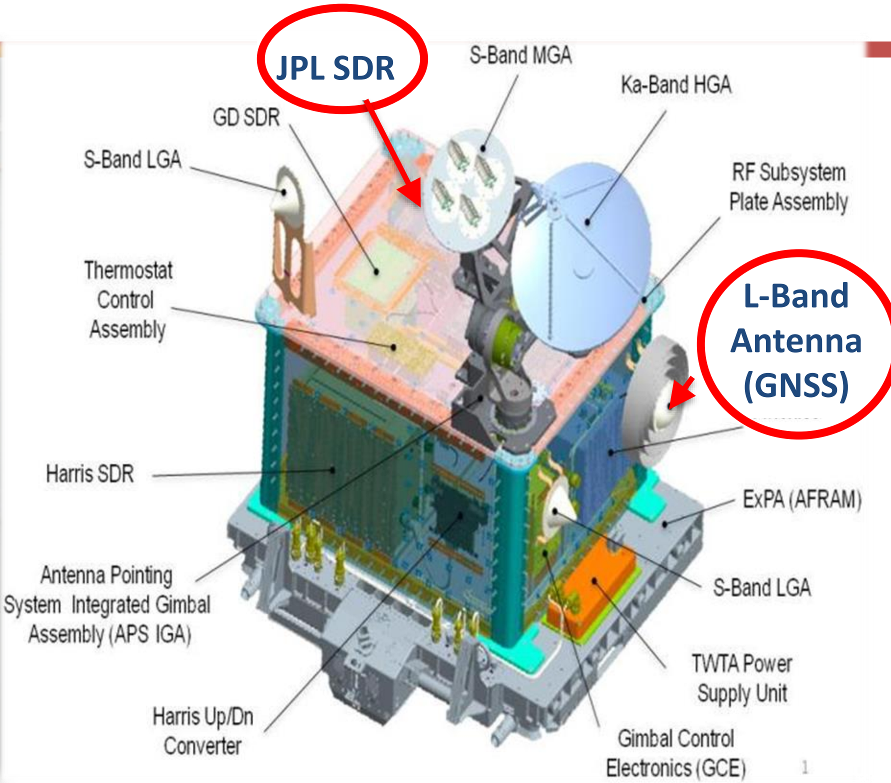
GAlileo Receiver for the ISS (GARISS)

- **Objectives:**
  - Demonstrate combined GPS/Galileo (L5/E5a) navigation receiver for on-orbit operations
  - Analyze/validate navigation performance of dual-constellation receiver function
- **Approach:**
  - Adapt existing PNT code for software Galileo receiver for Software Defined Radio (SDR)
  - Operate waveform to conduct experiments and tests on-orbit
- **Benefits:**
  - Shows flexibility of SDR technology through development of Software/Firmware waveform for L-band SDR in SCAN Test-Bed
  - Illustrates efficiencies in development brought by use Space Telecommunications Radio System (STRS) operating environment
- **Timeline:**
  - Initial discussions at International meetings (mid-2014)
  - Project formulation/export license (mid-2016)
  - Design and development of the Galileo/GPS waveform for SCaN Test-bed (STB) (late 2016-mid 2017)
  - Qualification and test the Galileo/GPS waveform (mid 2017-late 2017)
  - On-orbit testing and experiments (2018)



NASA's SCaN Testbed





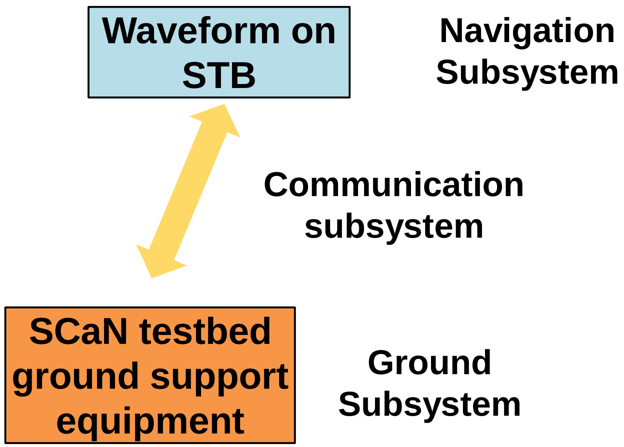
<u>Space Communication and Navigation (SCaN) Testbed</u>

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

Fully reprogrammable Software Defined Radio capability at L-band

Mission Concepts, CONOPS

- High Level Mission Concepts
  - Support for multi-constellation GPS and Galileo
  - Collection and performance assessment of Galileo and GPS raw measurements (Pseudo-range, carrier phase, etc.) in space
  - Computation of positioning in space (Position, Velocity and Time) and assessment of its performance
  - Warm start acquisition aiding from ground via file upload
  - Time aiding from ISS avionics interface
  - Focus on the L5/E5a band
    - requires multi-constellation satellite coverage
- Concept of operation
  - Transfer waveform from ground support equipment to STB
  - Operate waveform per STB schedule
  - Collect primitives



GARISS: Status

Status

- CDR successful (2 March 2017)
- TRR and Delta-TRR successful (May/July 2017)
- Waveform integration firmly underway
  - Acquired GPS L5 from detected signal in GIU using Qascom/NASA/STB code from simulated data (First Light with Qascom Waveform!)
- ESA(Qascom)/NASA conducted extended debugging of waveform 18 September- 6 October
  - 11 of the 19 planned tests of the waveform have been passed
  - Successful moved from initial acquisition phase into tracking phase
  - Processing up to Secondary Code Search achieved including Frequency, code and phase lock
  - Resolved many issues with Interrupt Service Routine
- Waveform debugging continues. Firmware/software issues and issues in STB radio and supporting waveform Operating Environment are being discovered and resolved

Achieved GPS tracking up to 4 minutes

Debugging is continuing—no major/unresolvable issues with waveform architecture yet identified

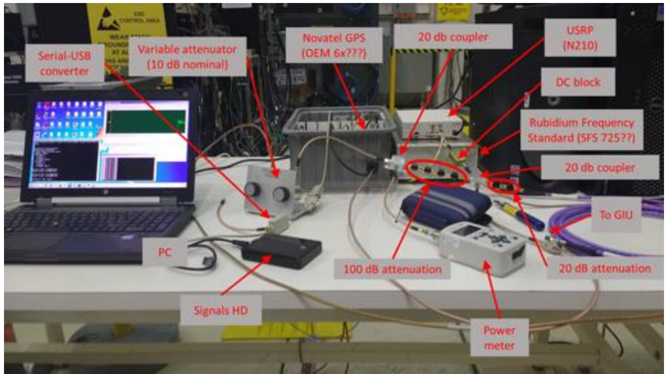
GARISS: Path Forward and Conclusions

Path Forward

- Complete waveform integration and test on STB Ground Integration Unit (GIU)
- Qualification Review (QR) planned for FY18Q2
- Experimentation expected to commence after QR
- Experimentation objectives potentially include: validation of inter-constellation time bias models, examination of multipath effects, and demonstration of PVT solutions for antenna pointing

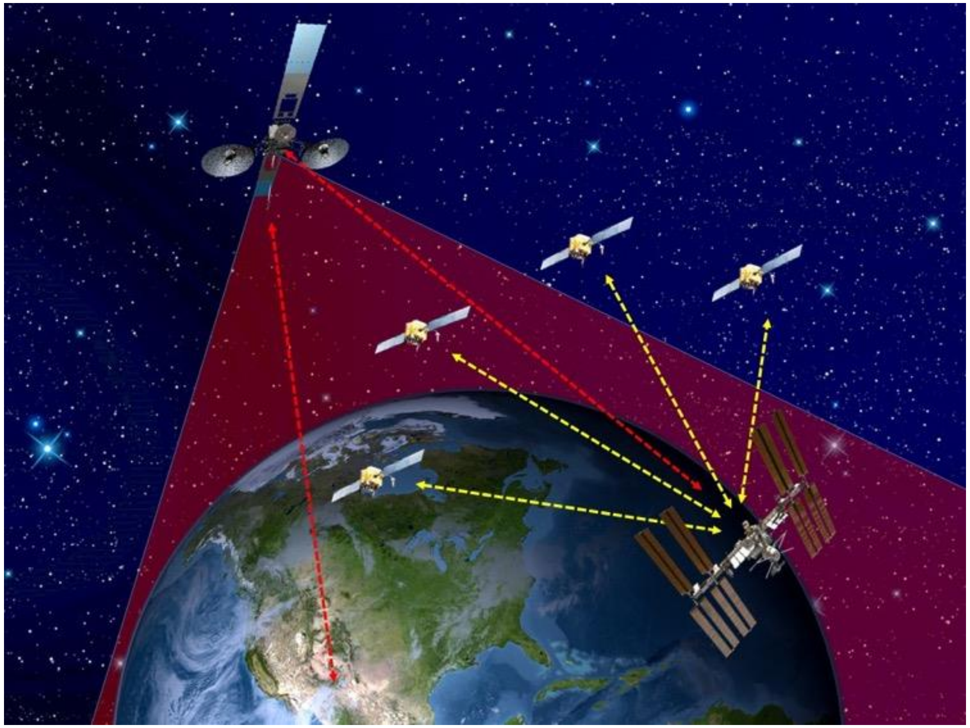
Conclusions

- GARISS leverages SCAN testbed, STRS development framework
- Will demonstrate effectiveness of multi-constellation/GNSS solutions
- Outstanding platform for experimentation and validation of key GNSS technologies in an orbital environment



Proposed System Under Development: Next Generation Broadcast Service (NGBS)

- NGBS would provide unique signals and data to *enhance user operations and enable autonomous onboard navigation*
- NGBS service may consist of:
  - Global coverage via TDRSS S-band multiple access forward (MAF) service
  - Unscheduled, on-demand user commanding
  - TDRS ephemerides and maneuver windows
  - Space environment/weather: ionosphere, Kp index for drag, alerts, effects of Solar Flares/CMEs
  - Earth orientation parameters
  - PN ranging code synchronized with GPS time for time transfer, one-way forward Doppler and ranging
  - Global differential GNSS corrections
  - GNSS integrity

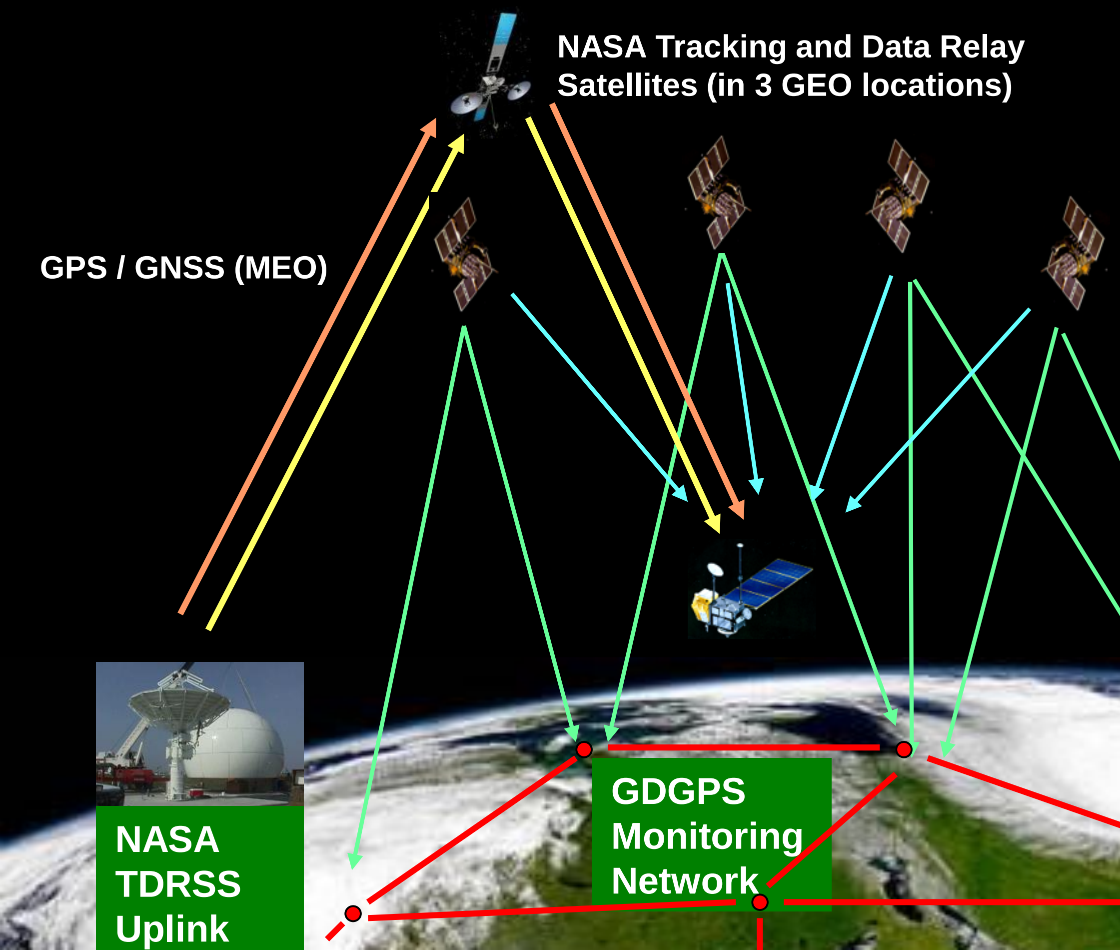


NGBS could have direct benefits in the following areas:

- **Science/payload missions**
- **SCaN/Network operations**
- **TDRSS performance**
- **GPS and TDRSS onboard navigation users**
- **Conjunction Assessment Risk Analysis**
- **Capabilities consistent with the modern GNSS architecture**

Next Generation Broadcast Service

- NGBS supports <u>all</u> space users:
  - Communication channel tracking / ground-in-the-loop users
  - GNSS-based on-board autonomous navigation



1) User spacecraft acquires GNSS signals

2) A ground network monitors GNSS satellites

3) TDRSS satellites relay GDGPS differential corrections to space users via the Multiple Access Antenna (MAA)

4) Evolved TASS signal could incorporate additional parameters:

- GNSS integrity Information
- Tracking Satellite Information (health, ephemerides, maneuvers)
- Space Weather Data
- Solar Flux Data
- Earth Orientation Parameters
- User-specific Command Fields
- Pseudorandom Noise (PRN) ranging code

NGBS: Benefits, Status, and Conclusions

- Benefits
  - Improves the level of autonomous operations for users
  - Improves coordination and responsiveness to transient scientific phenomena among multiple spacecraft (e.g. gamma-ray bursts, gravitational waves)
  - Provides alternative/additional navigation beacon to supplement GNSS, improving resiliency to users
- Conclusions
  - Enables user-initiated services (essential to science activities such as the study of transient astronomical events)
  - Provides user spacecraft with radiometrics and data to support autonomous, on-board navigation and operations
  - Makes space weather data available (of special interest to human spaceflight operations)
- Status
  - Requirements are being developed at NASA for the next generation TDRS relay

Engagement from the user community is critical. Seeking stakeholder feedback: what services would be beneficial?

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

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)

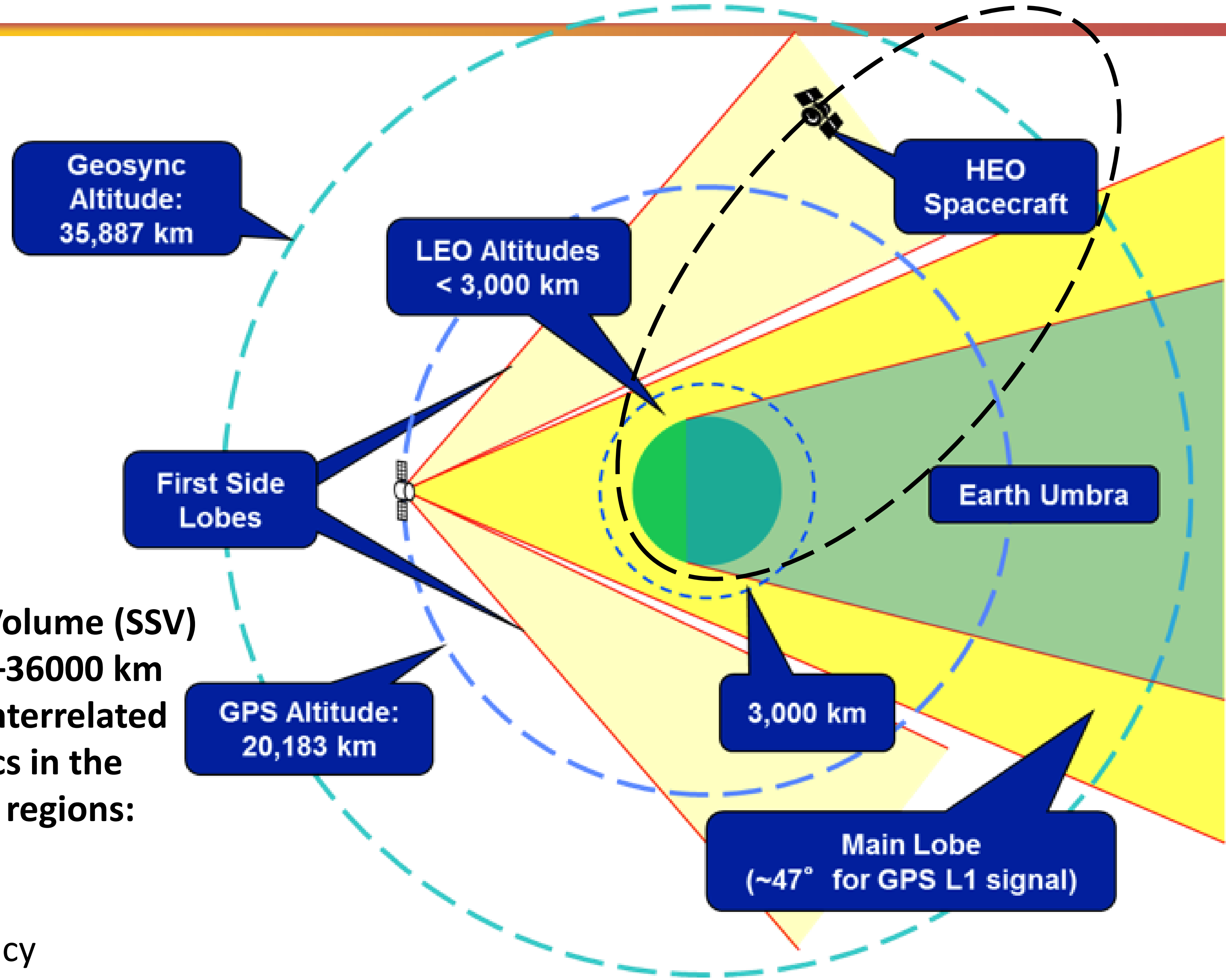
AFTS Fully Operational & Demonstrating its Critical Role of Protecting People & Property and Enabling Quicker Cadence of Launch Ranges

NASA Recent GNSS Activities Summary

- NASA is engaged in numerous space-critical GNSS initiatives that are bearing great fruit for future missions and additional PNT capability
- Some of these activities (e.g. GARISS) represent outstanding USA/international partnerships that will extend our GNSS understanding and signal utility
- The Next Generation Broadcast Service introduces a critical level of resiliency to GNSS and augments data and signals to further improve PNT
- The Automatic Flight Termination System (AFTS) improves Launch Range use, reduces launch costs and improves the safety of people and property
- We encourage GNSS providers to consider and report on these ideas and others to further enhance global support and utility of the interoperable GNSS in space

Backup Slides

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

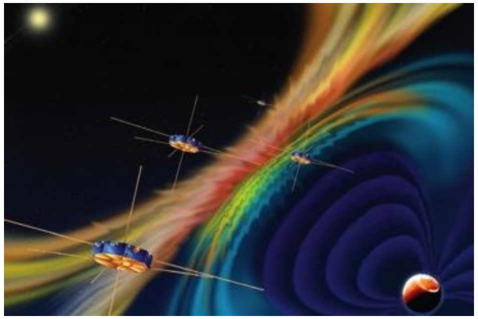
Pseudorange accuracy

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:

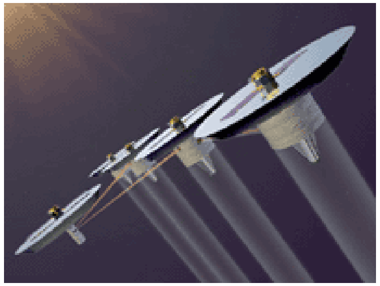
Earth Weather Prediction using Advanced Weather Satellites



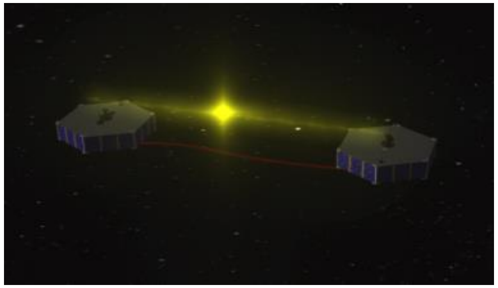
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications

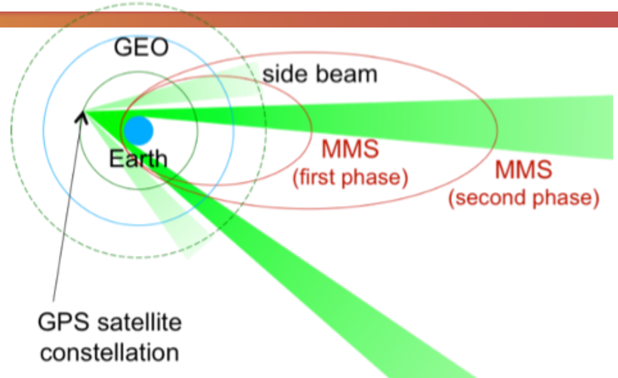


Formation Flying, Space Situational Awareness, Proximity Operations



Precise Position Knowledge and Control at GEO

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

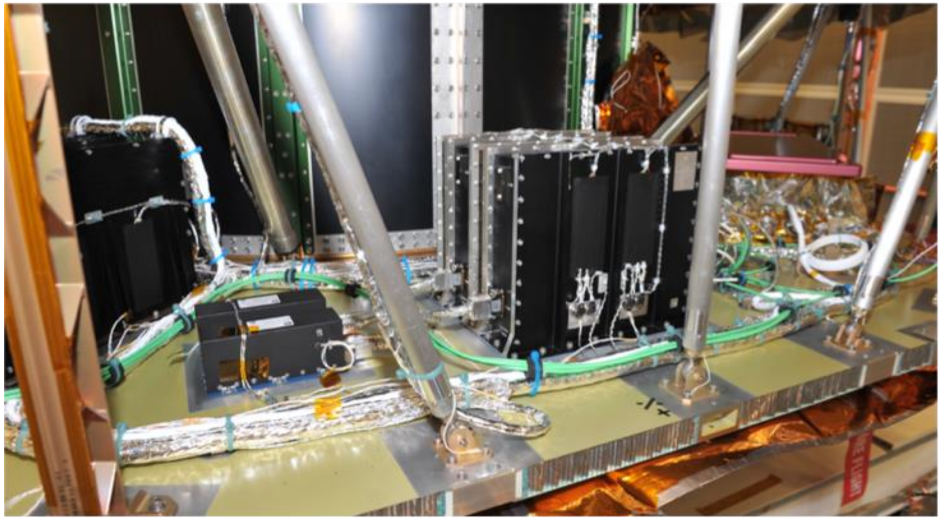
MMS Navigator GPS Hardware

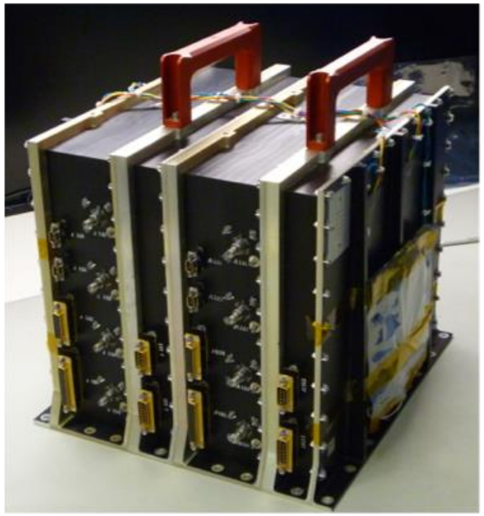
- GPS hardware all developed and tested at GSFC. Altogether, 8 electronics boxes, 8 USOs, 32 antennas and front ends.

Ultra Stable Osc.

Front end electronics assembly

GPS antenna





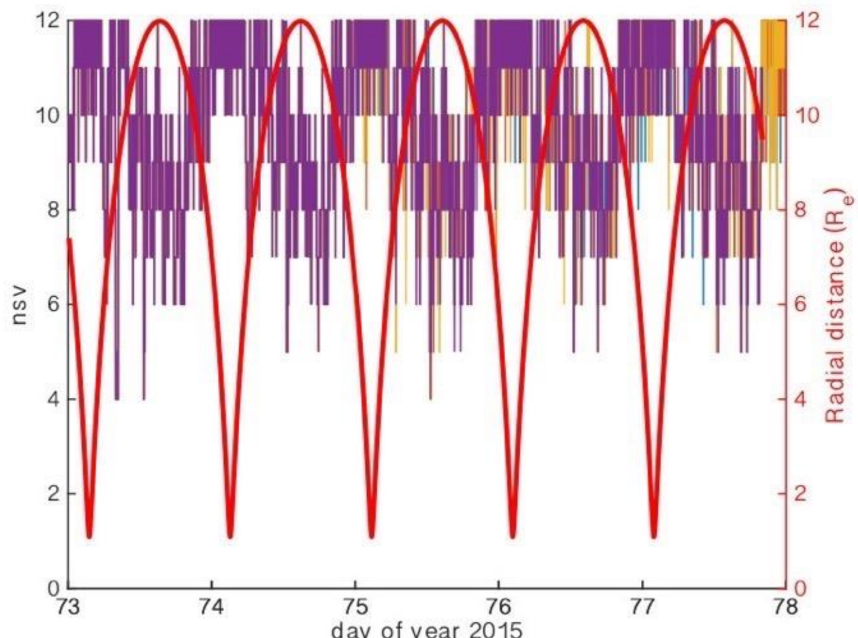
Receiver and USO on spacecraft deck

Redundant receiver electronics

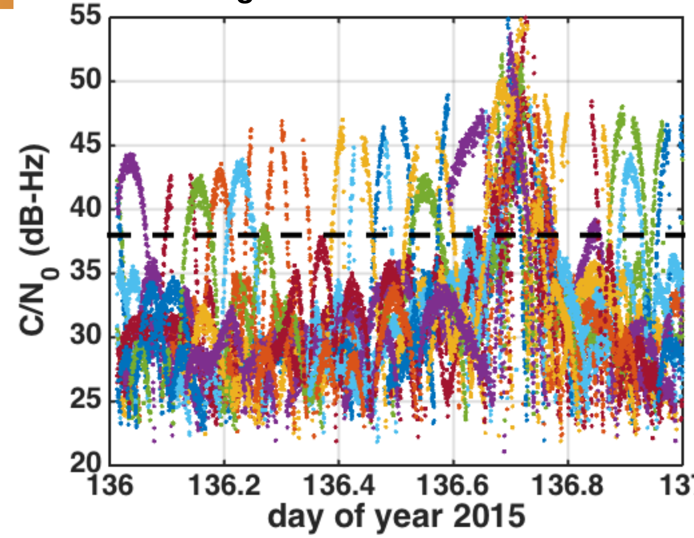
Phase 1 Performance: Signal Tracking

- 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

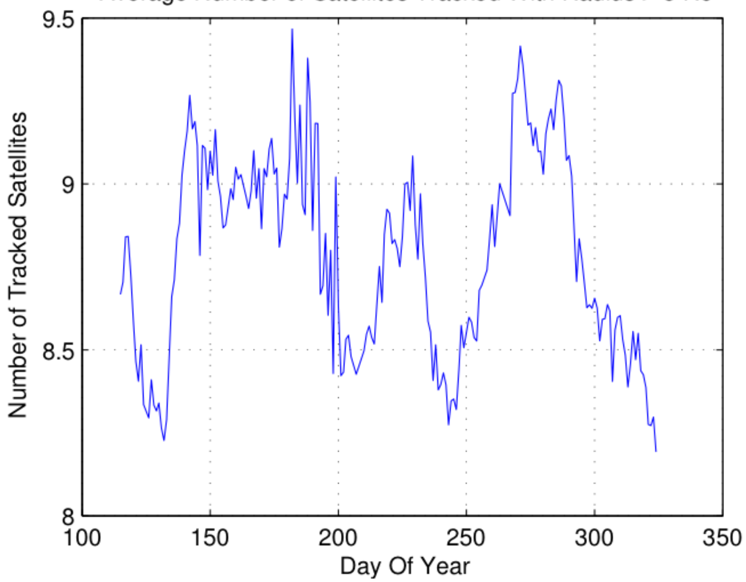
Signals tracked during first few orbits



Signal to noise vs. time

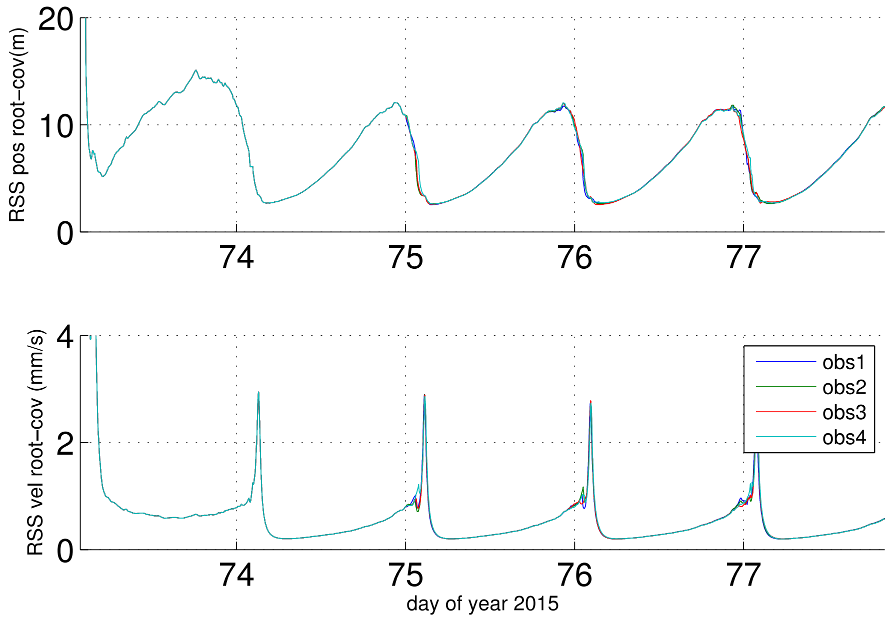


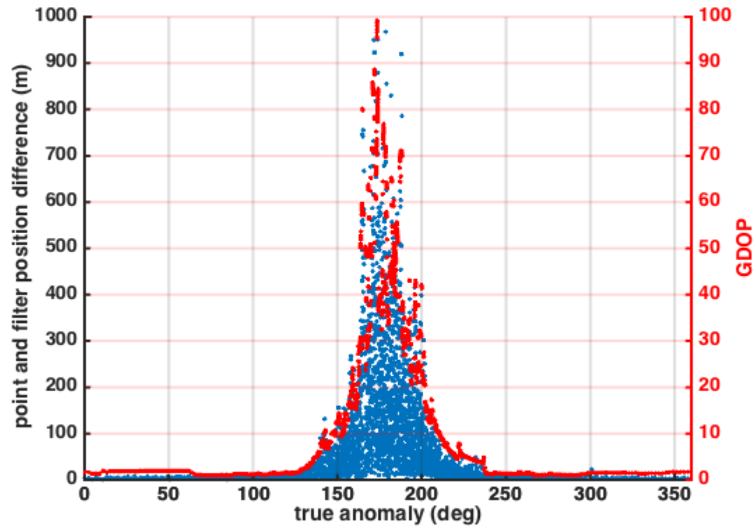
Average Number of Satellites Tracked With Radius > 8 Re

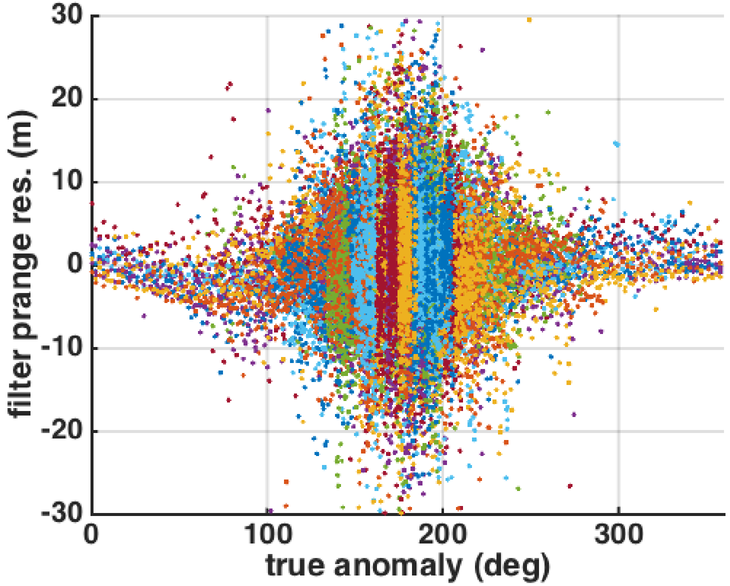


Phase 1 Results: Measurement and Navigation Performance

- 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 measurements are of high quality.







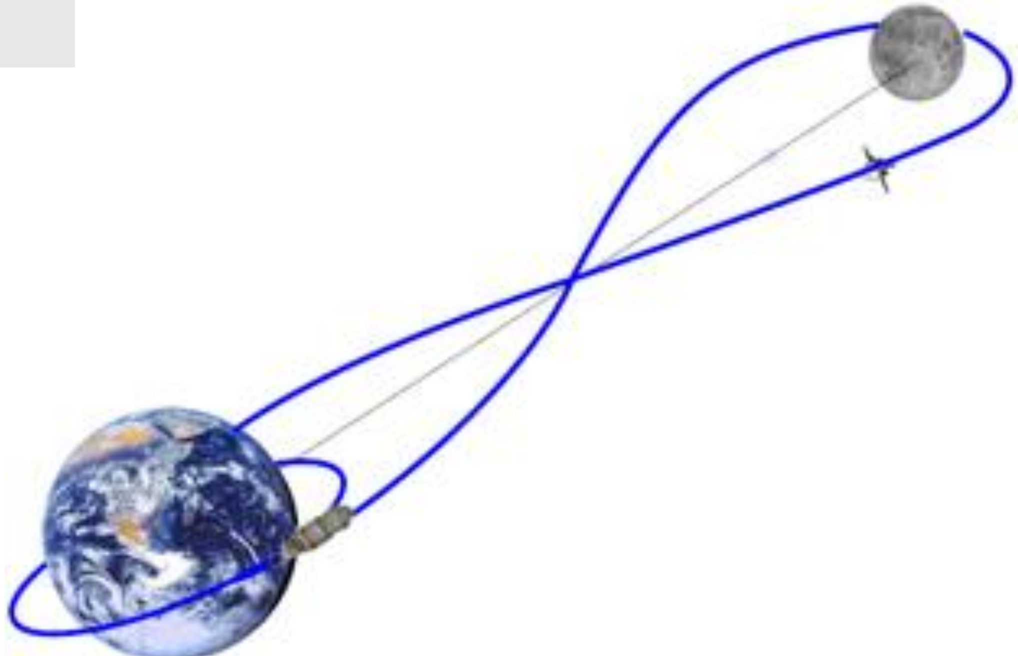
Phase 3 Lunar Case

Mission	Simplified lunar transfer, similar to Apollo 11, Exploration Mission 1 (EM-1)
Description	Free-return lunar trajectory with optional lunar orbit and return phases
Earth Periapsis	185 km alt
Moon Periapsis	100 km alt

Earth Inclination	32°
Duration	4 days
Attitude profile	Nadir-pointing
Receive antennas	Patch (zenith) + High-gain (nadir)

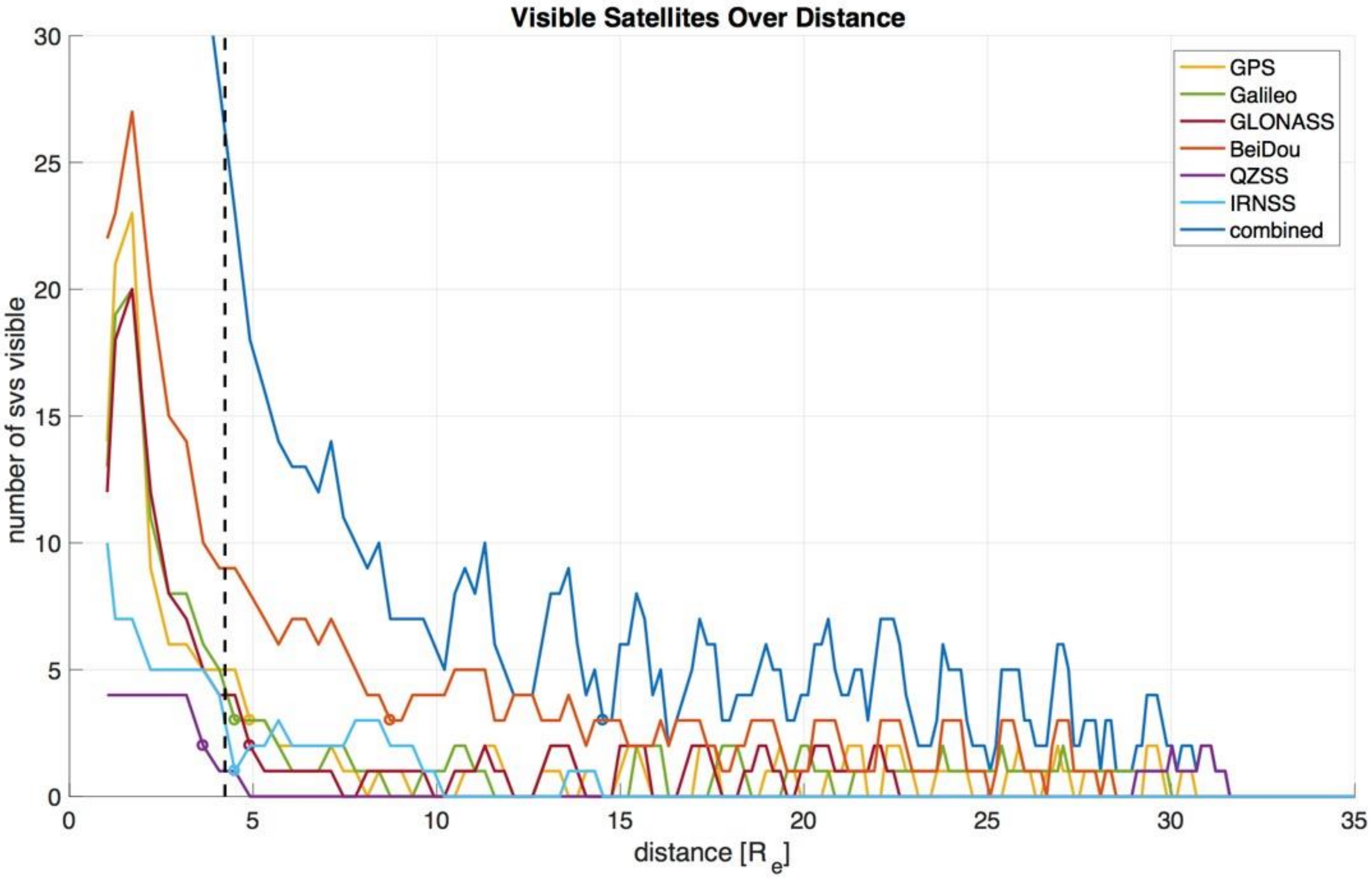
Status:

- NASA is lead for lunar case
- Specification complete
- NASA/ESA have completed implementation
- ESA comparing results

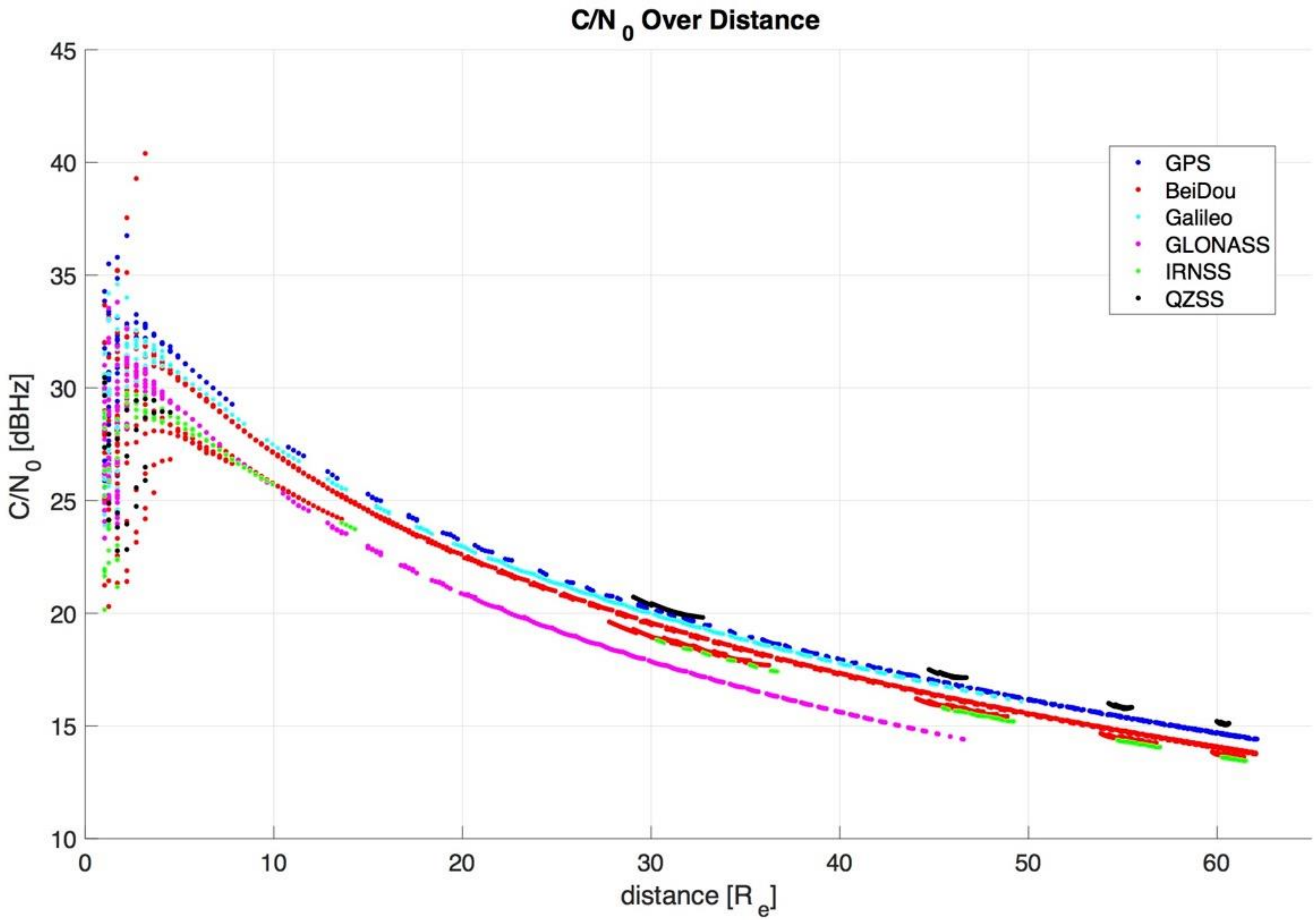


Phase 3 Lunar Case Results

- Metrics (same as HEO and GEO cases):
  - C/N_0, SV visibility over time/distance, Position Dilution of Precision (PDOP)



C/N_0 Over Distance



NGBS: Development History and Status

- **NGBS is an evolution of the TDRSS Augmentation Service for Satellites (TASS)**
- **Timeline**
  - 2000: GDGPS operational
  - 2006-2007: TASS demo service on a TDRSS satellite (TDRS-1). TASS signal tracked using a ground-based receiver.
  - 2016: Renamed NGBS; Demo 1 on TDRS-12 to validate beacon pattern
- **TASS Signal-in-Space Tests***
  - Validated all major system capabilities
  - Received and tracked carrier phase and PRN code
  - Real-time data streaming from the JPL
  - End-to-end GDGPS data authentication
  - Viterbi encoding/decoding
  - Validated both IF and baseband interface options for the TASS transmitter at White Sands Complex
  - Validated link budget and end-to-end latency (7 sec)

NGBS Capabilities*

	State of the Art (unaugmented GPS)	GDGPS
Real-time orbit determination	1-5 meters	0.1 - 0.3 m
Real-time time-transfer	~10 nsec	~1 nsec
Integrity **(GPS malfunction flags)**	Not available	Included

(*) Y. Bar-Sever, L. Young, J. Rush, F. Stockling, The NASA Global Differential GPS System (GDGPS) and The TDRSS Augmentation Service for Satellites (TASS), *Proceedings of the 2nd ESA Workshop on Satellite Navigation User Equipment Technologies*, 2004. http://www.gdgps.net/system-desc/papers/Bar-Sever.pdf

NGBS: Benefits to Current and Future Users

- A broadcast beacon service has the ability to improve the level of autonomous operations for users
  - Reduces time interval for coordinating Target of Opportunity observations across multiple spacecraft, **increases mission science return**
  - Facilitates autonomous or MOC-in-the-loop re-pointing for science observations
  - Provides common information for situational awareness
  - Provides unscheduled, continuously-available alternative to GPS navigation, or supplements and provides resiliency to GPS solution

- Many of our current and future science missions study transient phenomena (gamma-ray burst, gravitational waves)
  - Investigation of these events requires coordinated observations between ground and space-based assets. **Fast communication between observatories is essential.**
  - Missions that would benefit from this service:
    - Current missions: Fermi and Swift
    - MIDEX proposals: Survey and Time-domain Astronomical Research Explorer (STAR-X) and Transient Astronomy Observatory (TAO).

- Network benefits
  - Enables user initiated service
  - Reduces burden on the network for radiometric tracking scheduled time
  - Enables precise, autonomous navigation for the relay

Proposed Recommendation from WG-B Intercessional Meeting (Vienna)

Working Group-B (WG-B) Space Weather Coordination

Why should WG-B lead space weather coordination for ICG?

- Revised WG-B work plan, updated at ICG-10, Boulder, CO, November 2015 includes:
  - Working Group B (WG-B) of ICG will work to promote and coordinate activities aimed at enhancing GNSS performance, recommending system enhancements that shall eventually lead to New Services and Capabilities at System Level to better serve the different GNSS user communities
  - Task 5 of revised work plan: Establish a dialogue with Space Weather/Remote Sensing community in order to identify how GNSS can better support the advancement of Space Weather/Remote Sensing products and vice versa

- GNSS extensively employed on spacecraft to understand and measure the Sun-Earth connections that drive space weather

- Previous WG-B space weather discussions included more precise ionosphere modeling, comparing NEQUICK to Klobuchar models

- Developing an interoperability & augmentation strategy to improve space weather observation, alerts and prediction which supports WG-B's mission to enhance GNSS performance and develop new services and capabilities

Space Weather
Proposed WG-B Recommendation

Prepared by: Working Group B
Date of Submission: TBD
Issue Title: Space Weather GNSS Interoperability and Augmentation Strategy

Background/Brief Description of the Issue:
GNSS and GNSS-related augmentation systems provide opportunities to better understand and predict space weather as well as alert ground and space assets about major space weather events

Discussion/Analyses:
WG-B should work with space weather subject matter experts (SMEs) in their countries to define strategies for GNSS to better support space weather initiatives. This may require GNSS interoperability and/or coordination of augmentation systems.

Recommendation of Committee Action:
WG-B should develop a Space Weather sub-committee, invite WG-B members to support this sub-committee, commission them to query their SMEs for ideas and bring these back to WG-B at ICG-12 for discussion and follow-up WG-B strategies

ICG-11 (Sochi)
WG-B Recommendation #2 Status

ICG-11 WG-B Recommendation #2

- Recommendation:
  - Service providers, supported by Space Agencies and Research Institutions, are encouraged to contribute to the existing IOAG database of GNSS space users. Contributions should be reported to WG-B, which should then contribute to the IOAG via the ICG-IOAG liaison. The data included in the database should include the following:
  - Basic details:
    - Mission name & agency
    - Actual or planned launch date
    - Development phase (planned, in development, on-orbit, historical)
    - Orbit regime (LEO, HEO, GEO, cis-lunar, etc.)
  - GNSS usage:
    - GNSS constellations used
    - GNSS signals used
    - GNSS application (navigation, POD, time, radio occultation, etc.)
    - Acquisition methods used (traditional, carrier phase)
    - Solution method (point solution, filtered solution, etc.)

GNSS Mission Areas (1):

Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 14, 2017 Version (Updated for ICG-12 & and IOAG-21)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
1	ASI	COSMO SKYMED (CSK)	GPS	L1/L2 C/A, P(Y)	Precise Orbit Determinatin (POD), Time	Es	2007, 2008, 2010	4 satellites	2015-Oct-08	F.D'AMICO
2	ASI	COSMO SKYMED SECOND GENERATION (CSG)	GPS, Galileo Ready	L1/L2/L2C (GPS) ready for E1 (Galileo)	Precise Orbit Determinatin (POD), Time	Es	2019 1st SAT, 2020 2nd SAT	2 satellites	2017-Oct-30	F.D'AMICO
3	ASI	AGILE	GPS	L1 C/A	Orbit, Time	Ee	2007		2015-Oct-08	F.D'AMICO
4	ASI	PRISMA	GPS		Orbit, Time	Es	2018		2015-Oct-08	F.D'AMICO
5	CNES	CALIPSO	GPS	L1 C/A	Orbit, Time	Es	2006	CNES controls the in flight satellite .	2014-Apr-23	JMS
6	CNES	COROT	GPS	L1 C/A	Orbit, Time	Ep (90°)	2006	CNES controls the in flight satellite .	2014-Apr-23	JMS
7	CNES	JASON-2	GPS*	L1 C/A	Orbit, Time	Ei (66°)	2008	CNES controls the in flight satellite in case of emergency on behalf of NASA/NOAA or EUMETSAT.* GPS on Bus + GPSP on Payload (NASA)	2014-Apr-23	JMS
8	CNES	SMOS	GPS	L1 C/A	Orbit, Time	Es	2009	Launch was Nov 02, 2009. CNES controls the satellite in routine operations ; ESA operates the mission.	2014-Apr-23	JMS
9	CNES	ELISA	GPS	L1 C/A	Orbit, Time	Es	2011	The system is with four satellites launched in Dec 2011. Receiver: MOSAIC	2014-Mar-10	JMS
10	CNES	JASON-3	GPS*	L1 C/A	Orbit, Time	Ei (66°)	2015	CNES controls the in flight satellites in case of emergency on behalf of NASA/NOAA or EUMETSAT.* GPS on Bus + GPSP on Payload (NASA)	2014-Apr-23	JMS
11	CNES	MICROSCOPE	GPS, Galileo	L1 C/A, E1	Precise Orbit Determinatin (POD), Time	Es	2016	One satellite to be launched in 2016 Receiver: SKYLOC	2014-Mar-10	JMS
12	CNES	CSO-MUSIS	GPS, Galileo	L1 C/A, L2C, L5 E1, E5a	Orbit, Time	Es	2017	The system is with three satellites to be launched from 2017. Receiver : LION	2014-Mar-10	JMS
13	CNES	MERLIN	GPS, Galileo	L1 C/A, E1	Orbit, Time	Es (TBC)	2018	Receiver : not yet decided	2014-Mar-10	JMS
14	CNES	SWOT	GPS, Galileo (to be decided)	GPS L1 C/A, other (to be decided)	Orbit, Time	Ep (77,6°)	2020	Receiver : not yet decided	2014-Apr-23	JMS
15	CSA	Scisat	GPS		Orbit, Time	LEO	2003		2016-Oct-21	JF Levesque
16	CSA	Radarsat-2	GPS		Orbit, Time	LEO	2007		2016-Oct-21	JF Levesque
17	CSA	Neossat	GPS		Orbit, Time	LEO	2013		2016-Oct-21	JF Levesque
18	CSA	M3MSat	GPS		Orbit, Time	LEO	2016		2016-Oct-21	JF Levesque
19	CSA	RCM	GPS		Orbit, Time	LEO	2018	3 satellites	2016-Oct-21	JF Levesque

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20	DLR	TSX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	15-Jun-2007		2014-Mar-17	MP
21	DLR	TDX-1	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD, RO, precsie relative determination	Es	21-Jun-2010		2014-Mar-17	MP
22	DLR	TET	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	22-July-2012		2014-Mar-17	MP
23	DLR	TET NOX experiment	GPS	GPS L1 C/A, L1/L2 P(Y)	Experiment (POD, RO)	Ep	22-July-2012		2014-Mar-17	MP
24	DLR	BIROS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support)	Ep	2015		2014-Mar-17	MP
25	DLR	HAG-1	GPS	GPS L1 C/A	Experiment (navigation)	G	2014	GPS used for on-board experiment	2014-Mar-17	MP
26	DLR	Eu:CROPIS	GPS	GPS L1 C/A	navigation, flight dynamics	Ep	2016		2014-Mar-17	MP
27	DLR	ENMAP	GPS			Ep	2017		2013-May 27	MP
28	DLR/NASA	GRACE_FO	GPS GLO/GAL?)	GPS L1 C/A, L1/L2 P(Y), (others?)	Navigation, POD	Ep	2018	Joint mission with NASA.	2014-Mar-17	MP
29	DLR	DEOS	GPS	GPS L1 C/A	onboard navigation, orbit determination (flight dynamics support), relative navigation (formation flight/ rendezvous)	Ep	2017		2014-Mar-17	MP
30	DLR	Electra	GPS		orbit determination	G	2018		2013-May 27	MP
31	DLR	PAZ	GPS	GPS L1 C/A, L1/L2 P(Y)	Navigation, POD	Ep	2014	Same as TSX	2014-Mar-17	MP
32	ESA	Sentinel 6	GPS, GAL, GLO,BDS	GPS + GAL Dual Frequency, Receiver for PVT, POD plus one GNSS receiver using GPS, GAL, GLO, BDS	Navigation (PVT) and Precise Orbit Deyermination (POD) plus one GNSS receiver for scientific use	LEO	2020	Altimetry, Radio occultation	2017-Nov-08	WE
33	ESA	Sentinel 1 C	GPS and Galileo	GPS and GAL dual frequency Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2021	SAR	2017-Nov-08	WE
34	ESA	Sentinel 2 C	GPS and Galileo	GPS and GAL dual frequency Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2021	Altimetry	2017-Nov-08	WE
35	ESA	Sentinel 3 C	GPS and Galileo	GPS and GAL dual frequency Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2021	Altimetry & Imager	2017-Nov-08	WE
36	ESA	Sentinel 1 D	GPS and Galileo	GPS and GAL dual frequency Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	202X	SAR	2017-Nov-08	WE
37	ESA	Sentinel 2 D	GPS and Galileo	GPS and GAL dual frequency Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	202X	Altimetry	2017-Nov-08	WE
38	ESA	Sentinel 3 D	GPS and Galileo	GPS and GAL dual frequency Codephase and carrierphase	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	202X	Altimetry & Imager	2017-Nov-08	WE
39	ESA	Proba 2	GPS	GPS single Frequency, L1	Orbit	LEO	2009	Tech Demo	2017-Nov-08	WE
40	ESA/NASA	ISS	GPS and Galileo	Galileo: E1 and E5a, GPS: L1 and L5, Codephase and Carrierphase for GPS and Galileo	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2017	Joint demonstration mission with NASA, using NASA's SCAN Testbed on-board the ISS	2017-Nov-08	WE

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41	ESA	Proba 3	GPS and Galileo	Galileo: E1 and E5a, GPS: L1 and L5, Codephase and Carrierphase for GPS and Galileo	Navigation (PVT), Precise Orbit Determination (POD), Formation Flying relative POD Time	HEO	2019	FF Demo, 2 spacecraft	2017-Nov-08	WE
42	ESA	Small GEO	GPS	single Frequency, L1	Navigation (PVT)	GEO	2015	Telecom	2017-Nov-08	WE
43	ESA	FLEX	GPS and Galileo	Galileo: E1 and E5a, GPS: L1 and L5, Codephase and Carrierphase for GPS and Galileo	Navigation (PVT) and Precise Orbit Deyermination (POD)	LEO	2022	Clorofile Explorer (GPS similar to GPS & Galileo)	2017-Nov-08	WE
44	ESA	METOP-A	GPS	L1	Radio Occultation	LEO	2006	Atmospheric Sounder	2017-Nov-08	WE
45	ESA	METOP-B	GPS	L1	Radio Occultation	LEO	2012	Atmospheric Sounder	2017-Nov-08	WE
46	ESA	METOP-C	GPS	L1	Radio Occultation	LEO	2018	Atmospheric Sounder	2017-Nov-08	WE
47	ESA	MetOp-SG-A	GPS, GAL, GLO,BDS	GPS + GAL Dual Frequency, Receiver for PVT, POD plus one GNSS receiver using GPS, GAL, GLO, BDS	Navigation (PVT) and Precise Orbit Deyermination (POD) plus one GNSS receiver for scientific use - Radio Occultation	LEO	2021	8 Instruments for Earth Observation, including Radio occultation	2017-Nov-08	WE
48	ESA	MetOp-SG-B	GPS, GAL, GLO,BDS	GPS + GAL Dual Frequency, Receiver for PVT, POD plus one GNSS receiver using GPS, GAL, GLO, BDS	Navigation (PVT) and Precise Orbit Deyermination (POD) plus one GNSS receiver for scientific use - Radio Occultation	LEO	2022	7 Instruments for Earth Observation, including Radio occultation	2017-Nov-08	WE
49	JAXA	GOSAT	GPS	L1	Orbit, time	LEO	2009	Remote Sensing	2016-Nov-17	T.S
50	JAXA	GCOM-W1	GPS	L1	Orbit, time	LEO	2012	Remote Sensing	2016-Nov-17	T.S
51	JAXA	GCOM-C1	GPS	L1	Orbit, time	LEO	2017	Remote Sensing	2016-Nov-17	T.S
52	JAXA	ALOS-2	GPS	L1, L2	Precise orbit (3σ<1m), Orbit, time,	LEO	2014	Remote Sensing	2016-Nov-17	T.S
53	JAXA	HTV-series	GPS	L1	Orbit(relative)	LEO	2009-present	Unmanned ISS transportation	2013-May-27	T.S
54	JAXA	GOSAT-2	GPS	L1	Orbit, time	LEO	2018	Remote Sensing	2017-Oct-25	T.S
55	JAXA	XARM (ASTRO-H Backup)	GPS	L1, L2	Orbit, time	LEO	2020	Astronomical	2017-Oct-25	T.S
56	JAXA	SLATS	GPS	L1	Orbit, time	LEO	2017	Tech Demo	2016-Nov-17	T.S
57	JAXA	ALOS-3 (Advanced Optical Satellite)	GPS	L1, L2	Orbit, time	LEO	2020	Remote Sensing	2017-Oct-25	T.S
58	JAXA	ALOS-4 (Advanced Radar Satellite)	GPS	L1, L2	Orbit, time	LEO	2020	Remote Sensing	2017-Oct-25	T.S
59	JAXA	Next Engineering Test Satellite	GPS	L1	Orbit, time	HEO + GEO	2021	Engineering testing	2017-Nov-13	T.S
60	JAXA	JDRS	GPS	L1	Orbit	GEO	2019	Optical Data Relay	2017-Nov-13	T.S

GNSS Mission Areas (1):

Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 14, 2017 Version (Updated for ICG-12 & and IOAG-21)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
61	NASA	ISS	GPS	L1 C/A	Attitude Dynamics	LEO	Since 1998	Honeywell SIGI receiver	2014-Feb-4	JJ Miller
62	NASA	COSMIC (6 satellites)	GPS	L1 C/A, L1/L2 semicodeless, L2C	Radio Occultation	LEO	2006	IGOR (BlackJack) receiver; spacecraft nearing end of life	2014-Apr-28	JJ Miller
63	NASA	IceSat	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2003	BlackJack receiver; mission retired 14 August 2010	2014-Apr-28	JJ Miller
64	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	2016-Nov-8	L. Young
65	CNES/NASA	OSTM/Jason 2	GPS	L1 C/A, L1/L2 semicodeless	Precise Orbit Determination	LEO	2008	BlackJack receiver	2014-May-13	JJ Miller
66	NASA	SCAN Testbed on ISS	GPS, Galileo	L1 CA, L2C, L5, Galileo E1 and E5A	Demo of Software Defined Radio	LEO	2012	"Blackjack-based SDR. Monitoring of GPS CNAV testing began in June 2013. Development of Galileo E5a/GPS L5 waveform through agreement with ESA began in October 2016	2017-Nov-6	L.E.Young
67	NASA	Landsat-8	GPS	L1 C/A	Orbit	LEO	2013	GD Viceroy receiver	2014-Feb-4	JJ Miller
68	NASA	ISS Commercial Crew and Cargo Program - Dragon	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+		2014-Feb-4	JJ Miller
69	NASA	ISS Commercial Crew and Cargo Program: Cygnus	GPS	L1 C/A	Orbit / ISS rendezvous	LEO	2013+		2014-Feb-4	JJ Miller
70	NASA	GPM	GPS	L1 C/A	Orbit, time	LEO	2014	Navigator receiver	2014-Feb-4	JJ Miller
71	NASA	Orion/MPCV	GPS	L1 C/A	Orbit / navigation	LEO	2014 - Earth Orbit, 2017 Cislunar	Honeywell Aerospace Electronic Systems 'GPSR' receiver	2014-Feb-4	JJ Miller
72	NSPO/USAF/NASA	COSMIC IIA (6 satellites)	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation	LEO	2018	TriG receiver, 8 RF inputs, hardware all-GNSS capable, will track GPS + GLONASS at launch	2017-Nov-6	L. Young
73	NASA	DSAC	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Time transfer	LEO	2018	TriG lite receiver	2017-Nov-6	L. Young
74	CNES/NASA	Jason-3	GPS, GLONASS FDMA	L1 C/A, L1/L2 semicodeless, L2C	Precise Orbit Determination, Oceanography	LEO	2015	IGOR+ (BlackJack) receiver	2015-Oct-6	JJ Miller
75	NASA	MMS	GPS	L1 C/A	Rel. range, orbit, time	up to 30 Earth radii	2015	Navigator receiver (8 receivers)	2014-Apr-28	JJ Miller
76	NASA	GOES-16	GPS	L1 C/A	Orbit	GEO	2016	General Dynamics Viceroy-4	2014-Apr-28	JJ Miller
77	NASA	ICESat-2	GPS	-	-	LEO	2016	RUAG Space receiver	2014-Feb-4	JJ Miller
78	NASA	CYGNSS (8 sats)	GPS	-	GPS bi-scatterometry	LEO	2016	Delay Mapping Receiver (DMR), SSTL UK	2015-Oct-6	JJ Miller
79	NASA/DLR	GRACE FO	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P2, L5	Occultation, precision orbit, time	LEO	2018	TriG receiver with microwave ranging, joint mission with DLR	2015-Oct-6	JJ Miller
80	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 2015	TriG receiver with 1553,	2017-Nov-6	L. Young
81	NASA	GRASP	GPS, GLONASS FDMA, Beudou, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination	LEO	2020	Trig receiver (proposed)	2017-Nov-6	L. Young

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Precise Orbit Determination, Time, Relative Nav. for Rendezvous, Formation Flight, Radio Occultation, Oceanography

Nov. 14, 2017 Version (Updated for ICG-12 & and IOAG-21)

N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
82	NASA	NICER (ISS)	GPS	L1 C/A	Orbit	LEO	2016	Moog/Navigator receiver	2014-Apr-28	JJ Miller
83	NASA	Pegasus Launcher	GPS	L1 C/A	Navigation	Surface to LEO	Since 1990	Trimble receiver	2014-Feb-4	JJ Miller
84	NASA	Antares (formerly Taurus II) Launcher	GPS	L1 C/A	Integrated Inertial Navigation System (INS) & GPS	Surface to LEO	Since 2010	Orbital GPB receiver	2014-Feb-4	JJ Miller
85	NASA	Falcon-9 Launcher	GPS	L1 C/A	Overlay to INS for additional orbit insertion accuracy	Surface to LEO	Since 2013		2014-Feb-4	JJ Miller
86	NASA	Launchers* at the Eastern and Western Ranges	GPS	L1 C/A	Autonomous Flight Safety System	Range Safety	2016*	(*) Including ULA Atlas V and Delta IV (GPS system: Space Vector SIL, uses a Javad receiver). (**) Estimated initional operational test.	2014-Feb-4	JJ Miller
87	NASA/ISRO	NISAR	GPS, GLONASS, Galileo	L1 C/A, L2C, semi-codeless P2, L5	Precise Orbit Determination, timing	LEO	2020	TriG Lite receiver	2015-Oct-6	JJ Miller
88	NASA/CNES	SWOT	GPS, GLONASS FDMA	L1 C/A, L2C, L5, Galileo, GLONASS FDMA	Precise Orbit Determination - Real Time	LEO	2020	TriG Lite receiver with 1553	2015-Oct-6	JJ Miller
89	NASA/ISRO	(not available)	GPS, IRNSS	L1 C/A, L2C, semi-codeless P2, L5, IRNSS	Precise Orbit Determination, Occultation, Reflections (Scatterometry)	LEO	2020	TriG receiver	2017-Nov-7	L. Young
90	NASA	GEDI	GPS, GLONASS FDMA	L1 C/A, L2C, semi-codeless P1/P2, Glonass G1 & G2	Precise Orbit Determination	LEO/ISS	2018	Moog TriG-lite receiver	2016-Oct-31	L Winternitz
91	NASA	iSat	GPS	L1 C/A	Orbit Determination	LEO	2018	Iodine Satellite CubeSat. 1 Year LEO Mission.	2016-Nov-03	T Freestone
92	NASA	MAPS	GPS	L1 C/A	Orbit Determination	LEO			2016-Nov-03	T Freestone
93	NASA	SLS - ICPS	GPS	L1 C/A	End-of-Mission Disposal	Ascent, LEO, Cislunar, EoM Disposal	2018		2016-Nov-03	T Freestone
94	NASA	SLS - EUS	GPS	L1/L2 C/A, P(Y) [I think P(Y)]	Ascent Range Safety, Orbit Determination	Ascent, LEO, Cislunar	2020		2016-Nov-03	T Freestone
95	NASA	GOES-S	GPS	L1 C/A	Orbit	GEO	2018	General Dynamics Viceroy-4	2017-Nov-9	Joel Parker
96	NASA	GOES-T	GPS	L1 C/A	Orbit	GEO	2019	General Dynamics Viceroy-4	2017-Nov-9	Joel Parker
97	NASA	GOES-U	GPS	L1 C/A	Orbit	GEO	2024	General Dynamics Viceroy-4	2017-Nov-9	Joel Parker
98	NASA	Fermi Gamma-ray Space Telescope (GLAST)	GPS	L1 C/A	Orbit	LEO	2008	General Dynamics Viceroy	2017-Nov-9	Joel Parker

ASI	Agenzia Spaziale Italiana
CNES	Centre national d'études spatiales
CSA	Canadian Space Agency
DLR	German Aerospace Center
ESA	European Space Agency
JAXA	Japan Aerospace Exploration Agency
NASA	National Aeronautics and Space Administration

Notes: Orbit Type: Ee = Equatorial Earth Orbiter; Ei = Inclined Earth Orbiter; Ep = Polar Earth Orbiter; Es = Sun Synchronous Earth Orbiter; G = Geostationary; H = High Elliptical Earth Orbit; R = Earth orbiter Relay; O = Other orbit type (specify in remarks)