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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Session 2

Review of the Progress on recent ICG-12 WG-B Recommendations

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

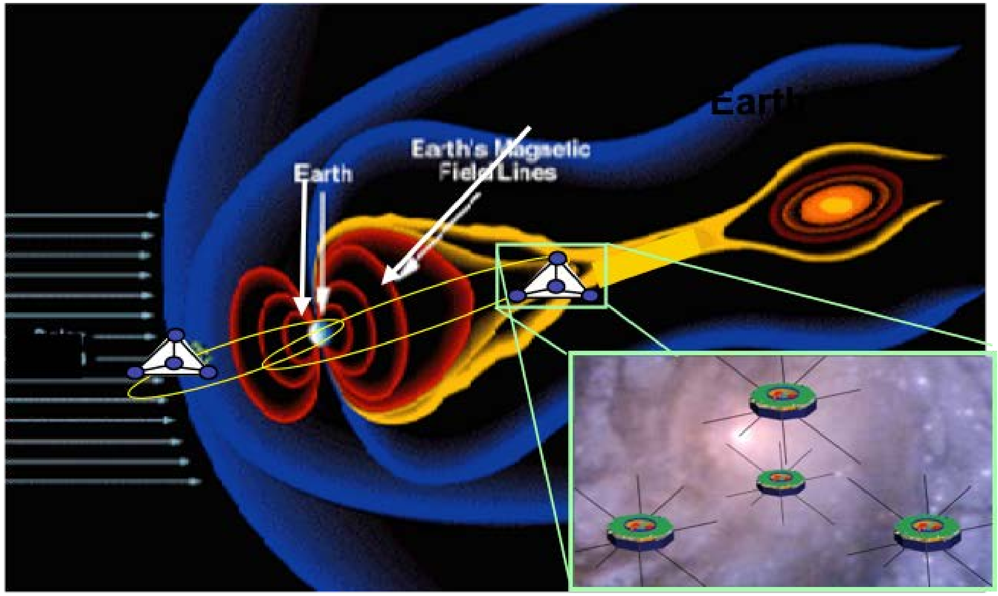
- These studies represent early GPS-only analyses that could be used as basis for WG-B in-depth analysis.

[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

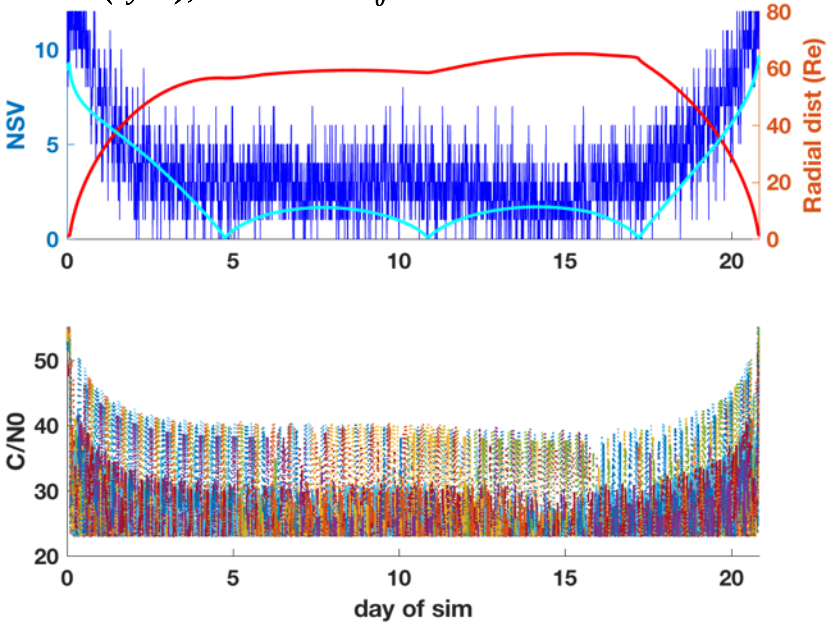
- Discover the fundamental plasma physics process of reconnection in the Earth's magnetosphere.
- Coordinated measurements from tetrahedral formation of four spacecraft with scale sizes from 400km to 10km
- Flying in two highly elliptic orbits in two mission phases
  - Phase 1 1.2x12 R_E (magnetopause) Mar '14-Feb '17
  - Phase 2B 1.2x25 R_E (magnetotail) May '17-present



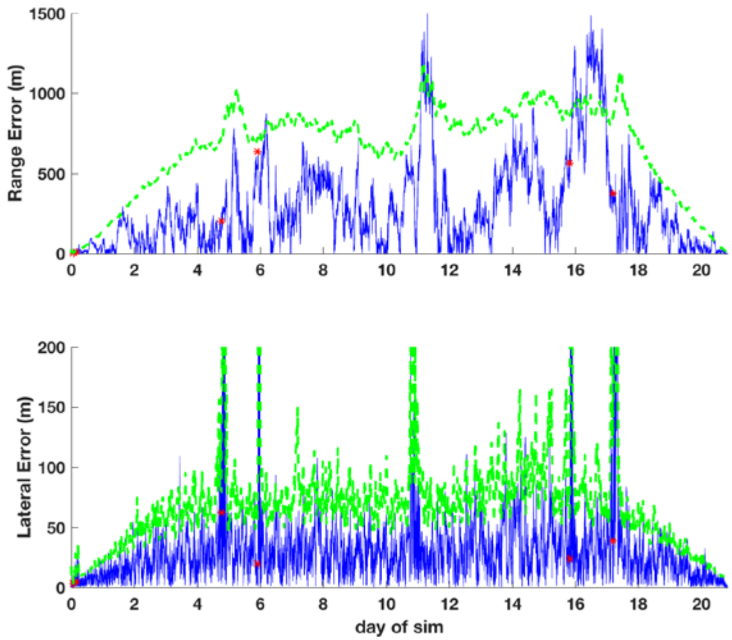
MMS study: Concept Lunar mission

- **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

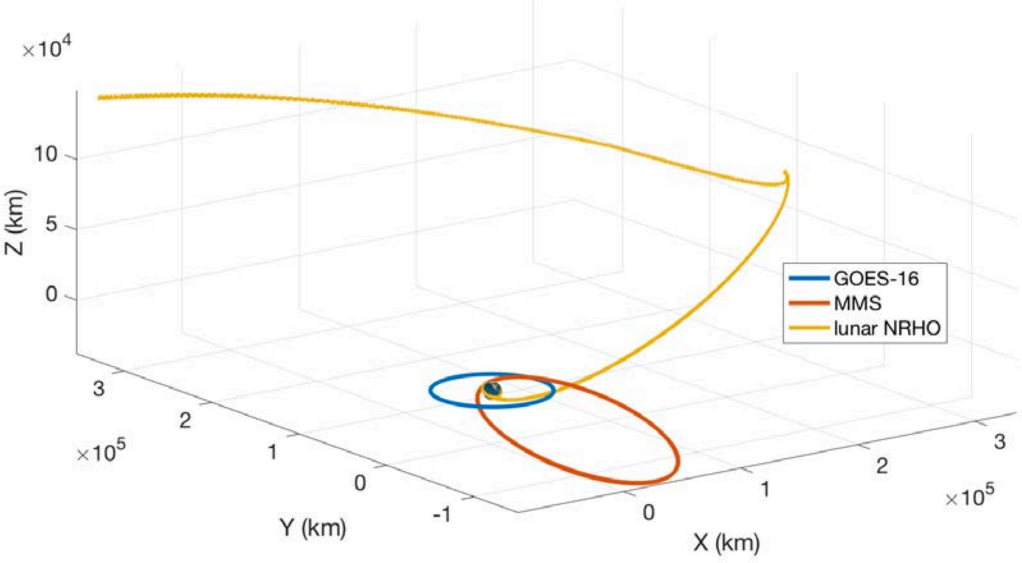


Filter position formal (3σ) and actual errors

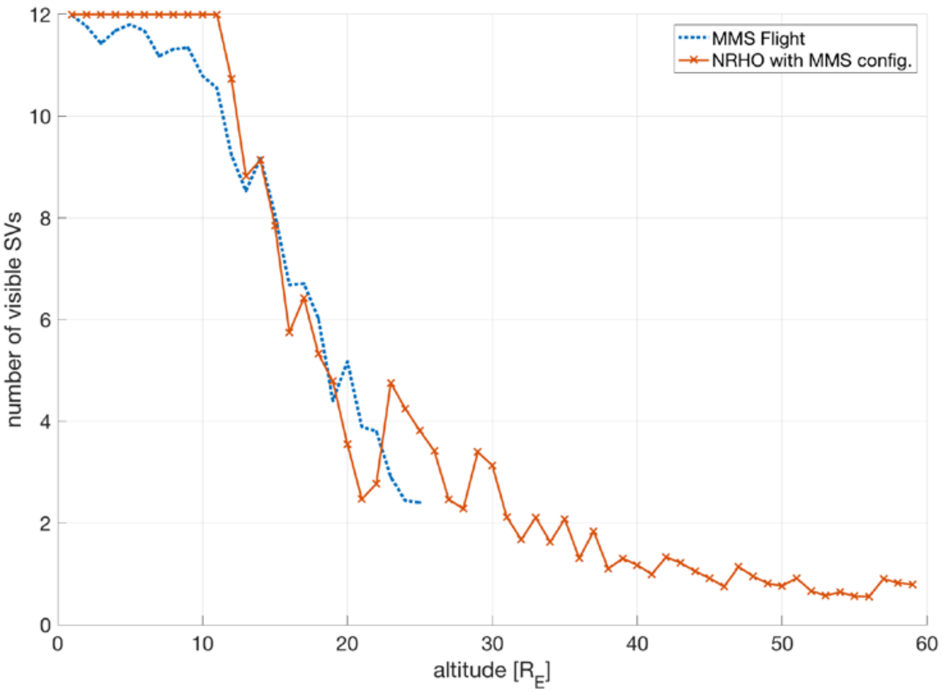


Lunar GPS Visibility Simulation

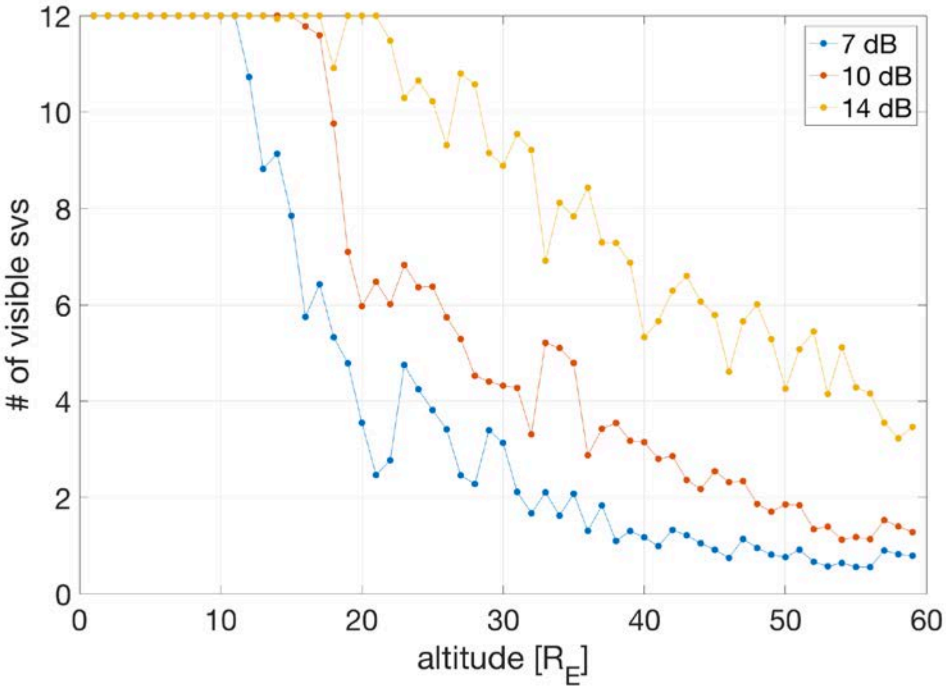
- US plans to return to human exploration of the Moon and cislunar space with EM-1 and EM-2; one long-term objective is the Deep Space Gateway, an international, permanent way-station in the vicinity of the moon
- Near Rectilinear Halo Orbit (NRHO) is one proposed orbit; this is used here for the lunar 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



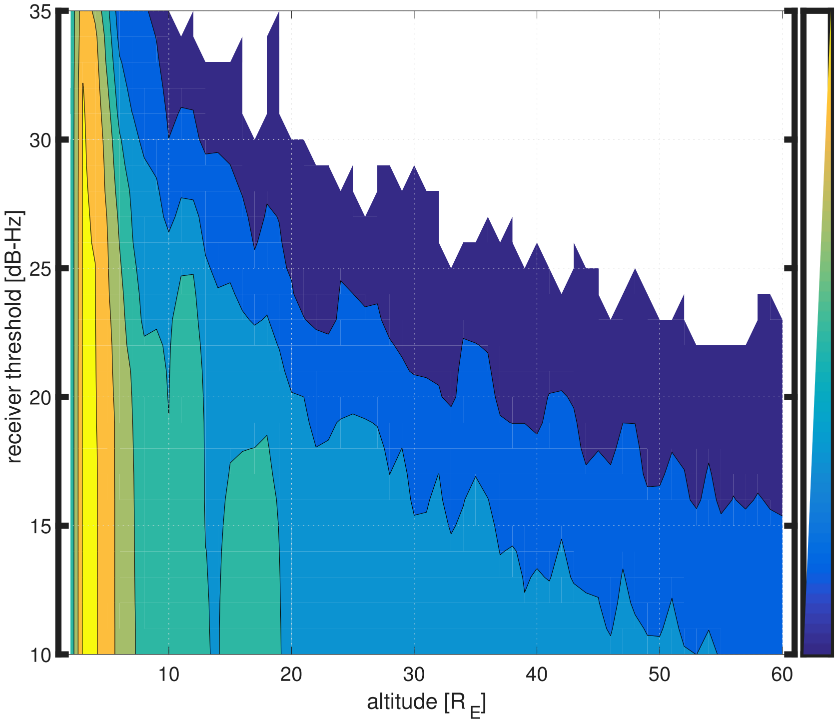
Number of satellites visible by altitude for different antenna gains

Lunar GPS Visibility Simulation

- Outbound lunar NRHO visibility with 22 dB-Hz acq/trk threshold:

Peak Antenna Gain	1+	4+	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 gain or sensitivity increases coverage significantly



Number of satellites visible by altitude and receiver threshold

Conclusions: Lunar GPS

- MMS 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, 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.

NASA Proposed Realization of Recommendation

- Conduct GNSS SSV Cislunar/Interplanetary Workshop
- Scoping:
  - How far is "beyond"?
  - What does it include? Cislunar space? Lagrange points? Mars/Interplanetary?
- Workshop to be held prior to or immediately after ICG-13 meeting in X'ian, China
- Workshop will focus on trade study planning
- Trade study objectives:
  - Develop a PNT architecture, focusing on GNSS capabilities that will support missions within and around:
    - Cislunar space
    - Lagrange points
    - Mars orbit and Mars surface
  - 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, Deep Space Atomic Clock timing, Mars orbiter hosted payloads)
- Conduct regular meetings (once per month) to prepare for the workshop

Proposed Workshop on Future of SSV

- **Goal: Collect international input on future directions for the Multi-GNSS SSV.**
  - What are the major use cases?
  - What threshold performance is achievable?
  - What future SSV plans are in progress by the providers?
- **Time horizon:** 20–30 years
- **Participants:** Providers and Space Agencies
- **Venue (proposed):** Workshop alongside ICG-13, Xi’an, China.

- **Discussion:**
  - Is this agreeable path forward for ICG-12 Recommendation 2?
  - Interest by WG-B in participating in this discussion?
  - Comments on specific plan?

Session 4

Status of the SSV booklet & Discussion of Future work, Status of Outreach Activities

SSV VIDEO

Objectives

- Develop a short but comprehensive video on the multi-GNSS Space Service Volume initiative
- Video should:
  – Define multi-GNSS and SSV concepts
  – Describe the importance and the benefit to humanity of an interoperable multi-GNSS SSV

Target Audience

- Video directed towards a general audience with some knowledge of spacecraft development and operations and some knowledge of GNSS
- Note that most aerospace engineers really don’t understand how GNSS works, so they fit into a this audience
- US candidate audience includes:
  - US Congress
  - Senior executives in NASA and Other Government Agencies
  - Other decision makers
- International candidate audience includes:
  - UN COPUS
  - Senior Leaders in international space agencies
  - GNSS constellation providers
  - Space scientists
  - Space exploration experts
  - Satellite developers, especially spacecraft at GEO

Video Target Length

Research findings:

- **Blog posting: How Long Should Your Next Video Be?**
  Ezra Fishman on July 5, 2016
  https://wistia.com/blog/optimal-video-length

Blog Summary:

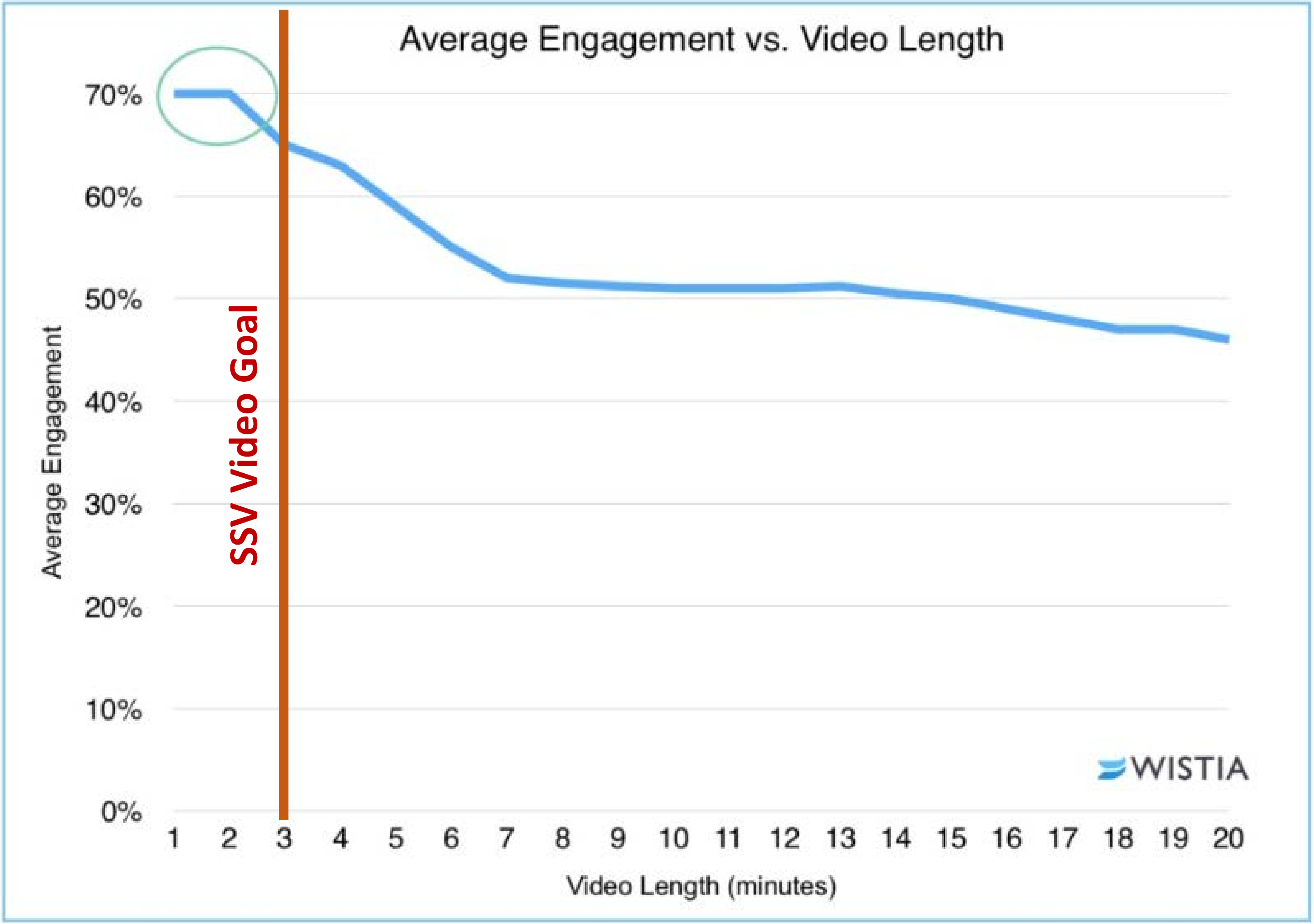
- Humans have short attention spans
- Engagement decreases with video length
- **2 minutes or less is best (70% engagement)**
- **Every second beyond 2 minutes lowers engagement**
- **Takeaway:** Push for 2 minutes. Beyond 2 minutes focus entirely on the content—make it immersive and use video to eliminate words

Additional information:

- NASA video experts confirm findings; feel <3 minutes is best for SSV type videos

SSV Video Goal

- **Work towards 3 minute goal**



Courtesy: WISTIA Ezra Fishman July 5, 2016

Video Takeaway

Individual Global Navigation Satellite System (GNSS) constellations in the Space Service Volume (SSV) have demonstrated outstanding operational and societal benefits but they supply insufficient available signals to fully support future missions

An interoperable, specified Multi-GNSS constellation capability in the SSV is critical for the continuous coverage required to support future beyond-low-earth orbit missions that a single constellation cannot provide

Video Script Content

- Major Topics:
  - GNSS Overview
  - SSV Overview
  - SSV applications
  - Conclusions (Including UN ICG collaborative efforts)

Script
GNSS Overview

- **When we first started to explore our Earth we innovated ways to improve our knowledge of navigation and time to guide us.**
- **Today, we rely on Global Navigation Satellite Systems, or GNSS, constellations, to safely navigate to our destinations and to support intelligent agriculture, power grids, financial commerce, Earthquake monitoring and many others.**
- **There are 4 navigation satellite constellations with global coverage-- Russia's GLONASS, United States' GPS, Europe's Galileo, China's BDS, as well as regional systems—India's NAVIC system and Japan's QZSS.**
- **The term Multi-GNSS refers to the use of two or more of these interoperable constellations to achieve enhanced performance and increased robustness.**

Script
SSV Overview (Part 1)

- **Many spacecraft use GNSS in low Earth orbit—those below 3000 km altitude--including the International Space Station. Space users in low Earth orbit enjoy GNSS performance similar to that of ground users.**

This is a great place to put your high definition video clips of your spacecraft!

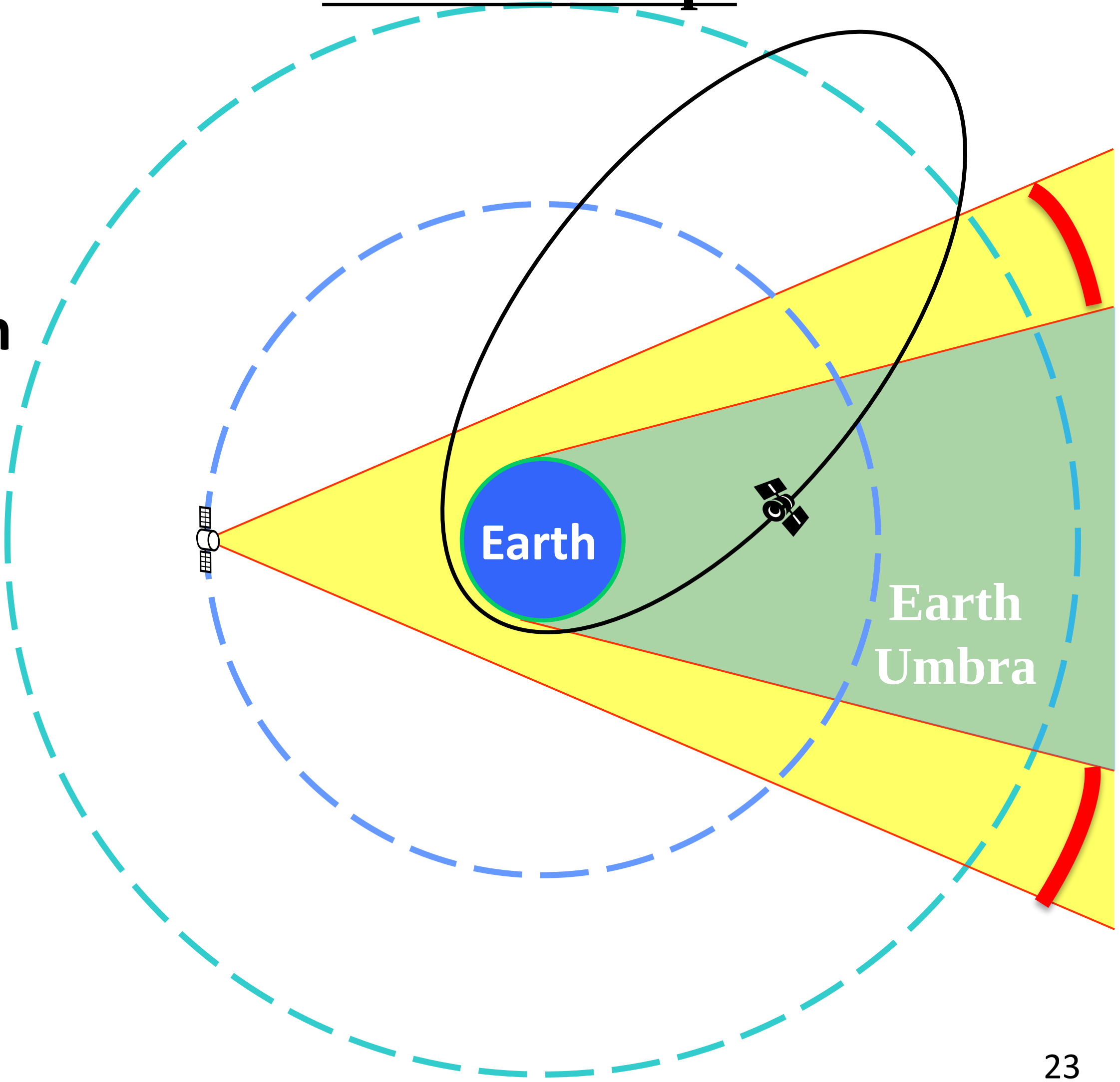
- **More recently, space vehicles have started using GNSS in the more challenging Space Service Volume or SSV, which is that area of space beyond 3,000 km altitude and reaching up to 36,000 km**

Script
SSV Overview (Part 2)

Script Segment

- **Spacecraft in the SSV endure significant challenges when compared to spacecraft in low Earth orbit**
- **Among these are fewer signals in view due to the Earth obscuring most of the GNSS signals and the tight GNSS beamwidth**

Visual Concept

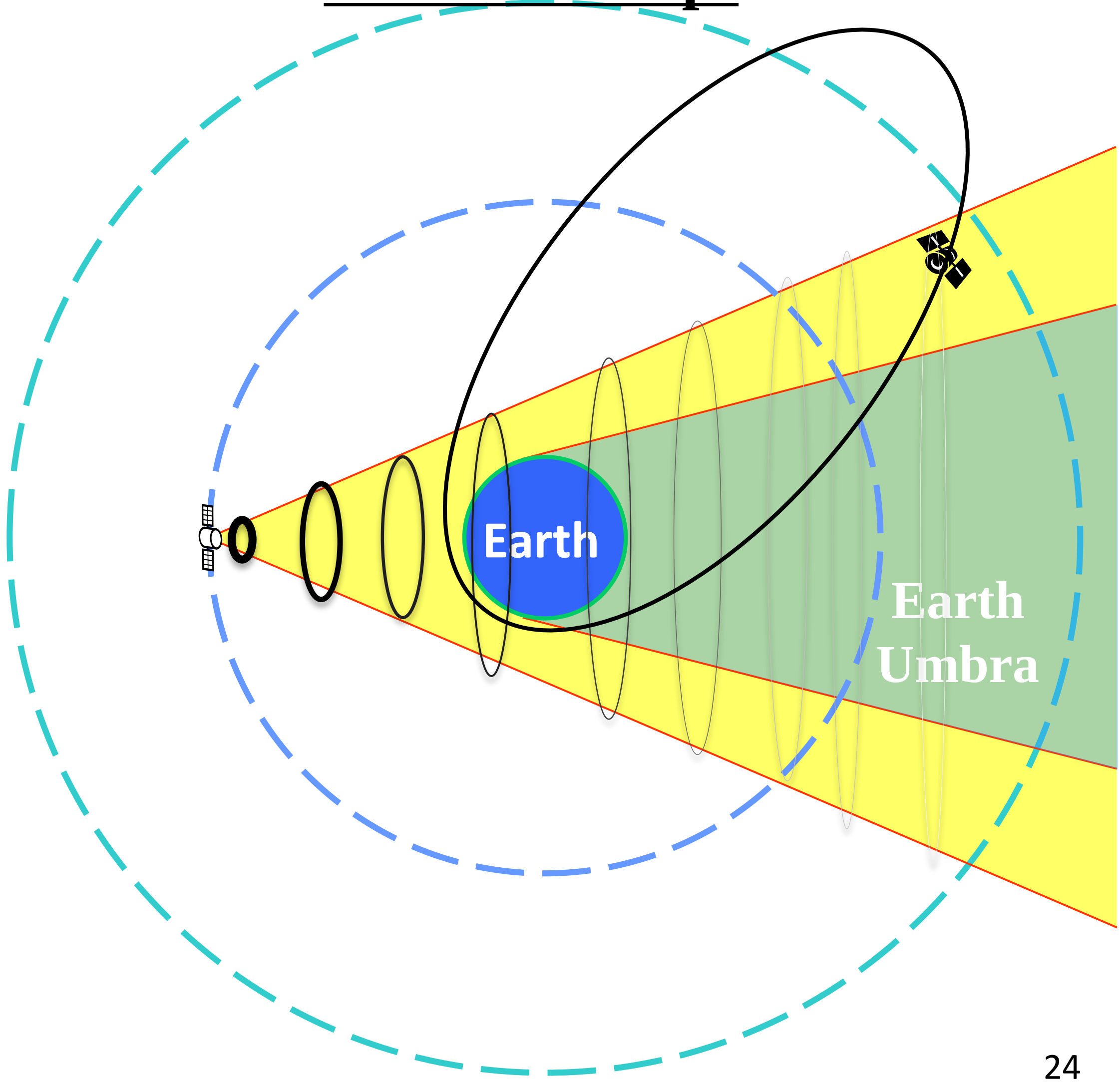


Script
SSV Overview (Part 3)

Script Segment

- Spacecraft signals in the SSV are also much weaker signal strength due to the longer signal paths at these altitudes

Visual Concept

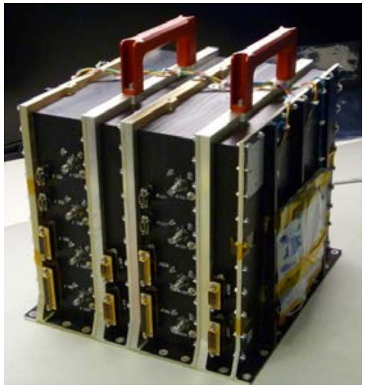


Script
SSV Overview (Part 4)

Script Segment

- **Engineers have developed special weak signal receivers to improve SSV reception and developed software to ensure robust performance with as little as one GNSS signal at a time**
- **But a single GNSS constellation cannot guarantee one signal in view at all times. And the availability of more signals further improves performance and robustness**

Visual Concept



NASA Navigator SSV Receiver

Script
SSV Overview (Part 5)

Script Segment

- **Analyses have shown that at low Earth Orbit, many signals are in view. But as the spacecraft approaches high altitudes in the SSV, a single GNSS system provides very few signals in view and signal outages can be over an hour.**
- **However, when all GNSS constellations are employed, an average of 4–12 signals are in view, and at least 1 signal is always in view, resulting in substantially better performance**

Visual Concept

- Use tachometer to represent # signals in view—a key performance metric
  - Tachometer goes from 0-12: 0-1 "red" 2-3 "yellow" & 4-12 "green"
- Spacecraft in GTO trajectory from LEO to GEO
- With 1 GNSS constellation at LEO, tachometer hits stops at 12
- As spacecraft traverses from LEO to GEO, tachometer drops precipitously from 12 (green) to 0-1 signals in view (red)
- As multiple constellations are added, tachometer goes from red to green; shows benefits of multi-GNSS

GNSS Signals in View

Script
SSV Applications

- An interoperable Multi-GNSS SSV is a satellite gamechanger, supporting missions such as:
  - Next generation weather satellites, such as EUMETSAT in Europe, GOES-R in the US, Himawari in Japan and Electro in Russia, substantially improving the quality of weather data collected and being a safety sentinel, warning people in danger of flash floods or wildfires.
  - Human exploration out to the moon
  - Space weather mission alerts to protect the world's critical infrastructure against solar storms
  - Missions to learn more about the Sun's corona and
  - Allows more accurate positioning of satellites in the dense geostationary belt
  - Other benefits include reduced spacecraft operations costs through automation and autonomy and enabling new, exciting science through formation flying missions in the SSV

***All for the benefit of society*.**

Need HD video clips of your SSV Applications Please!!

Script
Conclusions

- Collaborative efforts, through the United Nations International Committee on GNSS, or ICG, are overcoming SSV technical hurdles through interoperability, common definitions and simulations and specifications.
- Individual GNSS constellations in the SSV have demonstrated superb operational and societal benefits but supply insufficient available signals to fully support future missions.
- An interoperable multi-GNSS constellation capability in the SSV is critical for the continuous coverage that a single system cannot provide.
- Once fully implemented, the ICG-led multi-GNSS space service volume initiative will be transformative for space missions. It ensures continuous GNSS navigation and timing and enables innovative space mission concepts as we continue to explore our universe for the good of humanity.

Forward Plan

- NASA solicits constellation video clips and high quality pictures from international community **Action to China, Europe, India, Japan Russia, USA**
- NASA will work with video producer, animators and production unit to develop polished SSV video final draft
- Present to WG-B for final comments around September
- Final video draft prior to November ICG meeting in China

Video Clip and Picture Guidance

- Make sure all video clips and pictures align with the script
- Items we would like to obtain include:
  - High resolution (HD) clips with detailed view of your satellite in orbit
  - Current and future prospective missions, like your GEO weather satellite, etc. In other words, satellite users in the SSV
  - Other ideas?
- We would really appreciate your inputs. These will be part of a polished video that we can all use to describe the SSV to many

Tentative Schedule

- Finalize script and action plan: This meeting
- Final video clips due from all parties: August 1
- Production version draft: ~ September 15
- WG-B review and comment: September 15-October 1
- Final Draft copy for review: ICG-13
- External release: Prior to Jan 1 2019

SSV OUTREACH

Status: SSV Outreach

- **SSV Booklet current outreach plan:**
  - (Publication of SSV Booklet + Video)
  - 24–28 Sep 2018: ION GNSS+, Miami, FL, USA [2 papers]
    - Paper 1: Development of Multi-GNSS SSV
    - Paper 2: Technical Results of Multi-GNSS SSV Analysis
  - 1–5 Oct 2018: IAC 2018, Bremen, Germany
    - Paper: The Multi-GNSS SSV
  - 4–8 Nov 2018: ICG-13, Xi'an, China
  - Mar 2019: Munich Satellite Navigation Summit
- **3x papers for Sep/Oct conferences must be developed very soon.**
- **Needs for this meeting:**
  - Approval of paper plan document, incl. titles, scope, outline
  - Approval of schedule and roles/responsibilities
  - Lead author commitments from each provider

Paper Roles/Responsibilities

- **Lead author:** Responsible for management of writing process and final drafts of manuscripts and presentations; *may not be the same as first author*!
- **Writing team:** Small (~5-person) team tasked with initial content authorship; meets often (~weekly) and responsive via email; does not necessarily involve all providers
- **Review team:** Larger team responsible for review of milestone drafts; involves all providers; may consist of all of WG-B SSV team

Paper 1: IAC

- **Title:** The Multi-GNSS Space Service Volume
- **Status**: Abstract accepted for presentation
- **Scope**:
  - Describes the concept, history, development, benefits, and use cases of the Multi-GNSS SSV.
  - Condensed and contextualized version of SSV Booklet.
  - Technical content describing high-altitude GNSS, SSV, and benefits, but limited analytical detail.
  - Written for a broad space audience – stresses what's important, what's new, and what the impacts will be.
  - Generally, more emphasis on international collaboration than the ION technical paper, but with more of a focus on the future than the ION programmatic paper.
  - Provide a future vision of international architecture development and use in cis-lunar space, in particular the lunar gateway.

Paper 2: ION (Development)

- **Title:** Development of an Interoperable, Multi-GNSS Space Service Volume
- **Status**: Accepted for presentation
- **Scope**:
  - Similar to the IAC paper.
  - Provide a discussion of the UN ICG process in facilitating an interoperable SSV.
  - This is more detailed in terms of what has already been done; content on development and trades.
  - Potentially more detailed results, benefits, use cases.

Paper 3: ION (Technical)

- **Title:** Space User Visibility Benefits of the Multi-GNSS Space Service Volume: An Internationally-Coordinated, Global and Mission-Specific Analysis
- **Status:** Accepted as alternate
- **Scope:**
  - Details the analysis used to calculate global and mission-specific visibility estimates.
  - Covers constellation-specific configuration, simulation setup, assumptions, link budget, example missions, results analysis, verification.
  - Visibility and DOP.
  - Future work and technical refinements.
  - Hope to swap this with the other ION paper so that paper is the alternate and this one is presented.

Paper Schedule

Milestone	Description
Jun 21	ICG WG-B Meeting (approval of table of contents/plan for development/Roles and Responsibilities)
Aug 15	Final draft paper + presentation complete
Aug 16	Submit for review. For technical papers, only submission to space agencies is considered applicable. For policy or strategic papers, send to service providers for information, with deadline of Sept 10.
Aug 20	Space Agency/Institutional review submission deadline (final manuscript + presentation)
Sept 10	Provider feedback (if any)
Sept 10	Feedback from space agencies/institutions
Sep 17	IAC submission deadline (manuscript)
Sep 24	IAC/ION submission deadline (presentations)
Oct 5	ION submission deadline (manuscripts)

Session 7

Enhancement of GNSS signals and performance and required system enhancements

MISSION UPDATES

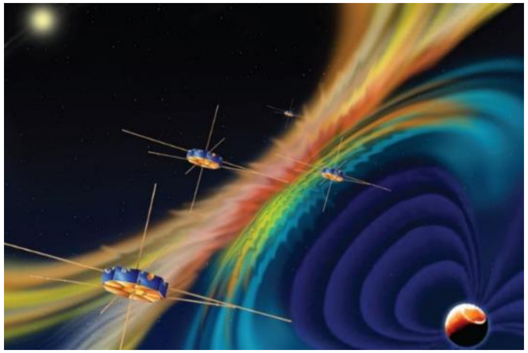
Recent SSV Experiences: NASA MMS Mission

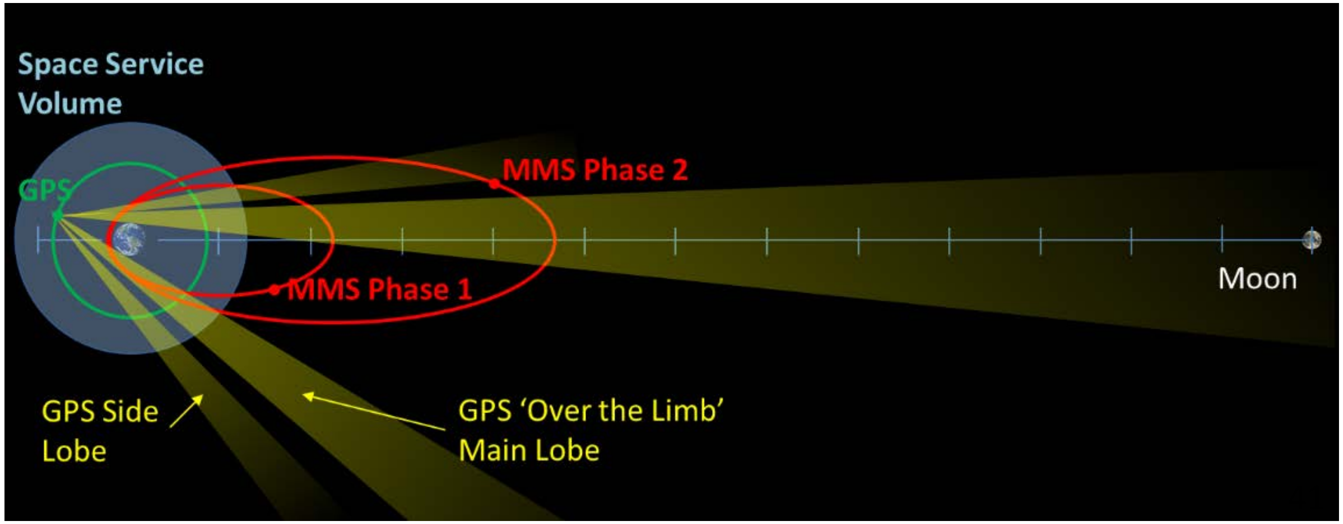
Magnetospheric Multi-Scale (MMS)

- 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 Guinness world record for the highest reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h

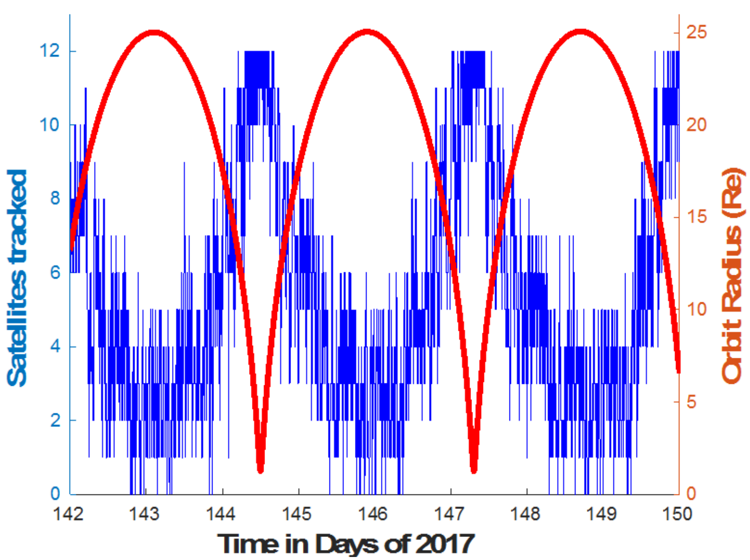




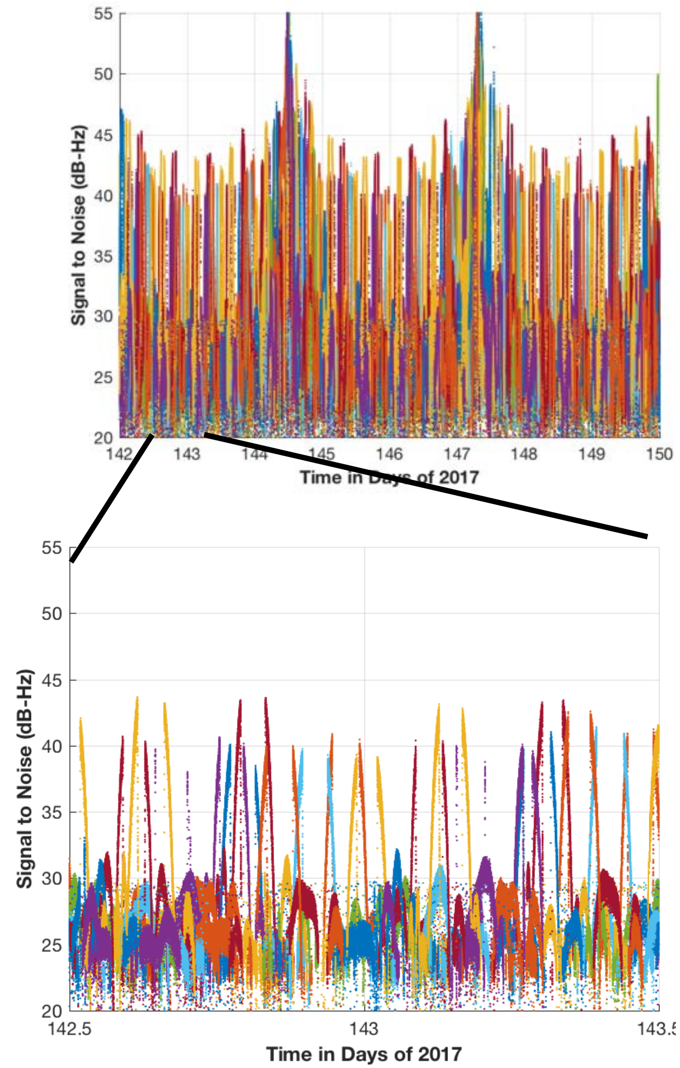
MMS on-orbit Phase 2B results: signal tracking

- 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

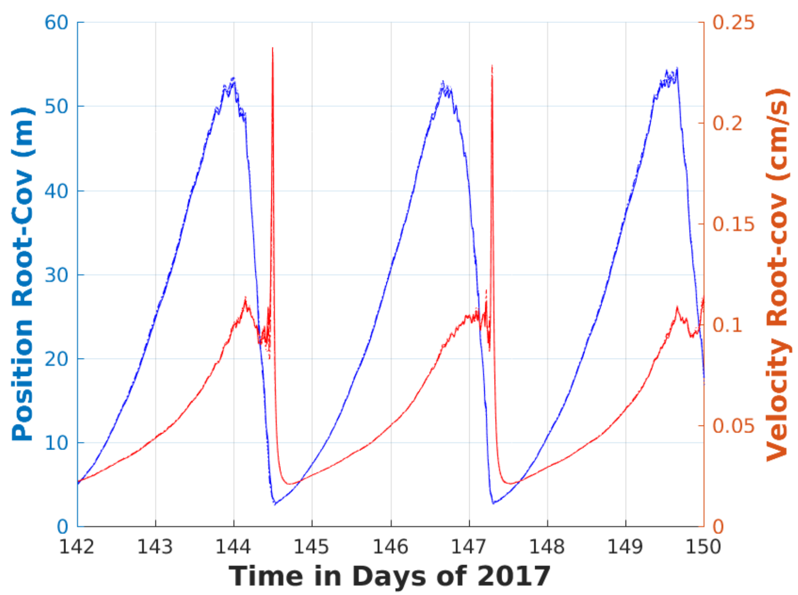


MMS on-orbit Phase 2B results: measurement and navigation performance

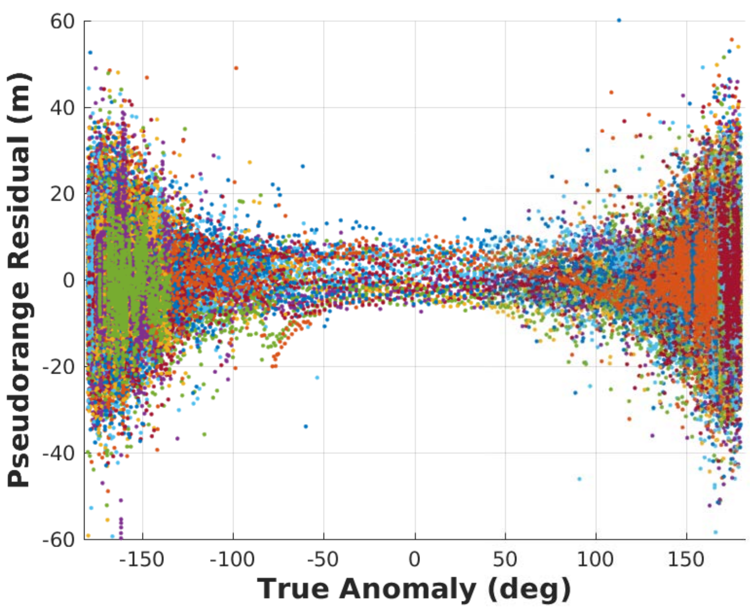
- GEONS filter RSS 1-sigma formal errors reach maximum of ~50m and briefly 5mm/s (typically <1mm/s)
- Measurement residuals are zero mean, of expected variation <10m 1-sigma.
  - Suggests sidelobe measurements are of high quality.

Description	Requirement	Phase 1	Phase 2B
Semi-major axis est. under 3 R_E (99%)	50 m (Phase 1) 100 m (Phase 2B)	6 m	15 m
Orbit position estimation (99%)	100 km RSS	65 m	55 m

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

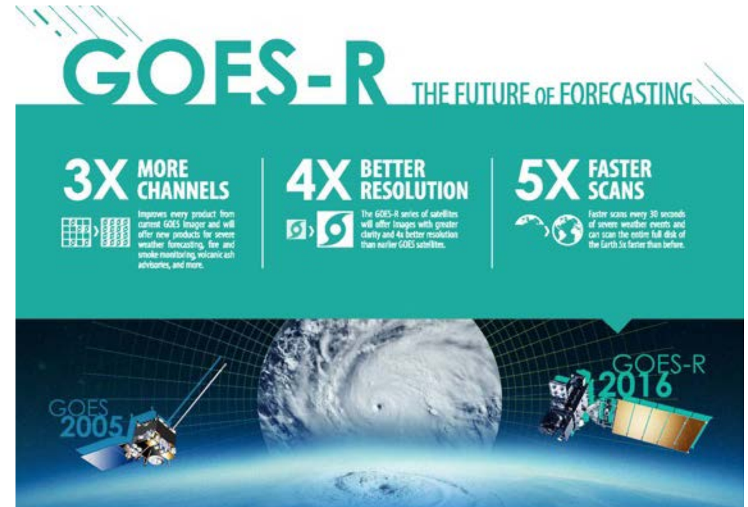


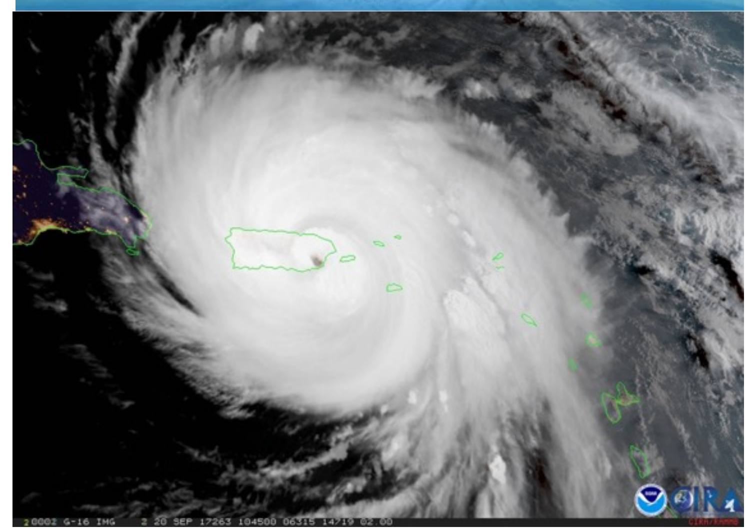
Pseudorange residuals



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
- Features new CONOPS over previous generation:
  - Daily low-thrust station-keeping maneuvers, rather than annual high-thrust events
  - Continuous data collection through maneuvers, <120 min of outage per year
  - Tighter navigation accuracy requirements and faster cadence needed to support highly increased operational tempo
- Employs on-board GPS at GEO to meet stringent navigation requirements
- Utilizes GPS sidelobe signals to increase SSV performance and ensure continuous availability



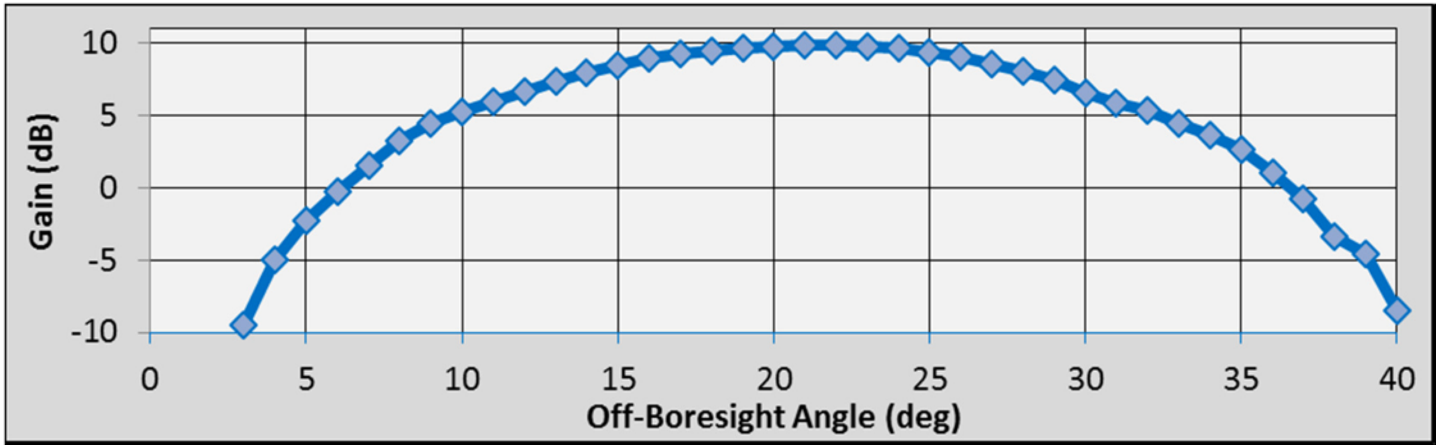


GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

GOES-R/GOES-16 Signal Reception

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

Antenna patterns



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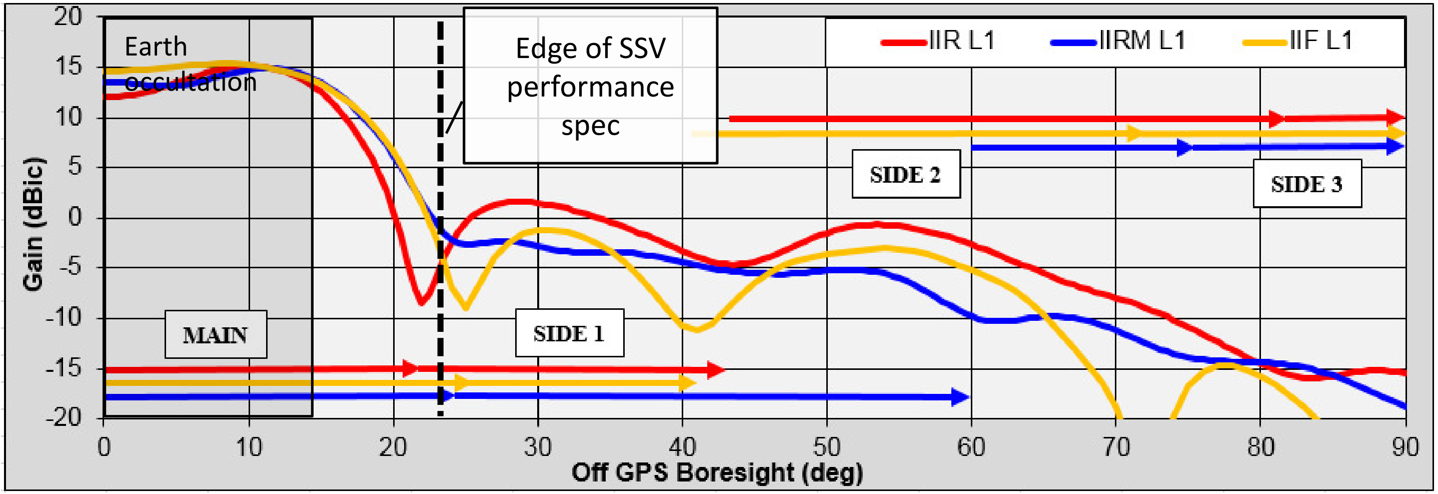

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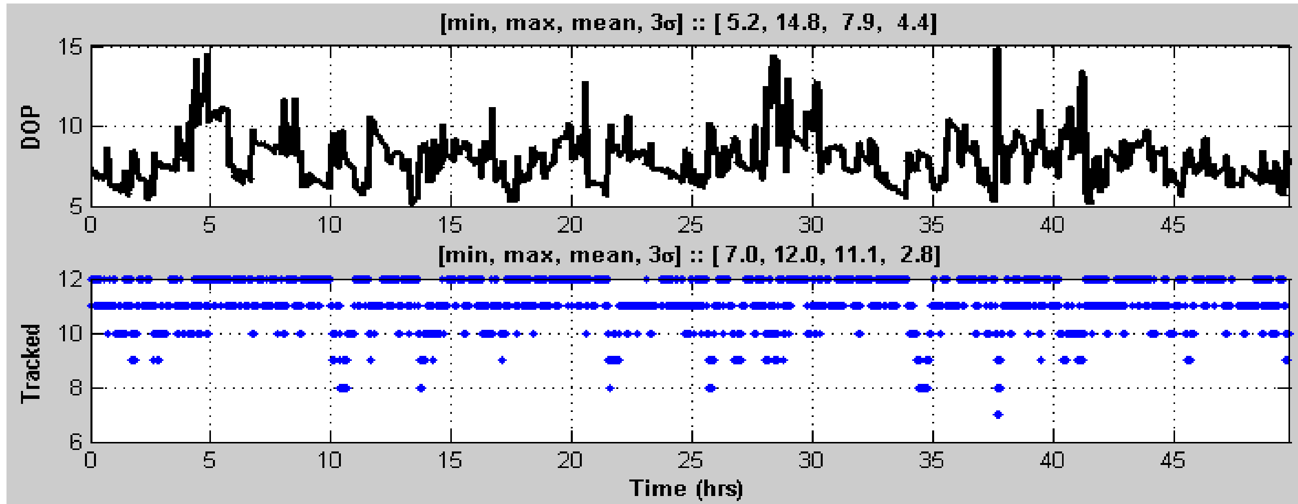
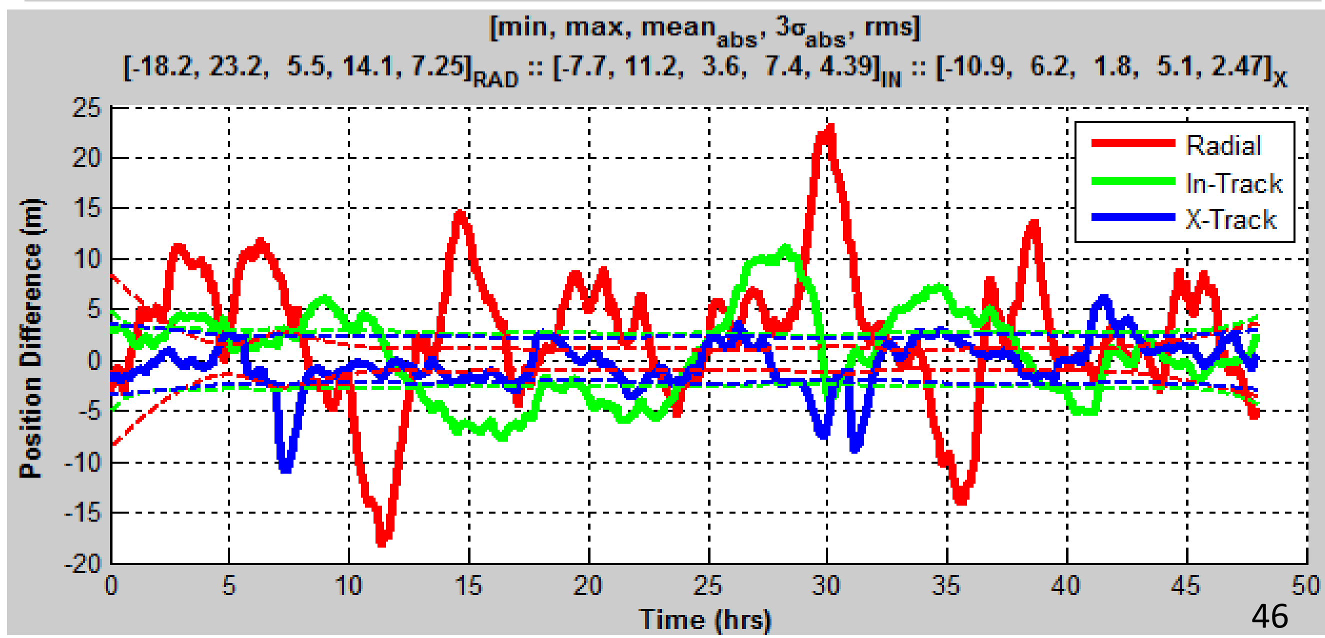
Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

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

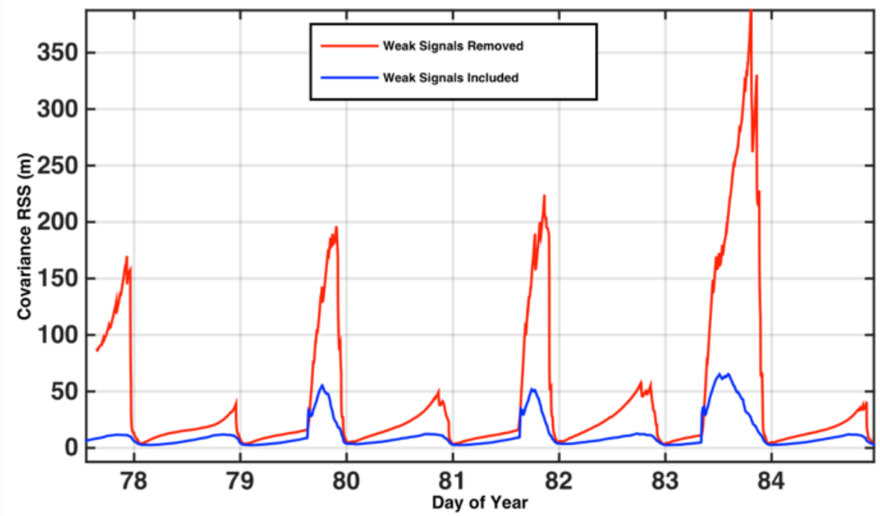




Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

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)

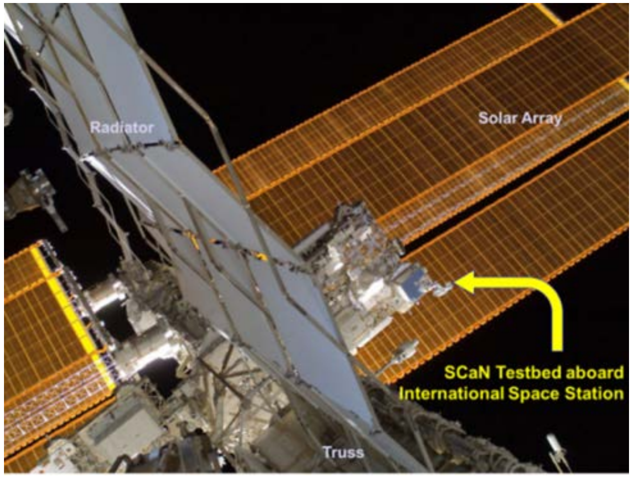
Notes:

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

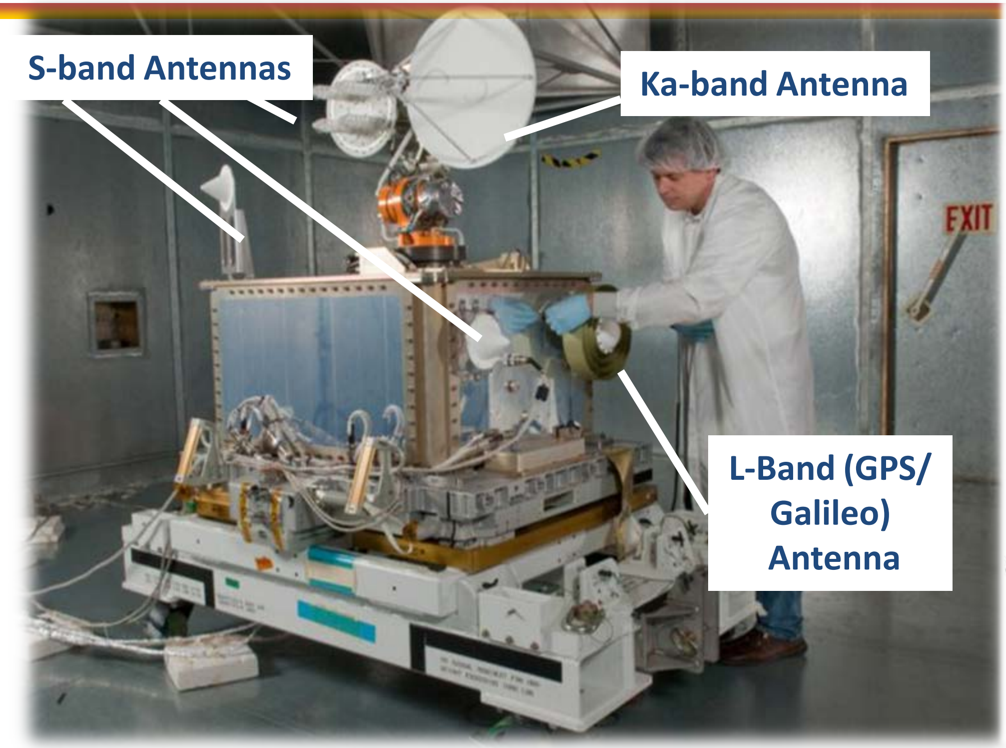
GARISS

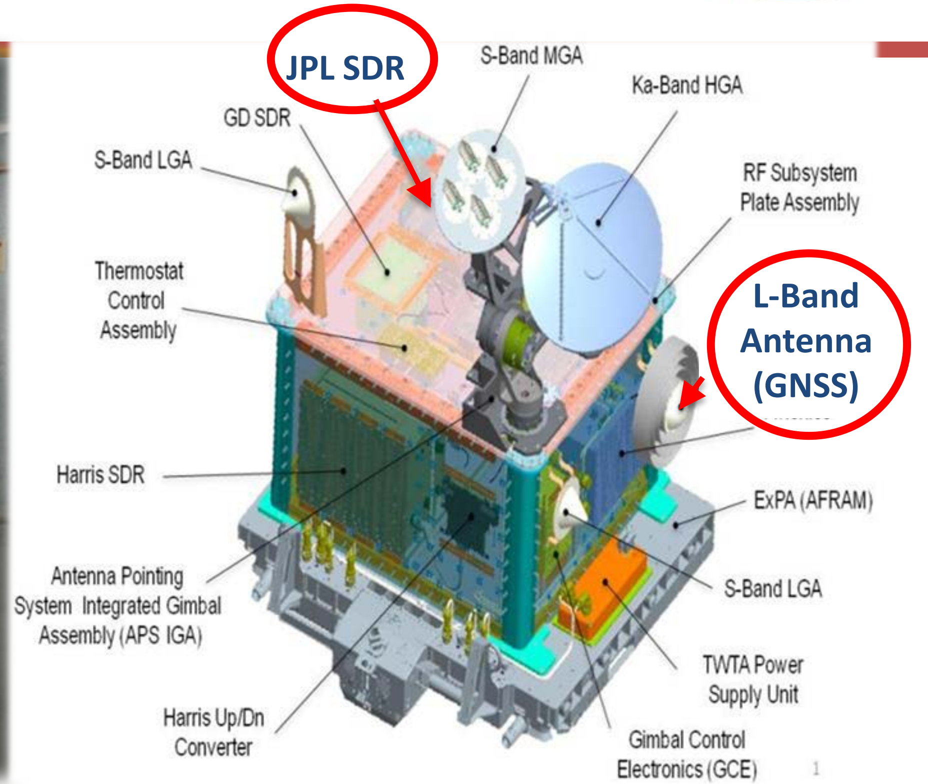
GAlileo **R**eceiver for the **ISS** (GARISS)

- **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





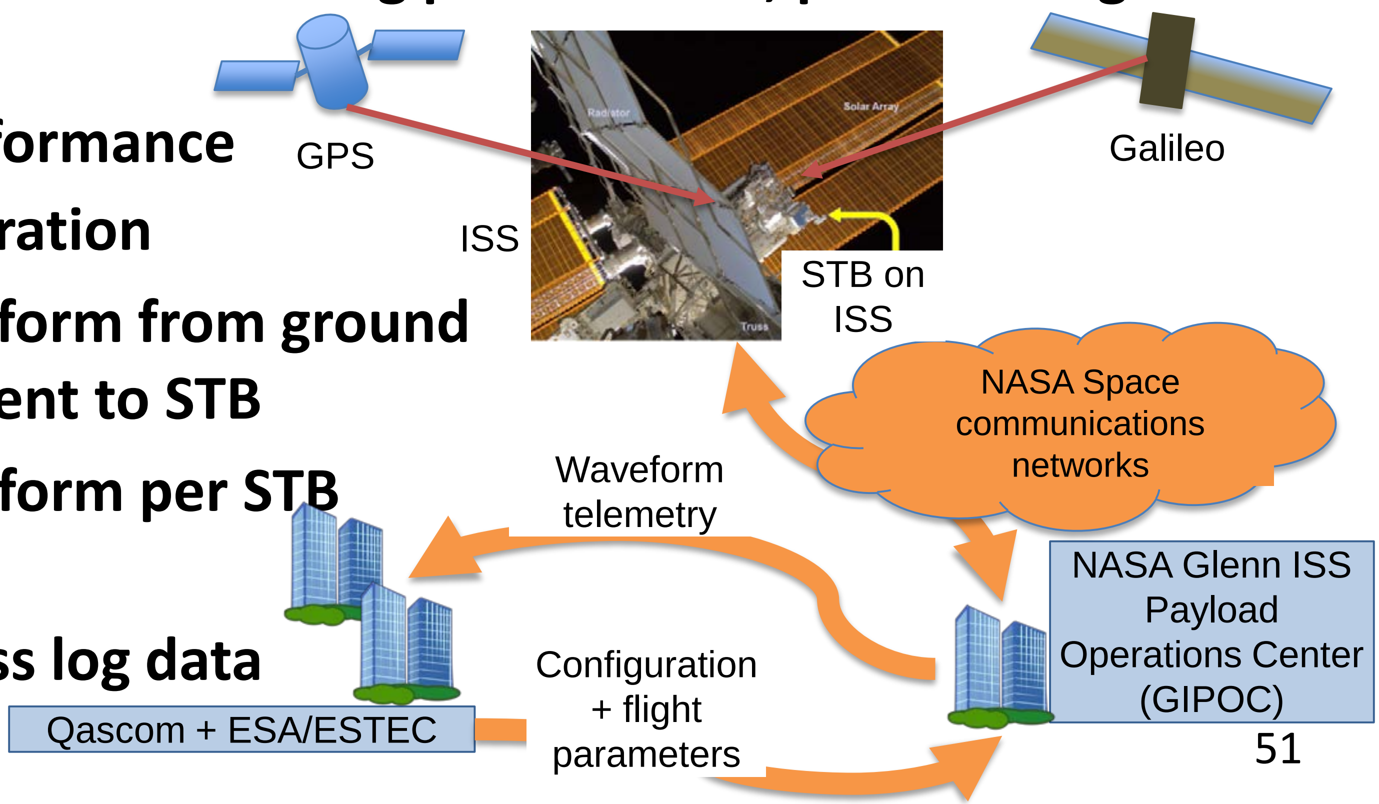
<u>**Space Communication and Navigation (SCaN) Testbed**</u>

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

Fully reprogrammable Software Defined Radio capability at L-band

Operational/Experiment Concepts

- Support for multi-constellation GPS and Galileo
- Exclusive use of L5/E5a band
- Warm start acquisition aiding from ground via file upload
- Assess acquisition and tracking performance, pseudo-range errors, etc.
- Assess PVT performance
- Concept of operation
  - Transfer waveform from ground support equipment to STB
  - Operate waveform per STB schedule
  - Collect/process log data



GARISS: Status

Status

- Mild re-architecting of Interrupt Task made to accommodate include adaptive strategy for management to keep correlation peaks within processing interval
- Successful acquisition, track and PVT with STB Ground Integration Unit (GIU) using roof antenna (March 2018)
- Moved integration and testing to on-orbit operations
- Successful on-orbit acquisition, track and PVT solution (April 2018)
- 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%
  - PVT performance issues remain.

Achieved Combined Galileo/GPS PVT availability greater than 90%

GARISS: Path Forward and Conclusions

<u>Path Forward</u>

- Investigation of errors in pseudo-range estimation and, possibly, inter-constellation bias is ongoing.
- [Pending] Experimentation objectives potentially include:
  - examination of multipath effects
  - validation of inter-constellation time bias models,

<u>Conclusions</u>

- GARISS leverages SCAN testbed, STRS development framework
- Demonstrated effectiveness of multi-constellation/GNSS solutions
- First-ever on-orbit direct acquisition or L5/E5a (no L1 aiding)

AFTS

Autonomous 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

Autonomous Flight Termination System - Operational Use

- In work over 18 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
- 25 additional successful SpaceX operational launches to-date (as of June 2018)
- The successful SpaceX F9 Heavy launch demonstrated that without AFTS, such a launch system with 2 fly-back boosters, a 1st stage fly-back core, and a 2nd stage could not be supported by traditional range operations using a MFCO.

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

IGS UPDATE

International GNSS Service (IGS)

- A voluntary federation of over 200 international agencies
- **Promotes and provides open** and **free** access to high quality GNSS data and analysis products
- Providing **high precision GNSS data, products and services,** including: GPS + GLONASS combined orbits, GPS clocks, GLONASS clocks
- Supports realization of the International Terrestrial Reference Frame

Recent Significant IGS Events and Changes

- Ruth Neilan (IGS representative to ICG) retired from JPL in March 2018, and is no longer associated with JPL or NASA
- Allison Craddock appointed by JPL as Central Bureau Director and confirmed by the IGS Governing Board in April 2018
- New **IGS Strategic Plan published** in February 2018 and is available at: https://kb.igs.org/hc/enus/articles/360001150012-2017-Strategic-Plan

GNSS Performance Monitoring ICG-IGS Joint Trial Project (IGS-IGMA)

- Background and Objective
  - Trial project of the **ICG Monitoring and Assessment Task Force (IGMA),** coordinated in partnership with the IGS
  - Monitoring of GNSS constellation status and the quality of navigation signals enables numerous applications, including worldwide time and frequency transfer, and GPS meteorology.
  - High-precision GNSS monitoring of the earth is not possible without GNSS performance monitoring
    - Orbit accuracies of a few centimeters for any point in time are a requirement, and determination of this is only possible if the properties of all GNSS are known to the best extent possible –or– can be determined in orbit determination processes.
    - Many **parameters** have to be determined by monitoring:
      - Broadcast Ephemeris Accuracy (Orbits and Clocks)
      - SIS User Range Error
      - SIS UTS Offset Error
      - PDOP for GNSSs
- Long term objectives:
    - Make all performance standard entries for each GNSS openly available
    - Provide a multi-GNSS service performance standard

IGS

GNSS Performance Monitoring ICG-IGS Joint Trial Project (IGS-IGMA)

- Current Status
  - 12 Groups have responded positively to Call for Particaption
  - Initial results have been gathered and a **standard methodology is in development**
  - IGS-IGMA recommends to the service providers to make the following info available:
    - the **antenna phase center** values of all the GNSS systems
    - Know for which signal(s) the clocks are given/valid
    - the attitude law of the satellites, in particular during eclipse, that is used for the broadcast ephemerides
- Future work includes:
  - Review and enhance comparison of broadcast ephemerides
  - Start converting orbit and clocks to common location and compare
  - Develop and implement clock comparison strategy
  - SISURE and UTC to follow after orbit and clock comparison is resolved

IGS

Multi-GNSS Extension (MGEX) Pilot Project

- MGEX work focuses on integration of the evolving global and regional satellite navigation systems Galileo, BeiDou, QZSS, and NavIC (IRNSS) into the IGS data archives and operational products.
- Integration of the multi-GNSS observation data was completed in 2016, but improving the product quality of the emerging GNSS to achieve the same quality as for the legacy GPS and GLONASS is still an ongoing process
- The IGS Multi-GNSS Working Group, led by Oliver Montenbruck, released a White Paper, titled **"Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products."**
  - The paper discusses the **parameters needed to ensure the highest possible performance of IGS products** for all constellations and motivates the need for provision of satellite and operations information by the GNSS providers.
  - All **information requested** by the IGS is considered to be **sufficiently abstract** such as to neither interfere with the GNSS providers' safety and security interests nor with intellectual property rights.
  - **Download** here: http://bit.ly/MGEXwhitepaper

IGS

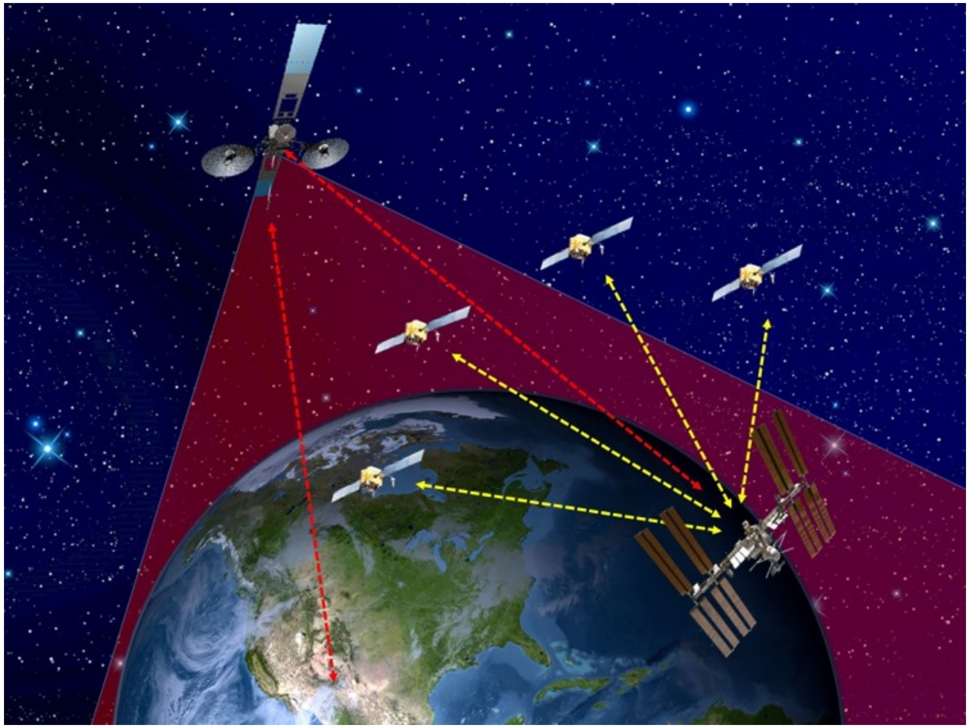
MGEX Achievements, Prospects, and Challenges

- MGEX has recently published a comprehensive paper detailing its achievements in the last five years, future prospects, and challenges.
- **“The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges,”** published in Advances in Space Research, Volume 59, Issue 7, 1 April 2017, Pages 1671–1697, discusses:
  - Multi-GNSS products derived from the IGS monitoring station network
  - Work towards full integration of new constellations into routine GNSS processing
  - Progress made within the MGEX project including BeiDou, Galileo, and QZSS for precise point positioning, atmospheric research, and other applications.
  - Biases; standards and conventions
- Due to copyright restrictions, a pre-print previous version of the article is available here: http://bit.ly/MGEXasr

NGBS

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

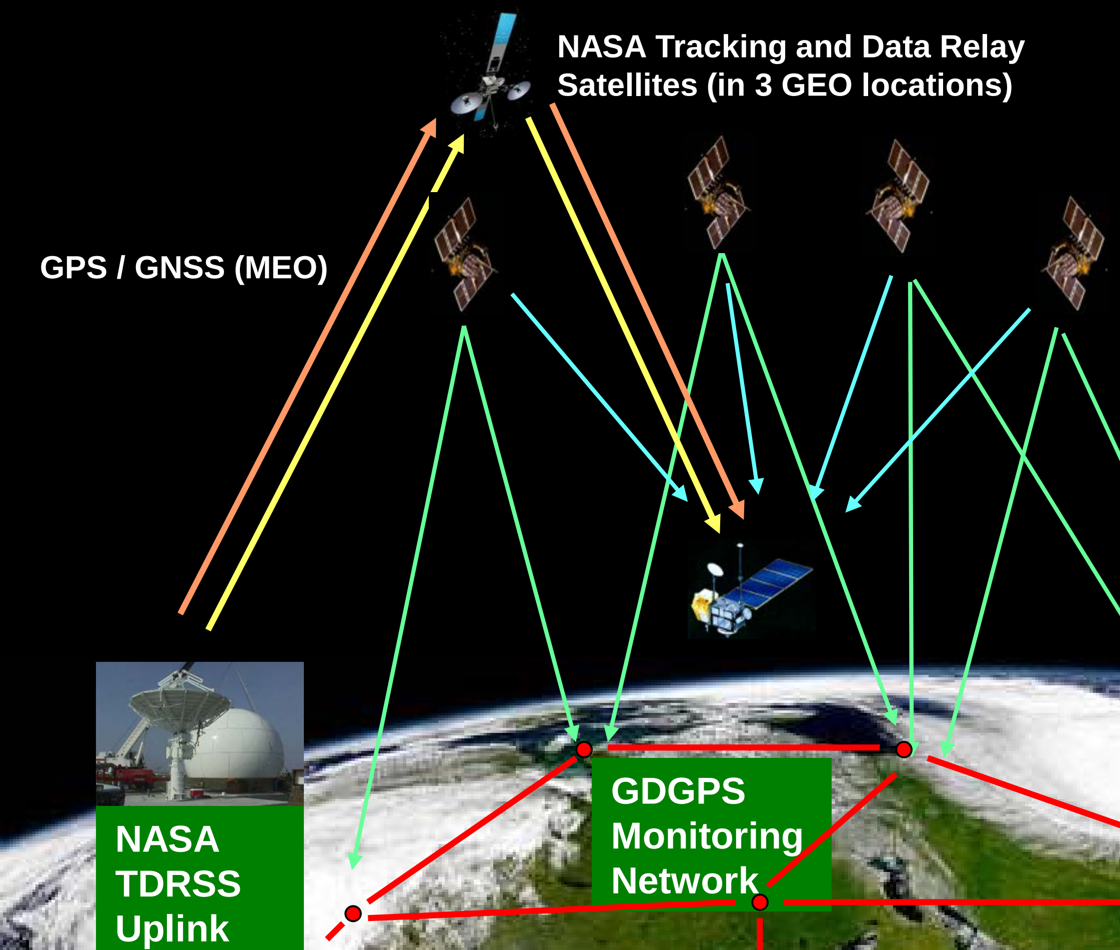


NGBS could have direct benefits in the following areas:

- **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 all 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 NGBS 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

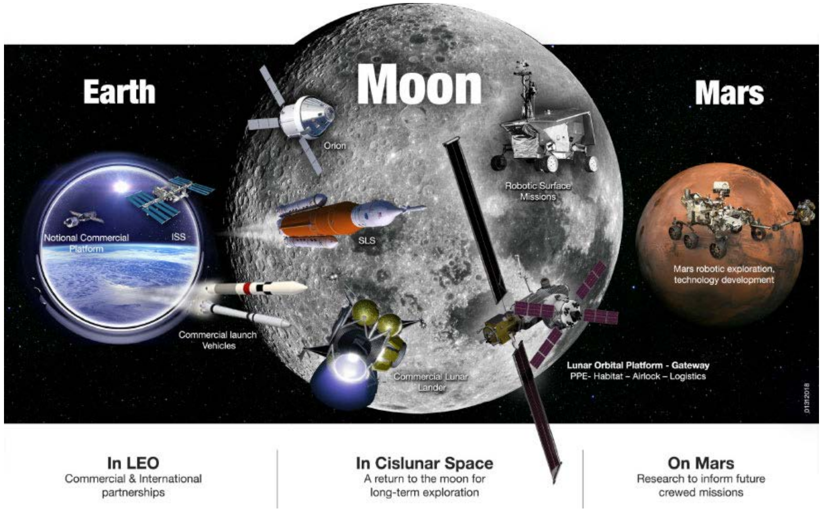
- Benefits
  - Improves the level of autonomous operations for users
  - Improves coordination and responsiveness to transient scientific phenomena among multiple spacecraft (e.g. gamma-ray bursts, gravitational waves)
  - Provides alternative/additional navigation beacon to supplement GNSS, improving 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

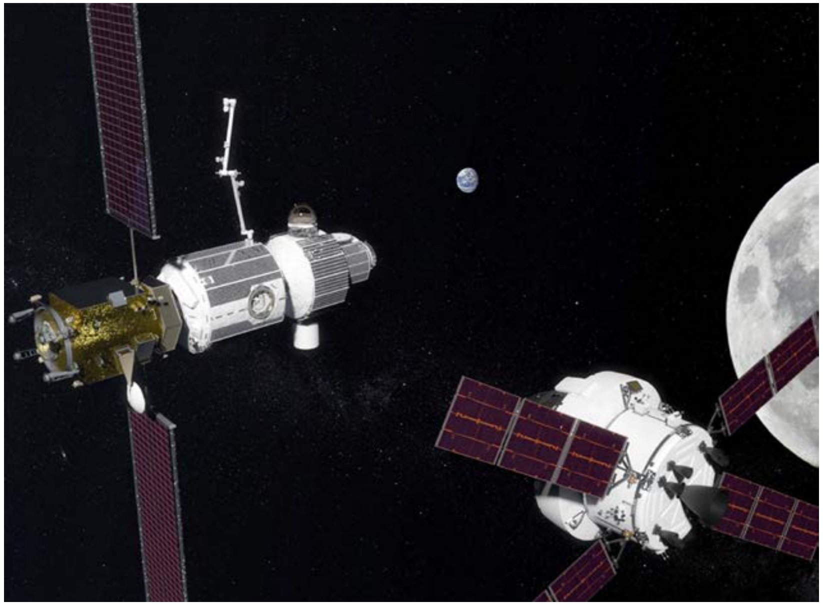
Engagement from the user community is critical. Seeking stakeholder feedback: what services would be beneficial?

FUTURE MISSIONS

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

BACKUP

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

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N°	Agency	Mission	GNSS System/s Used	GNSS Signals Used	GNSS Application	Orbit	Launch (Actual or Target)	Notes	Last Updated	Updated By
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)