Keeping the universe connected.

NASA Update: GNSS Space Service Volume Providers' Forum

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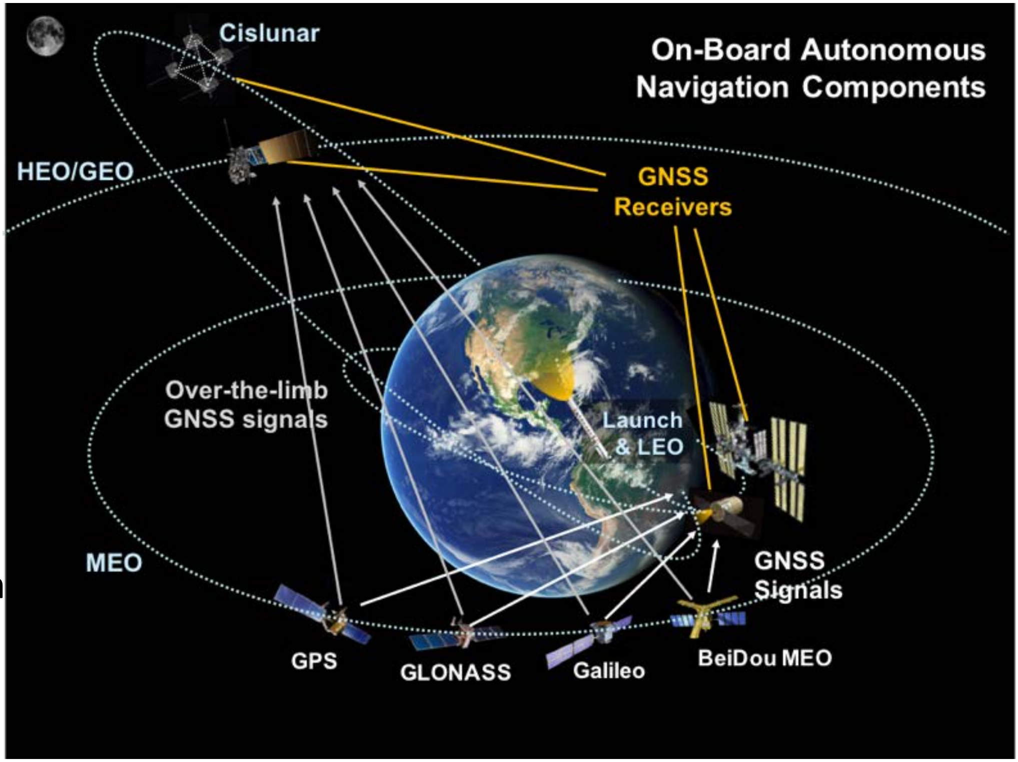
Vienna, Austria, June 18, 2018

Benefits of GPS/GNSS to NASA

- **Real-time On-Board Navigation:** Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **Earth Sciences:** Used as a remote sensing tool supporting atmospheric and ionospheric sciences, geodesy, geodynamics, monitoring sea levels, ice melt and gravity field measurements
- **Launch Vehicle Range Ops:** Automated launch vehicle flight termination; providing people and property safety net during launch failures and enabling higher cadence launch facility use
- **Attitude Determination:** Enables some missions, such as the International Space Station (ISS) to meet their attitude determination requirements
- **Time Synchronization:** Support precise time-tagging of science observations and synchronization of on-board clocks



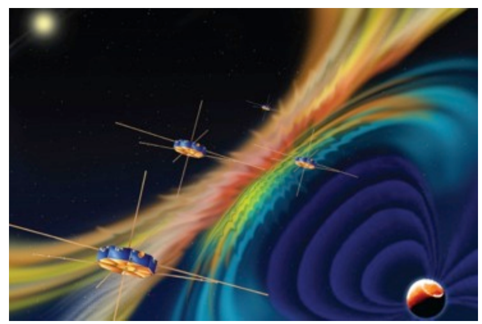
GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

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

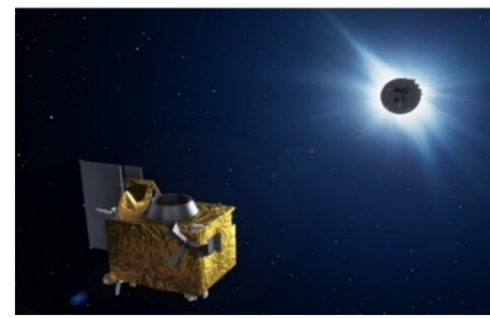
<u>Benefits of GNSS use in SSV:</u>

- 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:

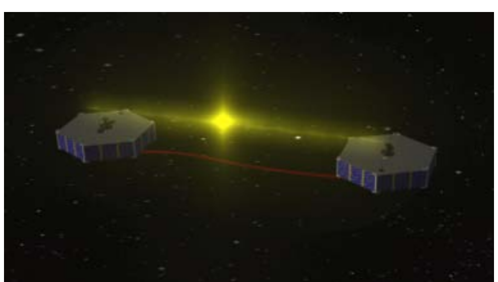
Earth Weather Prediction using Advanced Weather Satellites



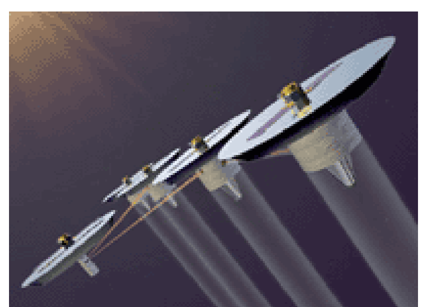
Space Weather Observations



Precise Relative Positioning



Precise Position Knowledge and Control at GEO



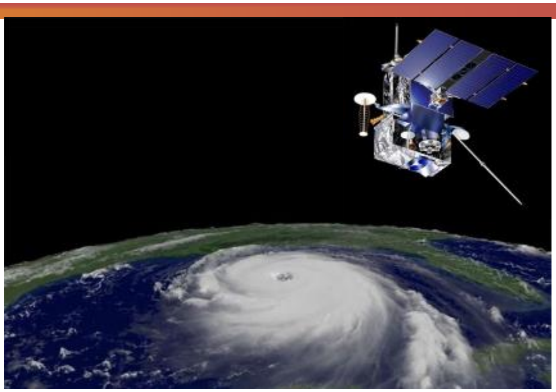
Formation Flying, Space Situational Awareness, Proximity Operations

Beyond GEO / Cislunar Space

Current U.S. Missions using GPS above the GPS Constellation

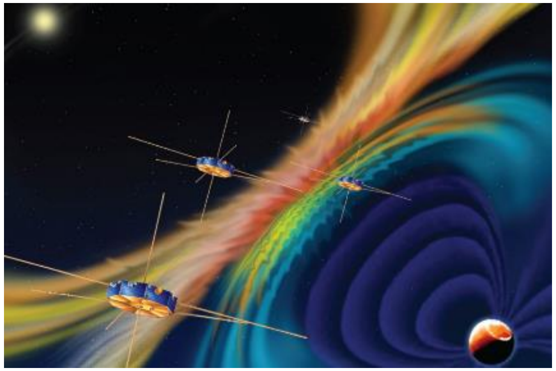
GOES-R Weather Satellite Series:

- Next-generation U.S. operational GEO weather satellite series; GOES-R/GOES-16 & GOES-S/GOES-17 on-orbit
- Series is first to use GPS for primary navigation
- GPS provides quicker maneuver recovery, enabling continual science operations with <2 hour outage per year
- Introduction of GPS and new imaging instrument are game-changers to humanity, delivering 3x more channels, 4x better resolution, 5x faster scans than previous series



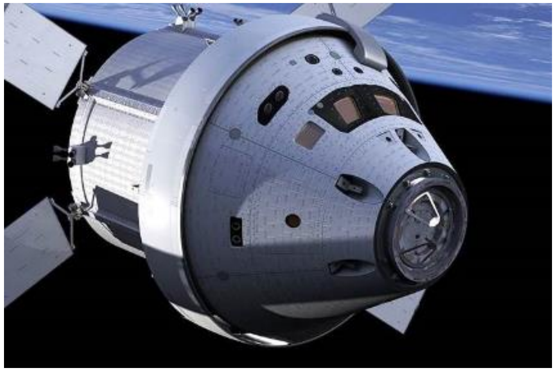
Magnetospheric Multi-Scale (MMS) Mission:

- Four spacecraft form a tetrahedron near apogee for magnetospheric science measurements (space weather)
- Highest-ever use of GPS; Phase I: 12 Earth Radii (RE) apogee; Phase 2: 25 RE apogee (40% of way to moon)
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping



Exploration Mission 1 (EM-1):

- First cis-lunar flight of NASA Space Launch System (SLS) with an Orion crew vehicle equipped with a Honeywell GPS receiver as an experiment
- Launch expected 2020



US Support to ICG WG-B Multi-GNSS SSV Efforts

- ICG efforts, coupled with outreach Initiatives are a key enabler for technical exchange, consensus, and action:
  - **SSV Booklet Development**
    - Documents and publishes SSV performance metrics for each individual constellation
    - Includes internationally coordinated SSV analyses and simulations
    - Communicates assumptions & analysis results
    - Supports international space user characterization of PNT performance in SSV
    - Booklet final draft distributed to ICG and providers for final approval; planned publication: mid-2018
  - **Companion SSV Outreach Video** being produced by NASA on behalf of ICG
  - **Coordinated Outreach Initiative** to communicate capabilities of SSV to future SSV users
  - **ICG-approved Recommendation to examine use of GNSS SSV for exploration activities in cis-Lunar space**

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

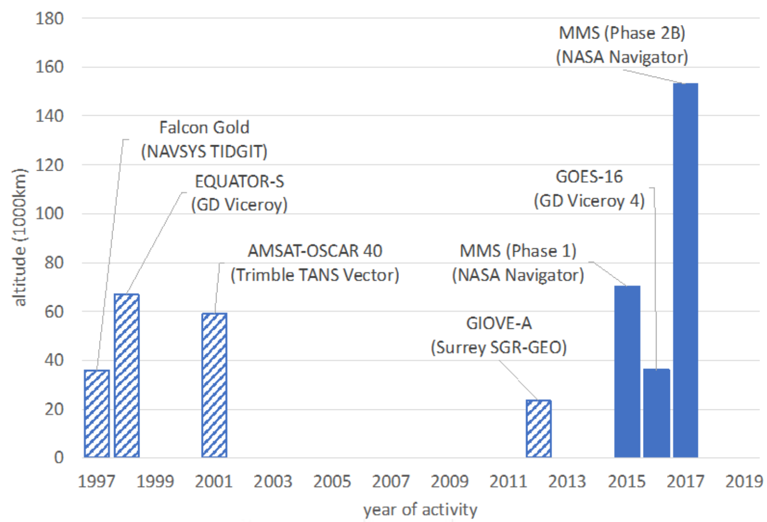
- These studies represent early GPS-only analyses that could be used as basis for WG-B in-depth analysis.

[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.

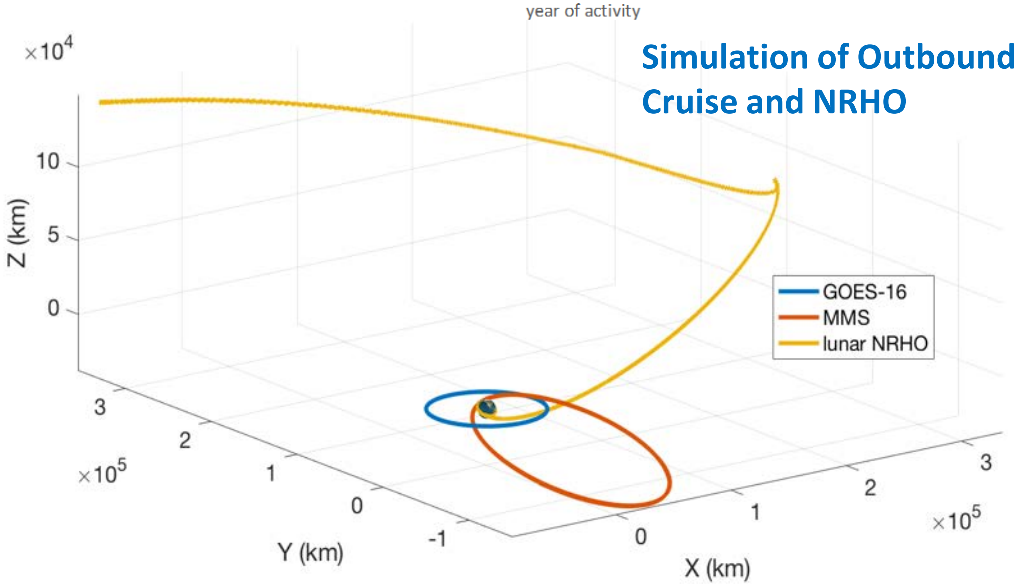
[2]Ashman, Benjamin W., Parker, Joel J. K., Bauer, Frank H., “Exploring the Limits of High Altitude GPS for Future Lunar Missions,” American Astronautical Society Guidance and Control Conference, Breckenridge, Colorado, USA, February 2–8, 2017.

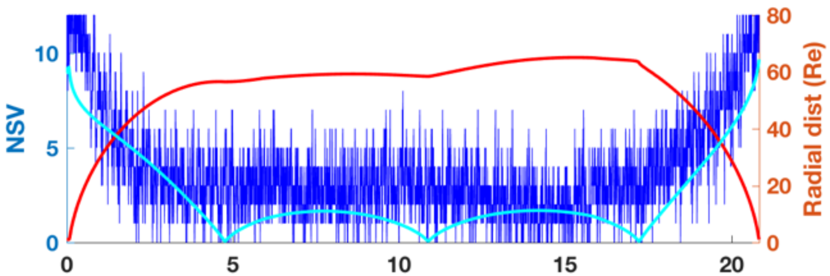
Recent Results: Lunar GPS

- In 2017 the NASA Navigator receiver on MMS tracked GPS signals at a distance of 153,000 km (40% of the way to the Moon)
- Simulations derived from MMS GPS and employing a high-gain antenna in a Lunar NRHO trajectory show that robust, accurate navigation is possible (~1km radial, ~100m lateral pos acc)
- A Near Rectilinear Halo Orbit (NRHO) is one of the proposed orbits for the NASA Lunar Orbiting Platform – Gateway



Simulation of Outbound Cruise and NRHO





MMS Simulation Results

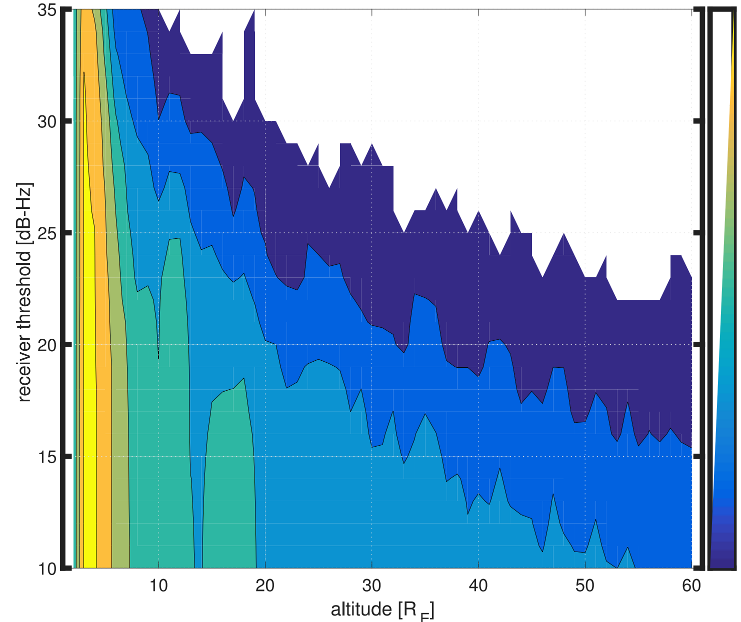
Recent Results: Lunar GPS

Lunar Simulation Results

- Outbound lunar NRHO GPS receiver reception 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 antenna gain or receiver sensitivity increases coverage significantly



Number of satellites visible by altitude and receiver threshold

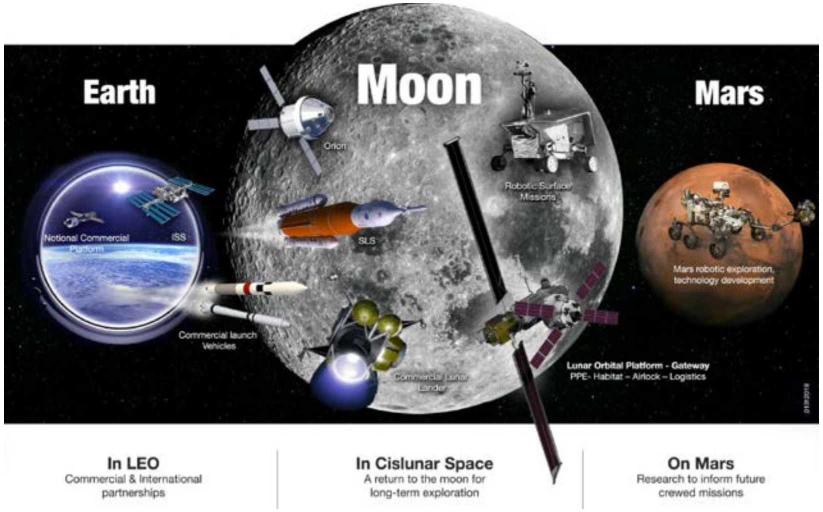
Conclusions

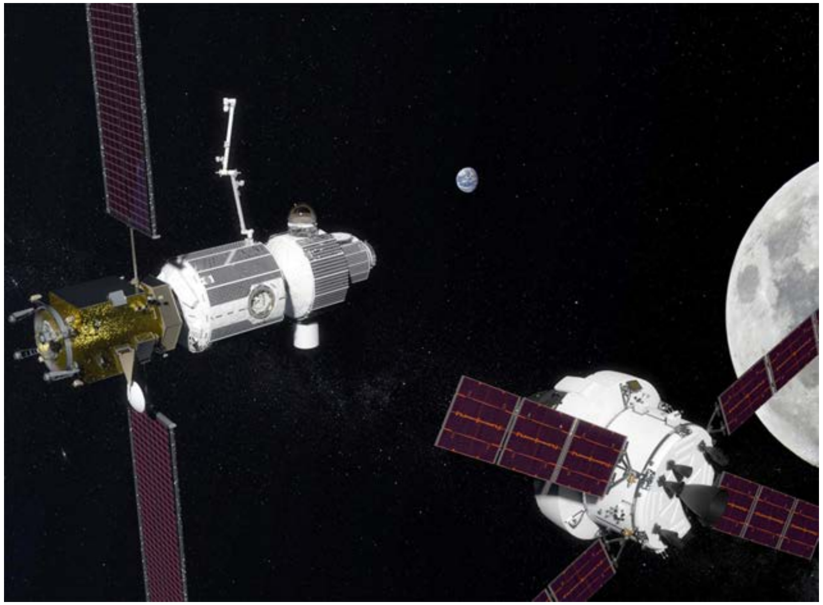
- GOES and MMS data have enabled the development of high altitude GPS simulation models that match flight data to within a few percent in overall visibility metrics
- These results show useful onboard GPS navigation at lunar distances is achievable *now* using *currently-available* signals and *flight-proven*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

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





US Proposal: Workshop on Future Directions for the SSV

- **Workshop Pre-work: ICG-13, X'ian, China;** Collect international inputs on future directions for the Multi-GNSS SSV in cislunar space and beyond
  - 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, Space Agencies, and Research Institutions
- **Workshop Venue (proposed):** NASA HQ, Washington, DC late January/early February, in conjunction with nearby ION ITM conference
- **Discussion to be held in WG-B intercessional meeting:**
  - Is this agreeable path forward for addressing ICG-12 Recommendation?
  - Is there interest by WG-B in participating in this discussion?
  - Discussion of scope of workshop and forward actions

GNSS SSV Observations and Forward Priorities

Observations:

- The International Committee on GNSS (ICG) WG-B is establishing an interoperable GNSS SSV through pre-work, analyses and meetings
- Efforts continue to enhance the ability for space users to employ navigation and timing in the SSV and beyond, by combining the capabilities of all GNSS and regional navigation systems into a multi-GNSS SSV
- Despite this, SSV users should not rely on **unspecified capabilities** from any particular GNSS
  - SSV capabilities that are currently available may not be available in the future unless they are documented in specifications for that GNSS

Forward Priorities:

GNSS service providers, supported by space agencies & research institutions encouraged to:

- Support SSV in future generation of satellites, preferably through the baseline of SSV specifications
- Measure and publish GNSS antenna gain patterns to support SSV understanding & use of the GNSS aggregate signal
- Share SSV user experiences and lessons learned to improve SSV responsiveness to emerging needs

Selected NASA GNSS Activities

MMS & GOES flight results

- Mission experiences continue to add to the operational knowledge base for high-altitude GPS
- NASA is interested in how best to leverage these experiences for community benefit

GARISS

- Demonstration of combined GPS/Galileo (L5/E5a) navigation receiver for on-orbit operations
- Hosted on NASA software-defined radio payload on ISS

Autonomous Flight Termination System

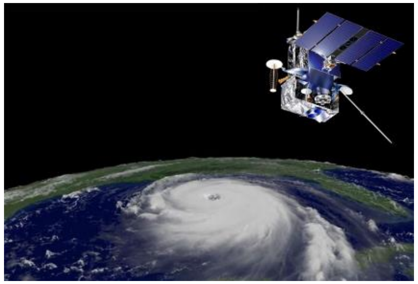
- Operational system utilizing GPS to automatically track and terminate off-nominal launches
- >25 operational launches to-date

IGS

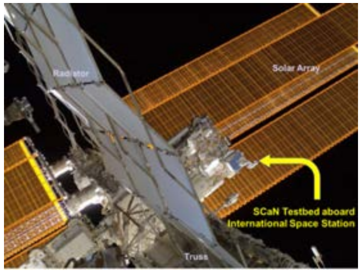
- Promotes and provides open and free access to high quality GNSS data and analysis products
- Recent change in Central Bureau Director after retirement of Ruth Neilan

Next-Generation Broadcast Service

- Concept for space user augmentation service broadcast by TDRSS
- Seeking Provider input on concept and services



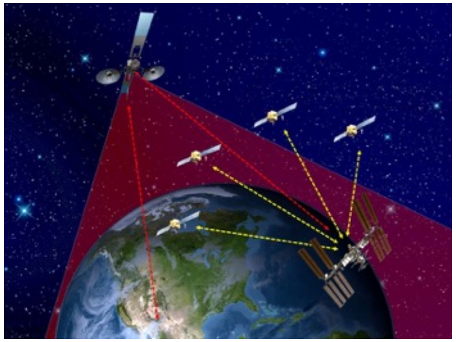
GOES



GARISS

AFTS

IGS



NGBS

Conclusions

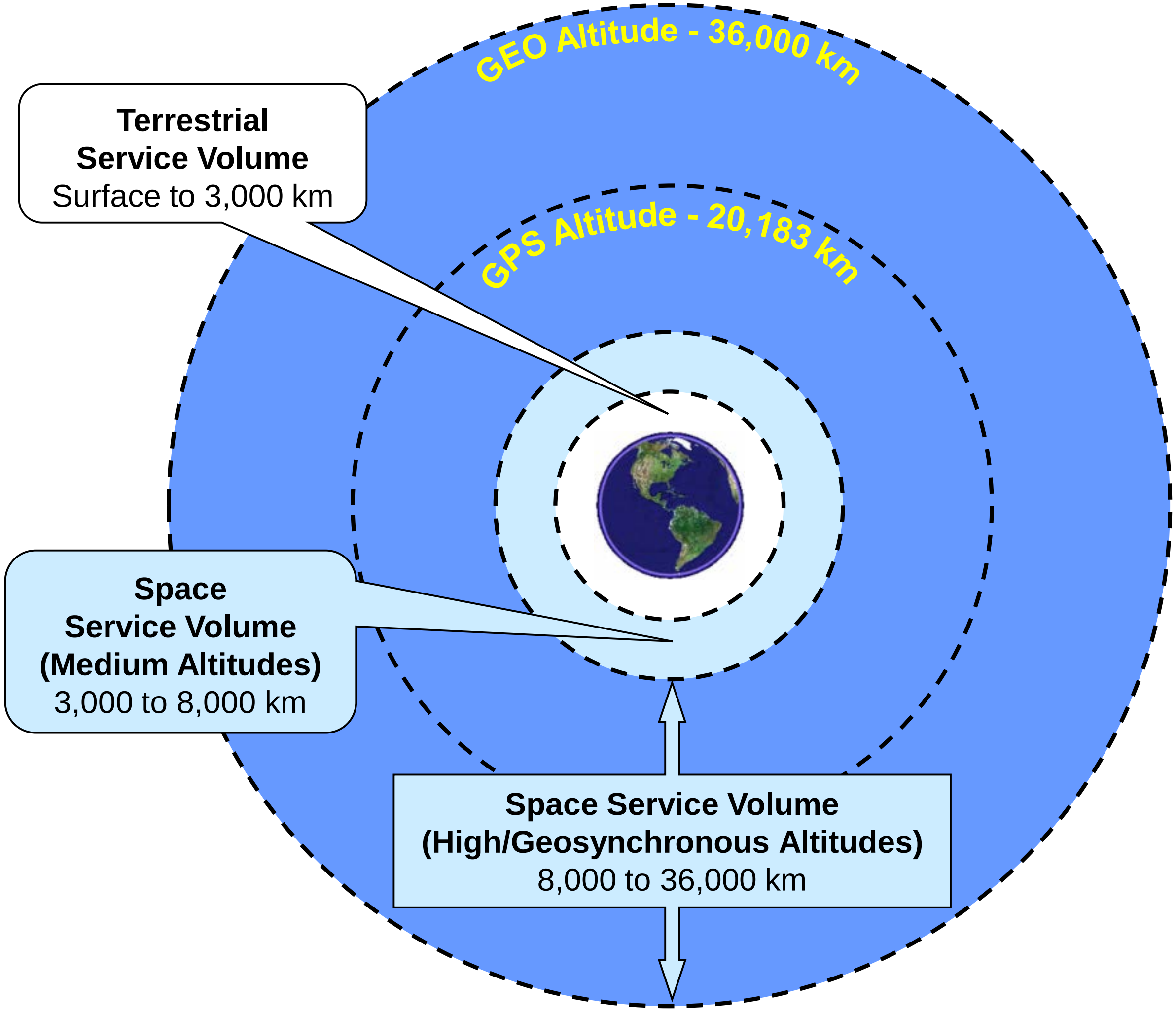
- The SSV, first defined for GPS Block IIF, **continues to evolve** to meet user needs. **GPS has led the way** with a formal specification for GPS Block III, requiring that GPS provides a core capability to space users
- Current and future space missions in the SSV are **becoming increasing reliant** on near-continuous GNSS availability to improve their mission performance
- Today, we **continue to work** to ensure that the SSV keeps pace with user demands, including its use throughout cislunar space:
  - Results derived from MMS and GOES data show useful onboard GPS navigation **at lunar distances** is achievable ***now*** using ***currently-available*** signals and ***flight-proven*** **receiver technology**.
  - 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.
- Developing and evolving an interoperable multi-GNSS SSV is a critical space utility, improving on-board PNT resilience and ensuring wider capabilities are available as needed
- NASA and the U.S. Government are **proud to work** with the GNSS providers to contribute making GNSS services more accessible, interoperable, robust, and precise for all users, for the **benefit of humanity**. We encourage all providers to continue to support this essential capability.

Backup Slides

Cislunar/Interplanetary Workshop Detailed Planning

- Conduct GNSS SSV Cislunar/Interplanetary Workshop
- Scoping:
  - How far is “beyond”?
  - What does it include? Cislunar space? Lagrange points? Mars/Interplanetary?
- Propose to conduct planning session during ICG-13 meeting in X’ian, China; workshop at NASA HQ late January/early February, in conjunction with ION ITM 2019
- 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; and depending upon definition of “beyond”:
    - 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)

Current GPS SSV Definition



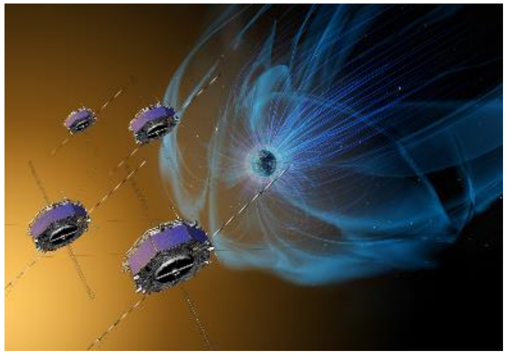
The GPS SSV is defined by three interrelated performance metrics for the SSV Medium Altitudes and the SSV High/Geosynchronous altitudes:

- Availability
- Minimum received power
- Pseudorange accuracy

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

Operational Users

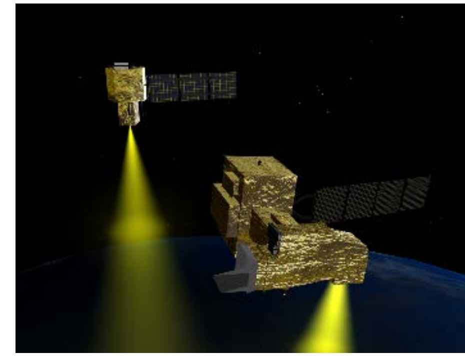
- MMS
- GOES-R, S, T, U
- EM-1 (Reentry)
- Satellite Servicing



Operational Use Demonstrates Future Need

Space Flight Experiments

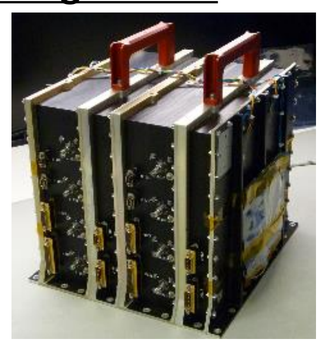
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar en-route)



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

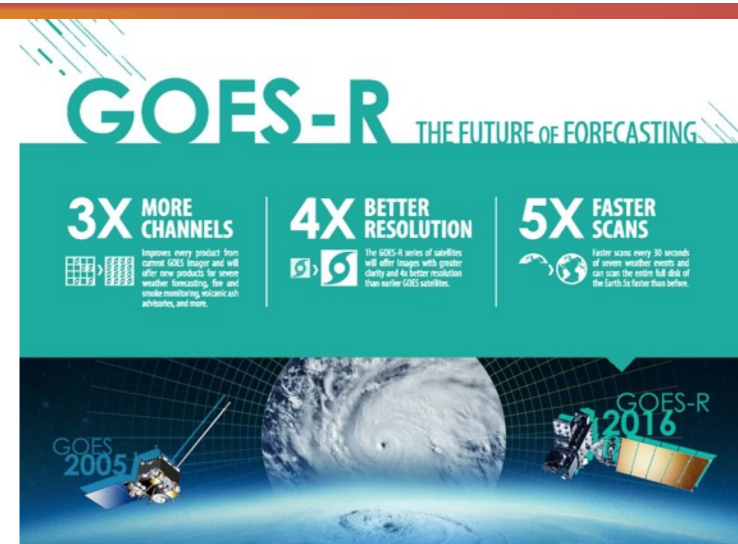
- SSV definition (GPS IIF)
- SSV specification (GPS III)
- ICG Multi-GNSS SSV common definitions & analyses

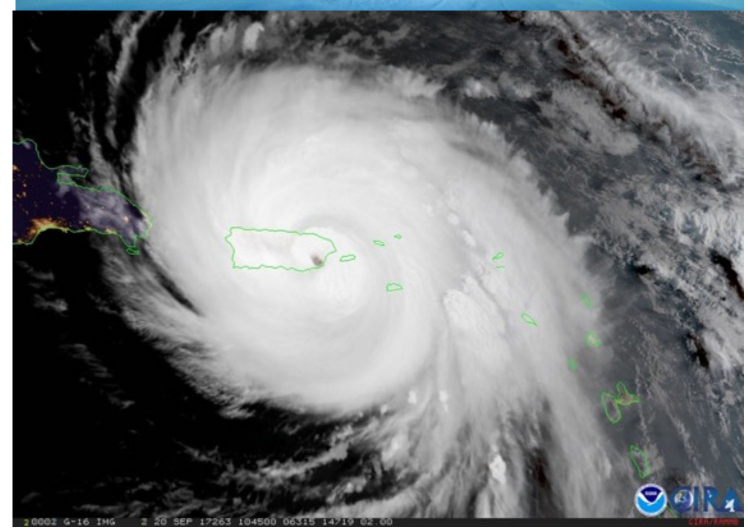
Operational Guarantees Through Definition & Specification

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

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



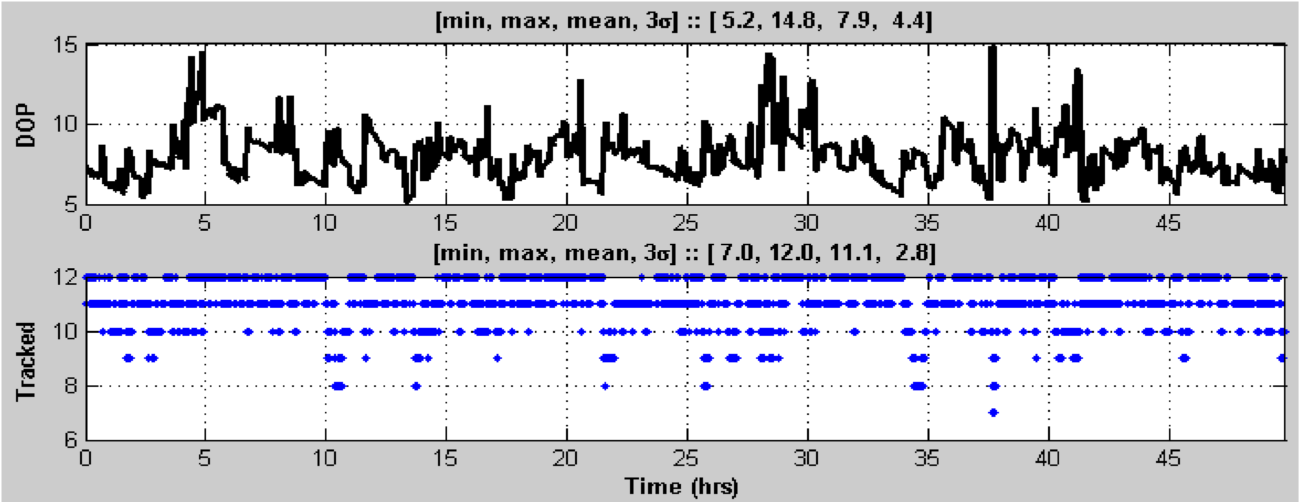


GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

GOES-R/GOES-16 In-Flight Performance

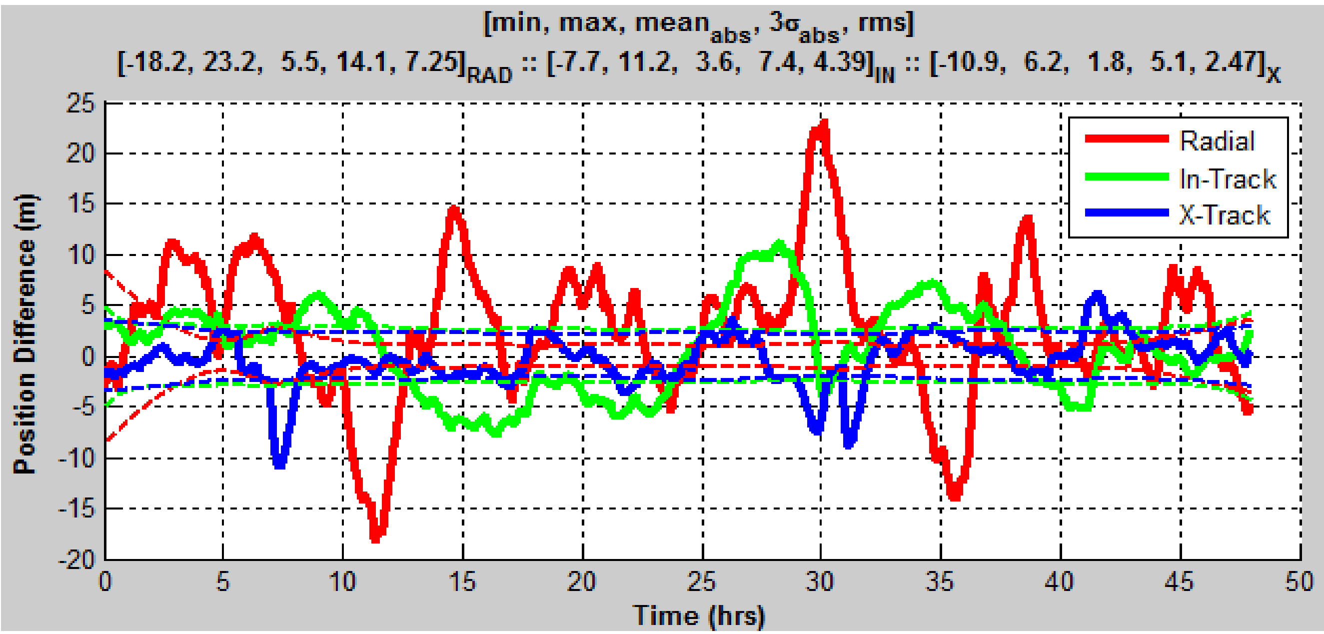
GPS Visibility

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



Navigation Performance

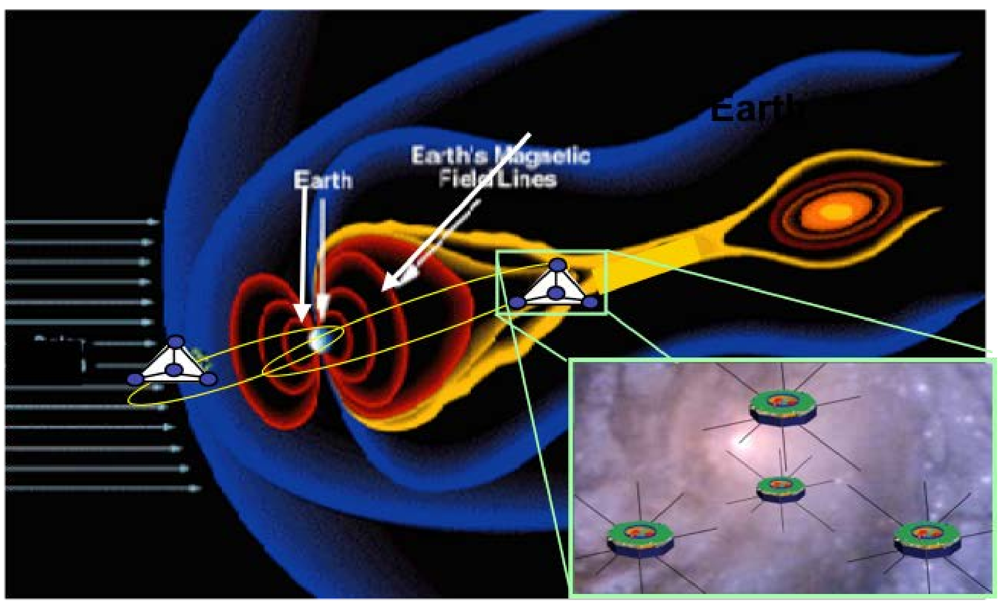
- 3σ position difference from smoothed ground solution (~3m variance):
  - Radial: 14.1 m
  - In-track: 7.4 m
  - Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m



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

NASA's Magnetospheric MultiScale (MMS) Mission

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



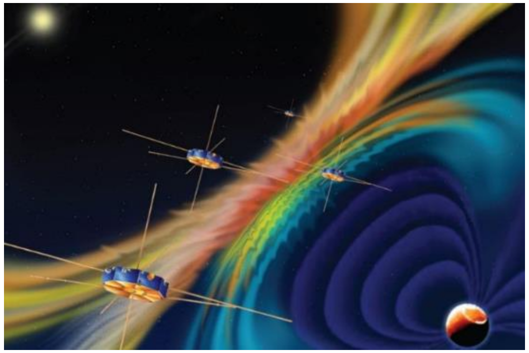
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

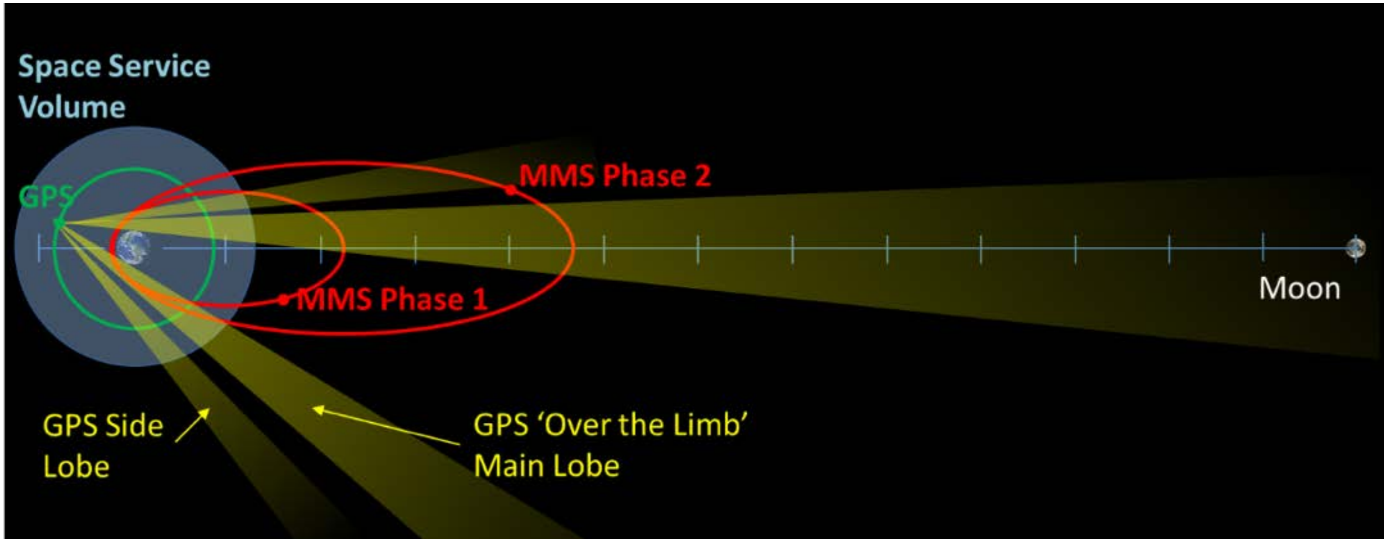
Magnetospheric Multi-Scale (MMS)

- 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 2: Extends apogee to 25 Re (~150,000 km) **(40% of way to Moon!)**

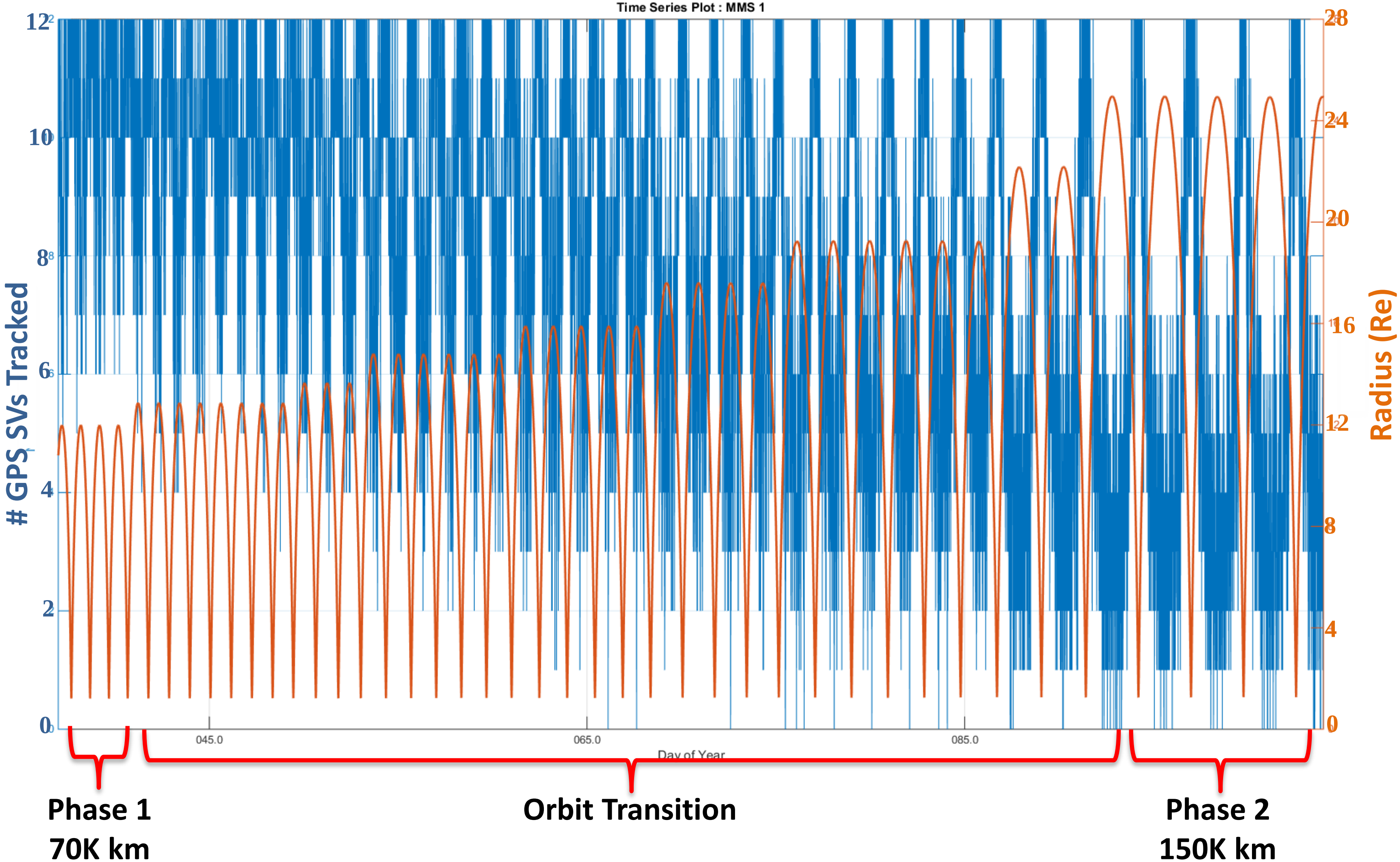
MMS Navigator System

- 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

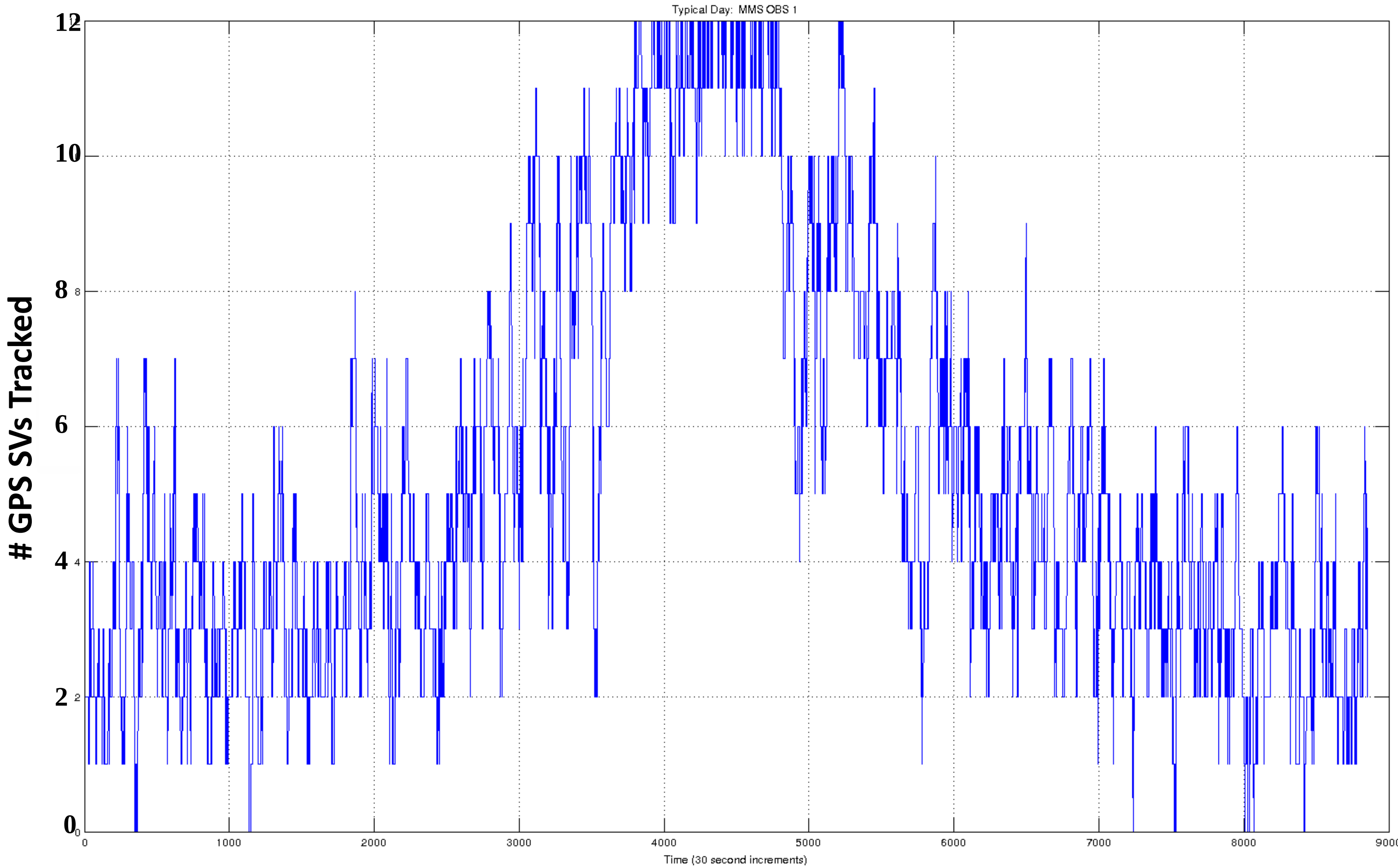




Signal Tracking Performance During Phase 1 to Phase 2 Apogee Raising (70K km to 150K km)



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

USAF –NASA Collaboration on SSV

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

IOAG-ICG Collaboration: 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)
- 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