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NASA Update: GNSS Space Service Volume Providers' Forum

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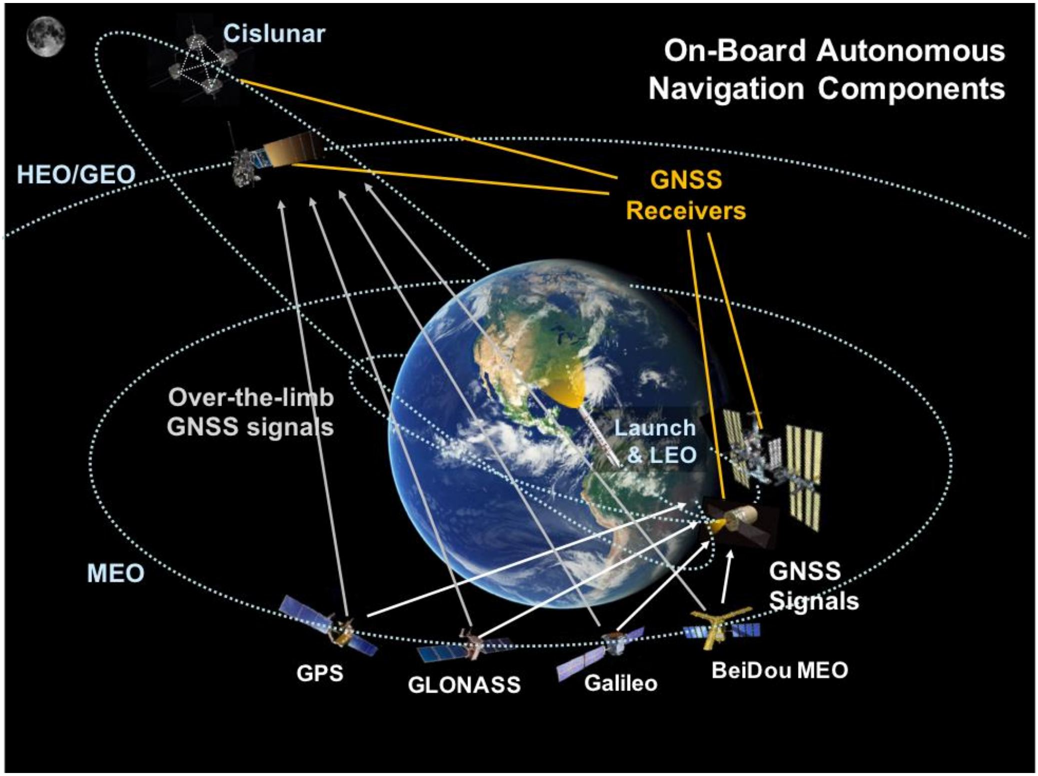
Human Exploration and Operations Mission Directorate (HEOMD), NASA

ICG-12, Kyoto, Japan, December 2, 2017

Benefits of GPS/GNSS to NASA

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



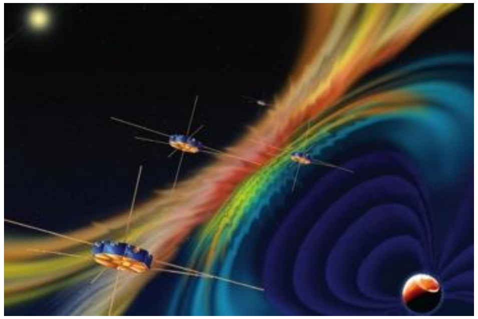
GPS capabilities to support space users will be further improved by pursuing compatibility and interoperability with GNSS

The Promise of using GNSS for Real-Time Navigation in the Space Service Volume

Benefits of GNSS use in SSV:

- 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 **HEO and GEO missions,** such as:

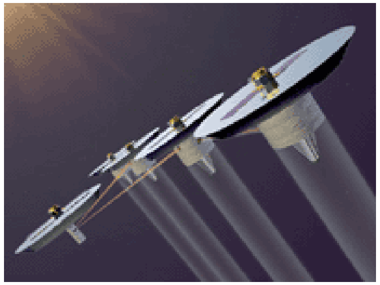
Earth Weather Prediction using Advanced Weather Satellites



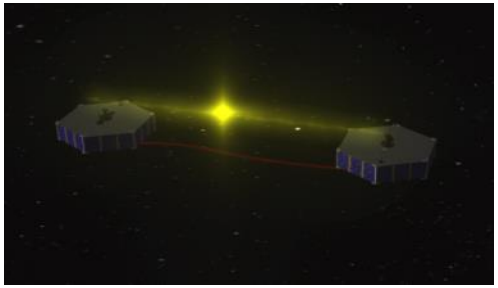
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



Formation Flying, Space Situational Awareness, Proximity Operations

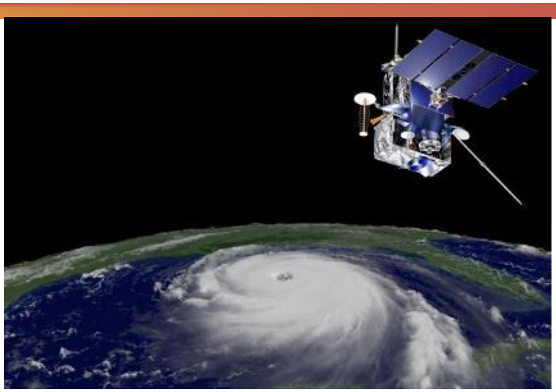


Precise Position Knowledge and Control at GEO

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

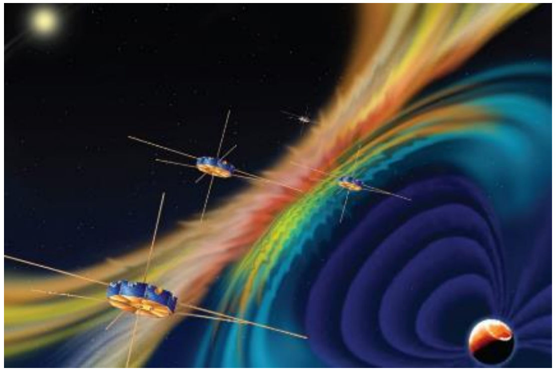
GOES-R Weather Satellite Series:

- Next-generation U.S. operational GEO weather satellite series
- 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 data products to substantially improve public and property safety



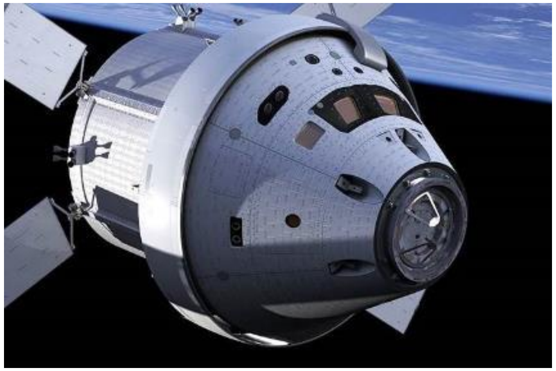
Magnetospheric Multi-Scale (MMS) Mission:

- 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
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping



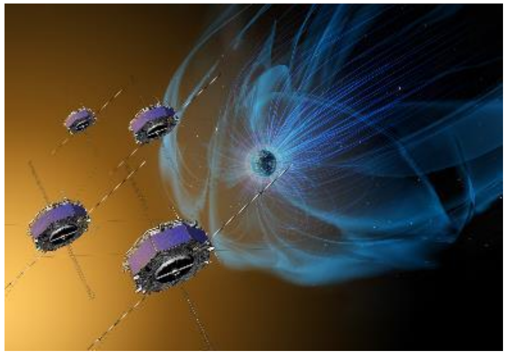
Exploration Mission 1 (EM-1):

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



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

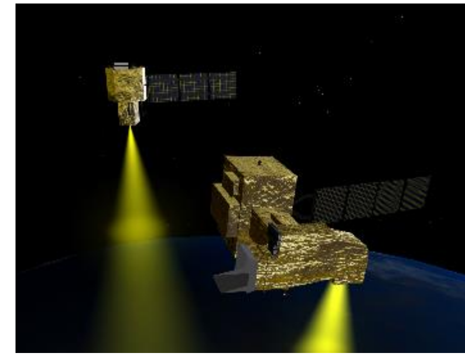
Operational Users



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

Operational Use Demonstrates Future Need

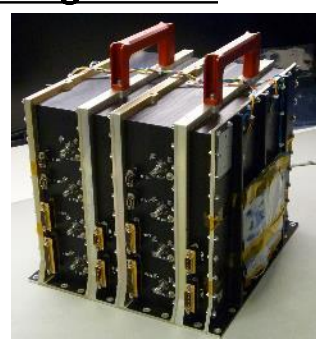
Space Flight Experiments



- 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

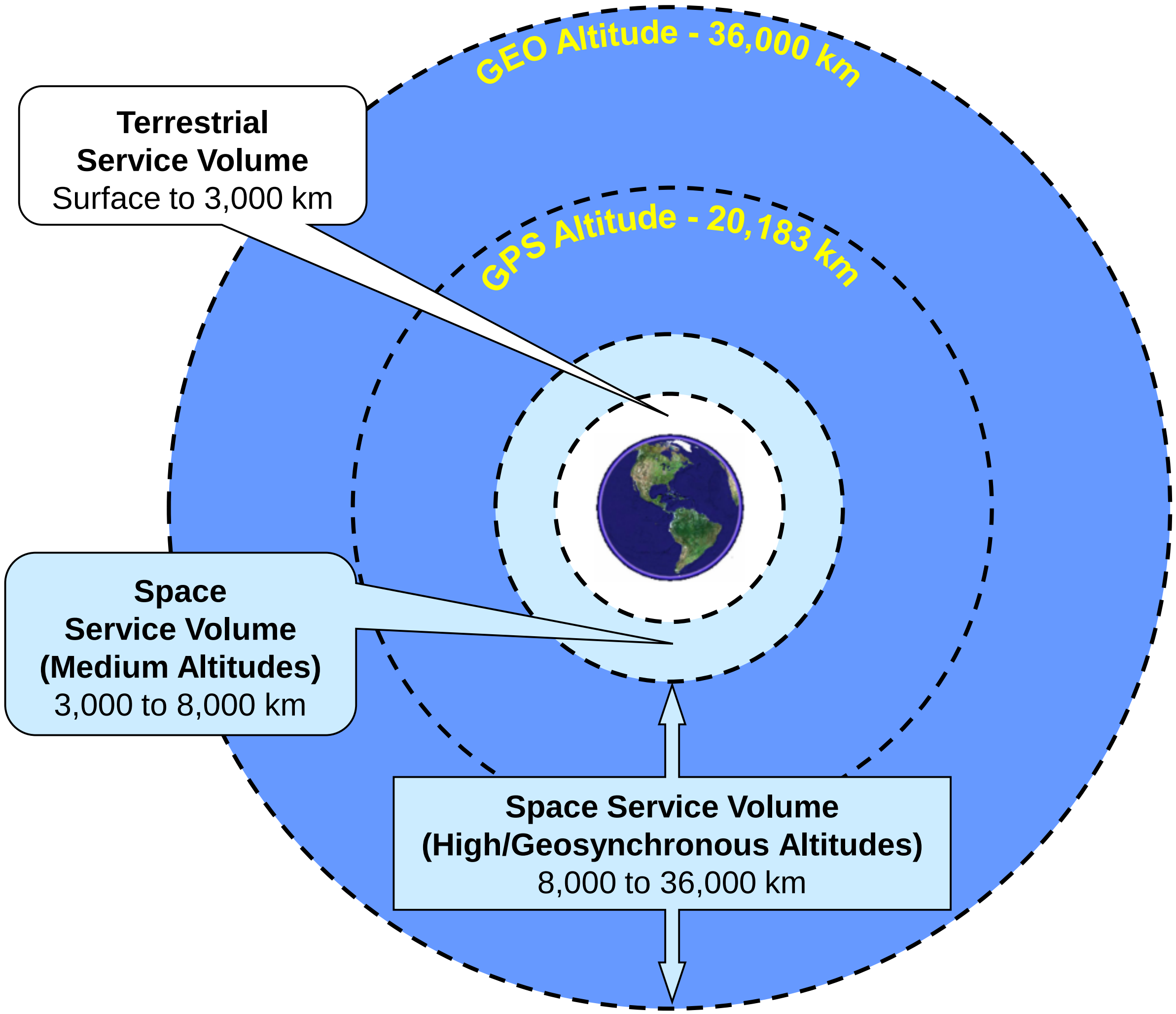
SSV Policy & Specifications

- 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

Current GPS SSV Definition

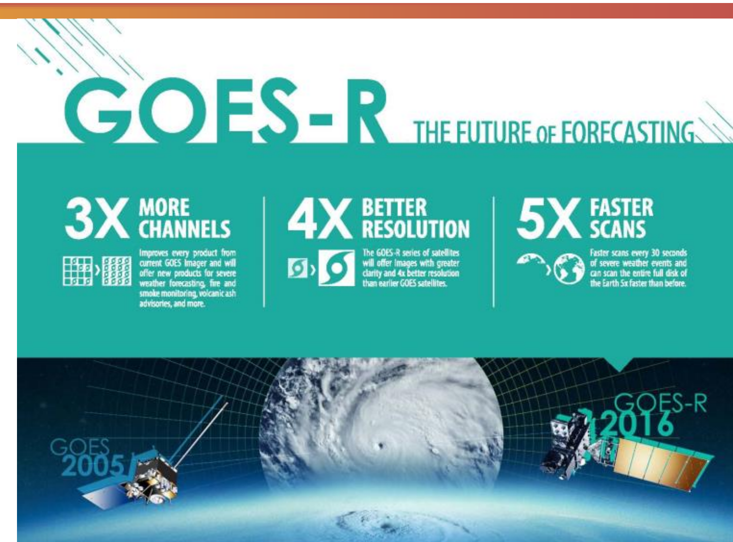


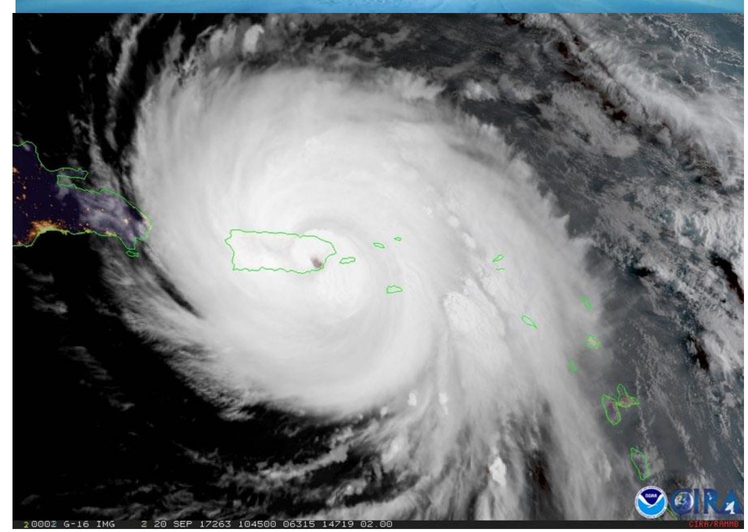
The GPS SSV is defined by three interrelated performance metrics for the SSV Medium Altitudes and the SSV High/Geosynchronous altitudes:

- Availability
- Minimum received power
- Pseudorange accuracy

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

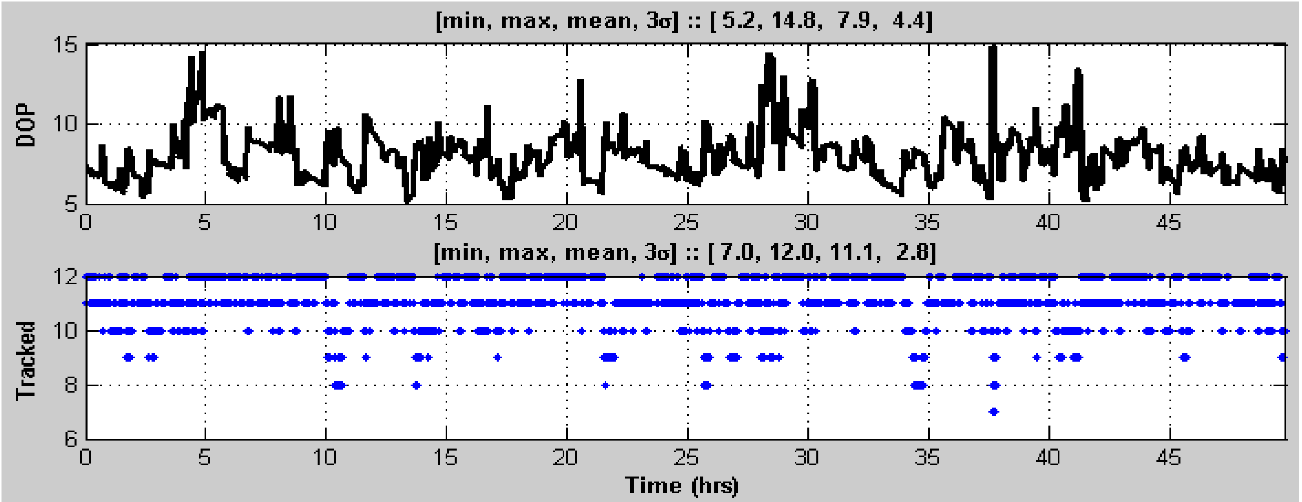




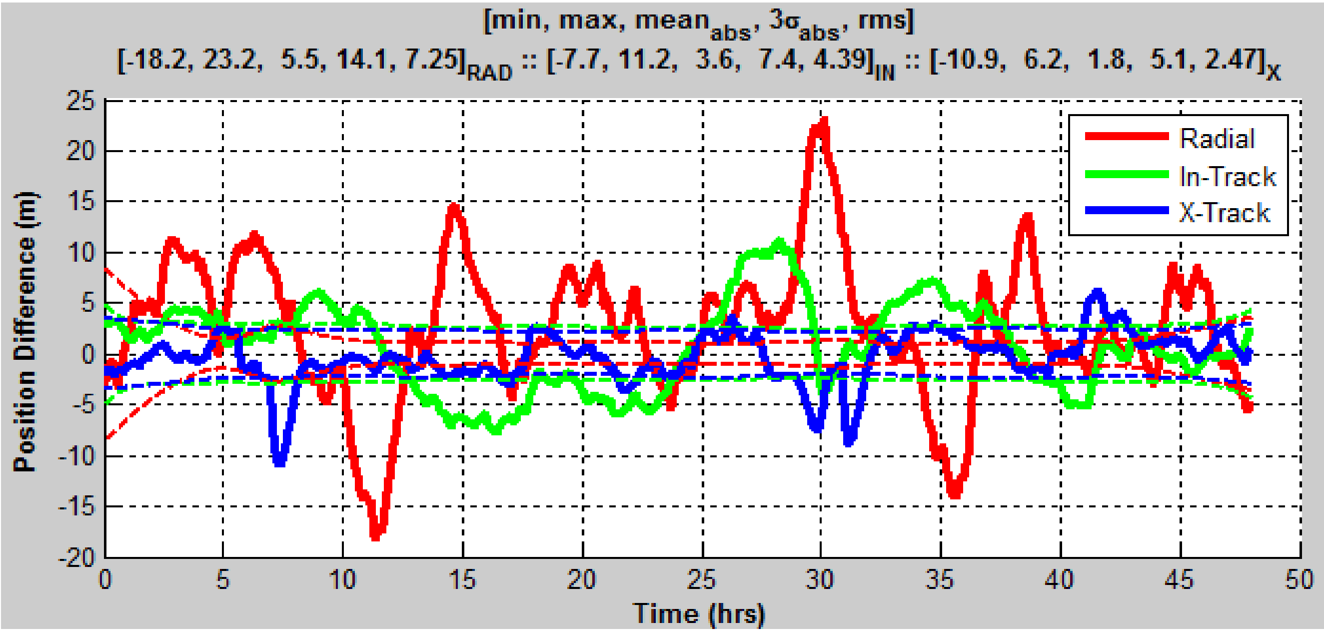
GOES-16 Image of Hurricane Maria Making Landfall over Puerto Rico

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)



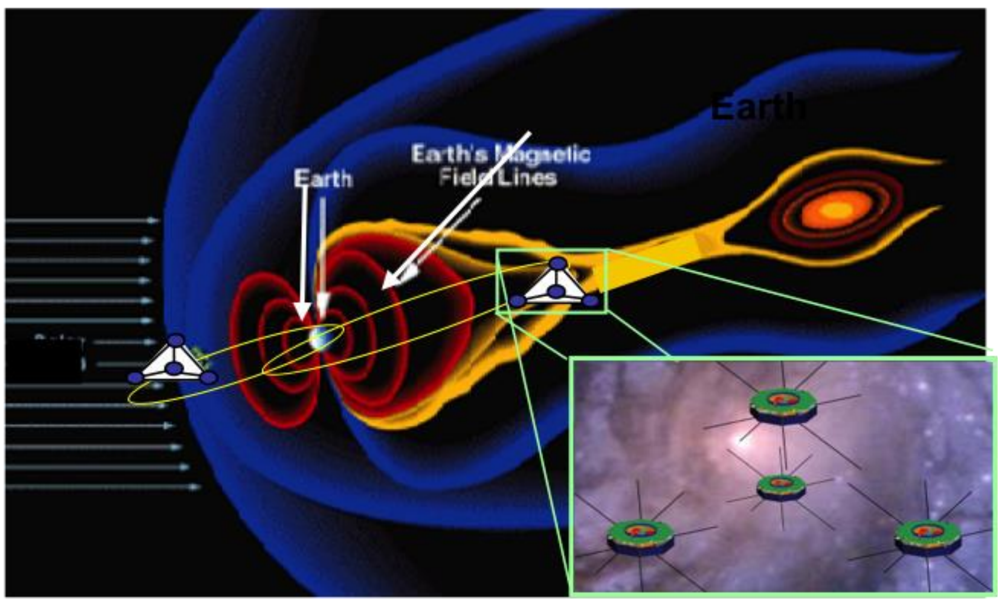
Navigation Performance
- 3σ position difference from smoothed ground solution (~3m variance):
  - Radial: 14.1 m
  - In-track: 7.4 m
  - Cross-track: 5.1 m
- Compare to requirement: (100, 75, 75) m



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**



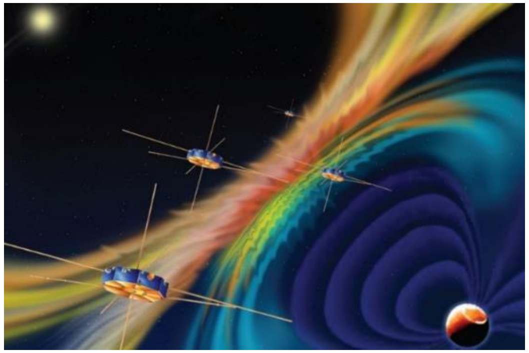
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

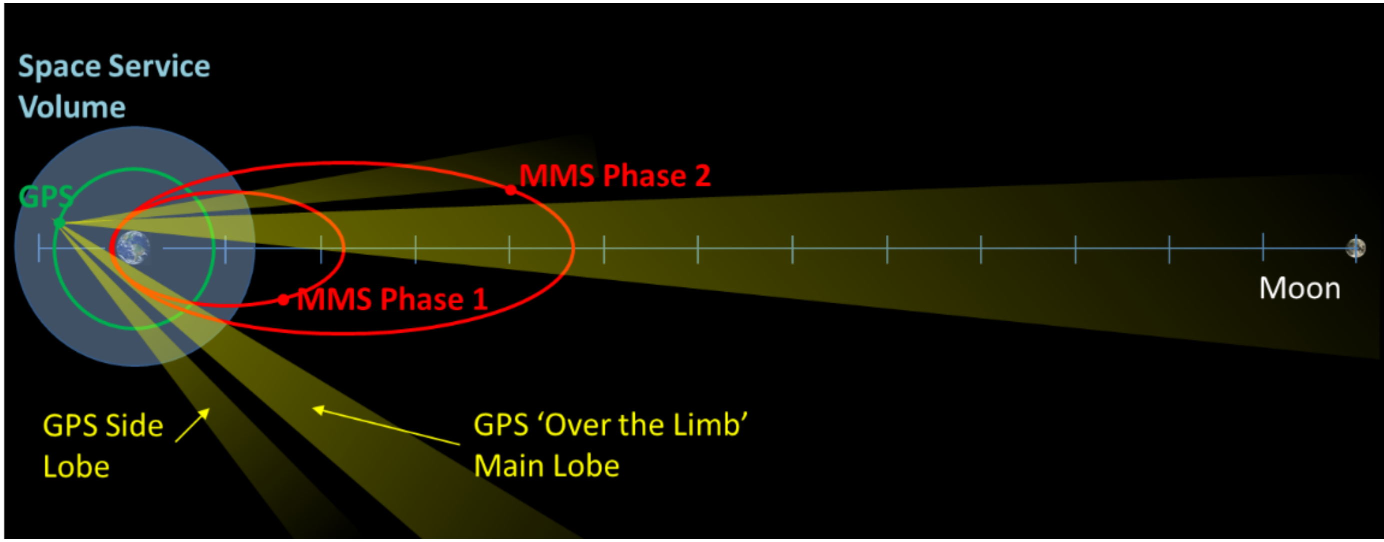
Magnetospheric Multi-Scale (MMS)

- 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!)**

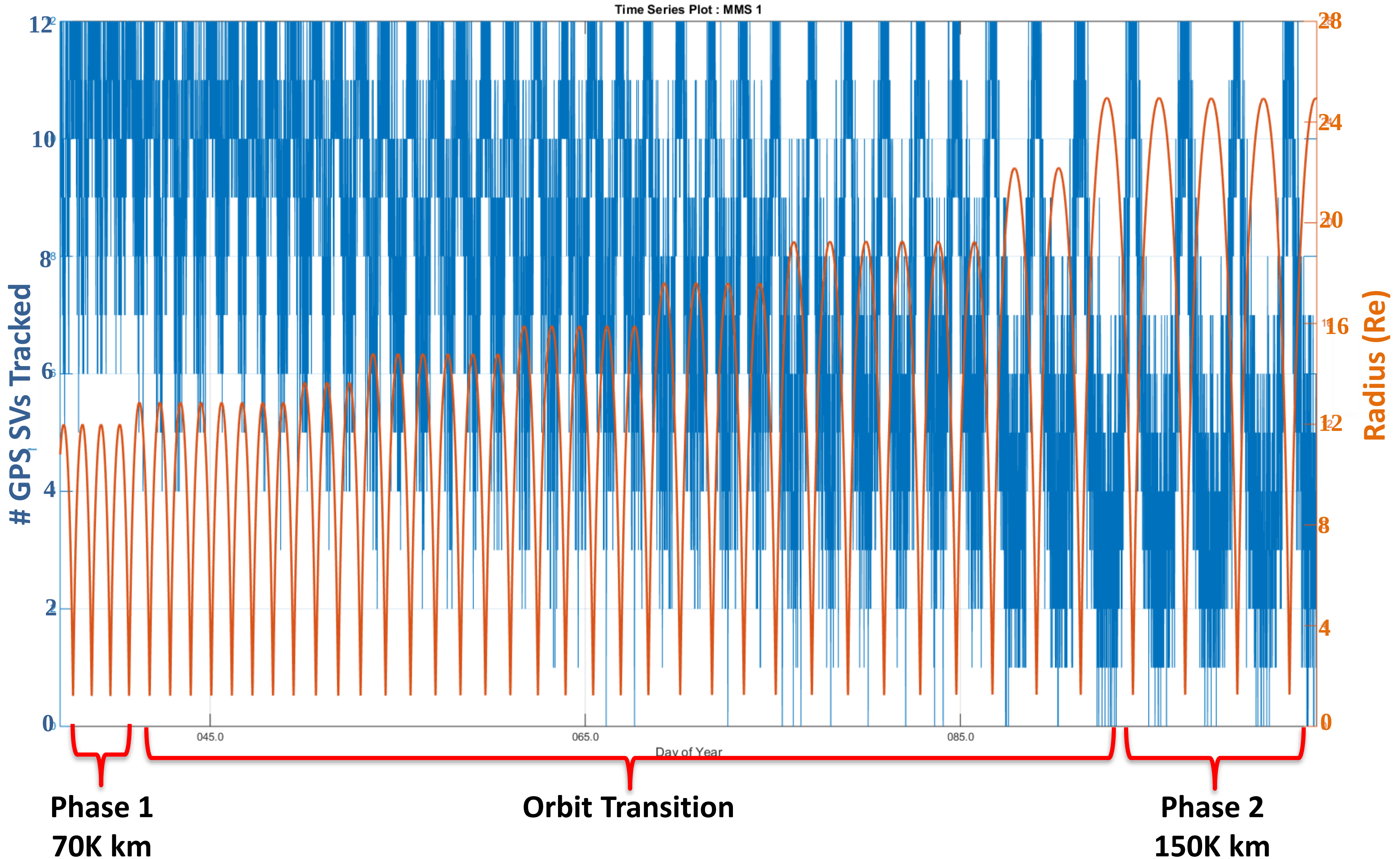
MMS Navigator System

- 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

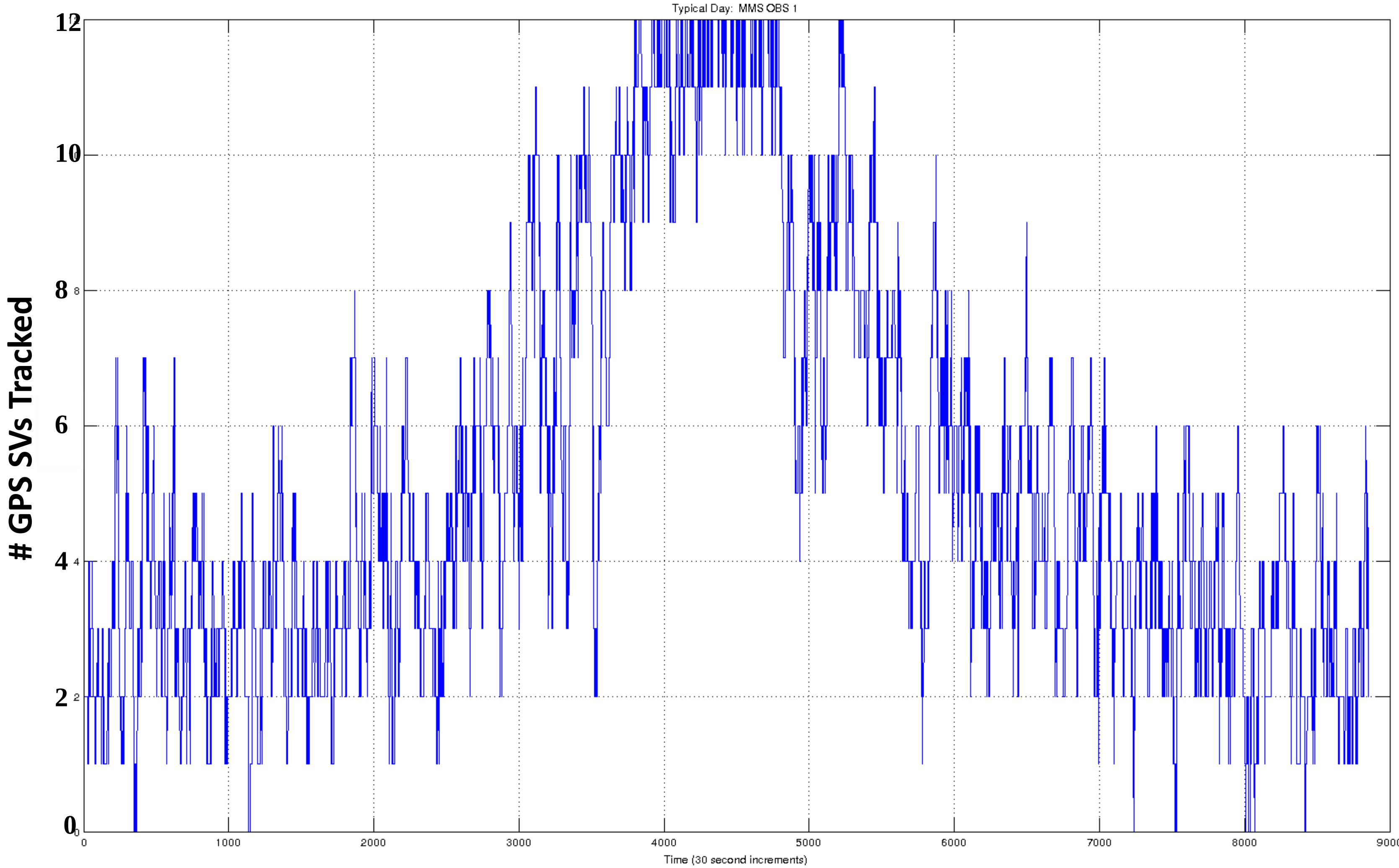




Signal Tracking Performance During Phase 1 to Phase 2 Apogee Raising (70K km to 150K km)



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

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
- Analyses are underway to solidify our understanding of an SSV that combines the capabilities of all GNSS and regional navigation systems
- 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

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:
  - For GPS, we are working with the Air Force to understand how future GPS block builds will continue to support the needs of emerging GPS-only users like the Geostationary Operational Environmental Satellite - R Series (GOES-R)
  - In partnership with foreign GNSS providers, we are working to characterize, analyze, document, and publish the capabilities of an **interoperable multi-GNSS SSV** with ultimate goal of provider specification
- **Both approaches** are equally critical: (1) a robust GPS capability enables and enhances new missions in applications that only rely on GPS signals; while (2) an interoperable GNSS SSV improves on-board PNT resilience and ensures that 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.