Keeping the universe connected.

Update on NASA GNSS Activities

18th Meeting of the Providers' Forum

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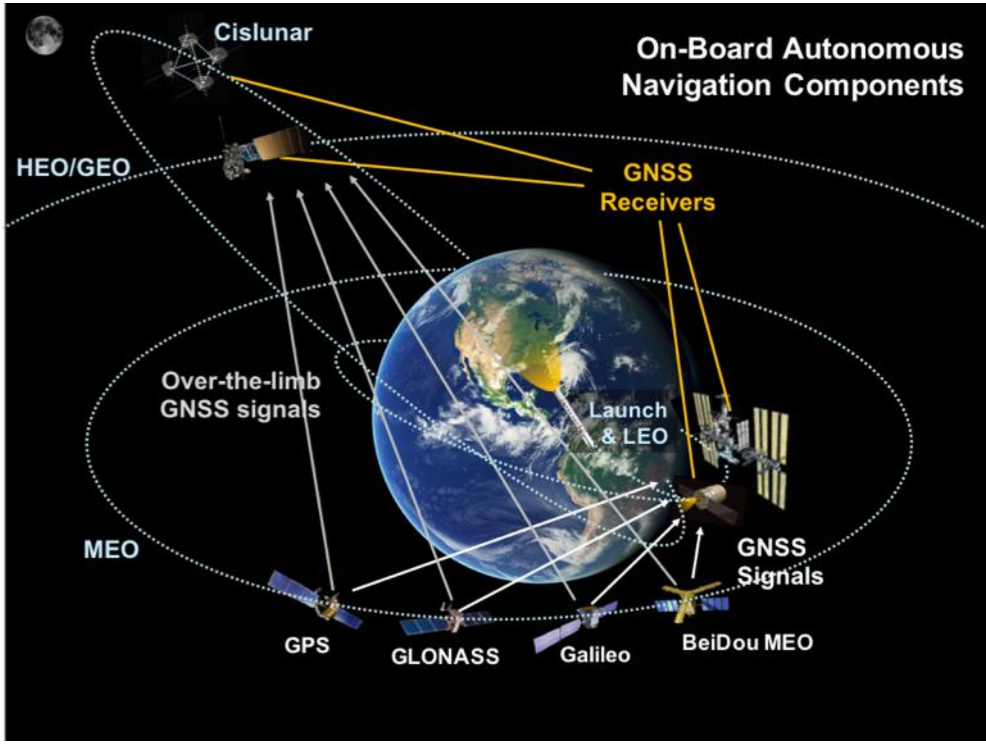
Vienna, Austria, June 6, 2017

Space Uses of Global Navigation Satellite Systems (GNSS)

- **<u>Real-time On-Board Navigation:</u>** Enables new methods of spaceflight ops such as precision formation flying, rendezvous & docking, station-keeping, Geosynchronous Orbit (GEO) satellite servicing
- **<u>Earth Sciences:</u>** GPS used as a remote sensing tool supports atmospheric and ionospheric sciences, geodesy, and geodynamics -- from monitoring sea levels & ice melt to measuring the gravity field
- **<u>Launch Vehicle Range Operations:</u>** Employs GPS to support launch vehicle flight termination function, providing safety net to people/property during launch failures & enabling higher cadence launch facility use
- **<u>Attitude Determination:</u>** Use of GPS/GNSS enables some missions to meet their attitude determination requirements, such as the International Space Station (ISS)



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

Automatic Flight Termination System (AFTS)

April 2006: WSMR Sounding Rocket

- 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)

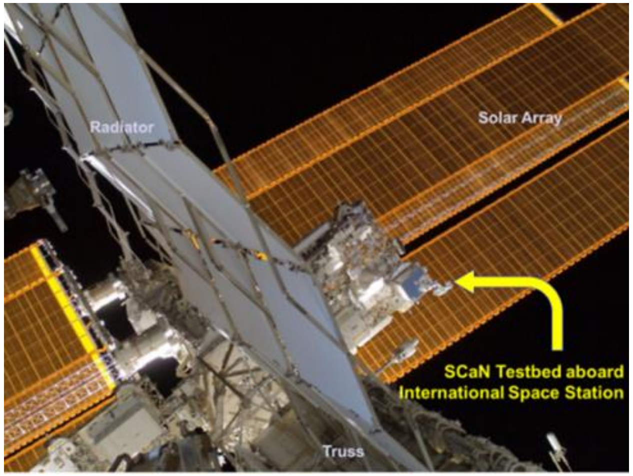
Mar 2007: SpaceX F1

Sept 2010: WFF Sounding Rocket

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

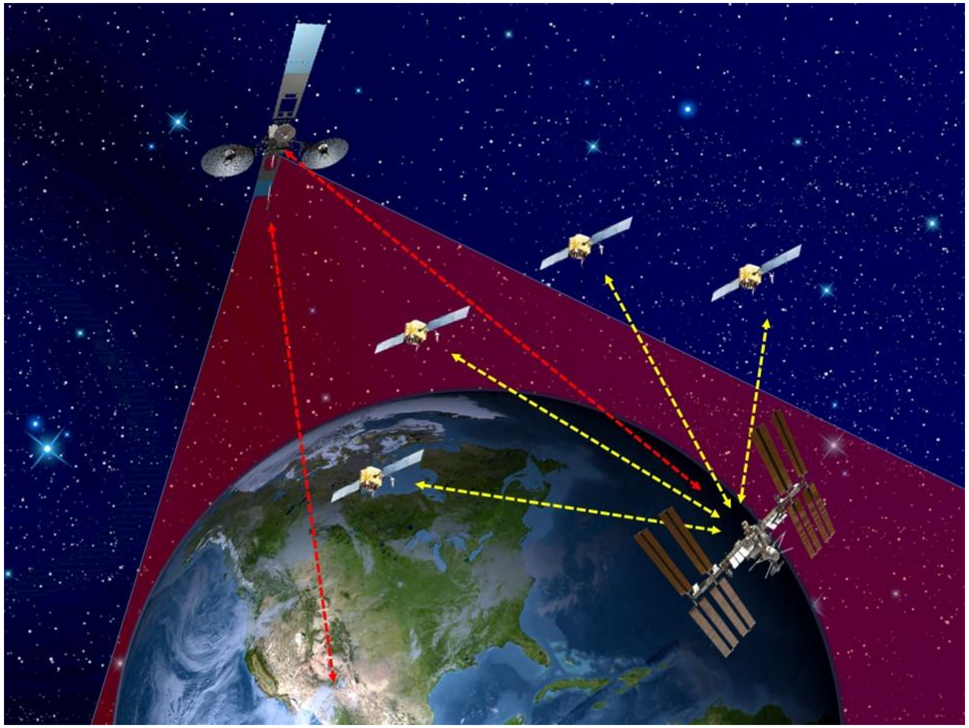
GAlileo Receiver for the ISS (GARISS)

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



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:

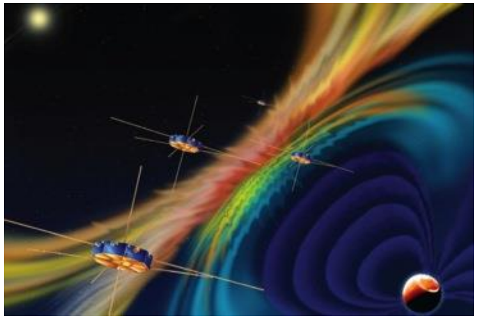
- **Science/payload missions**
- **SCaN/Network operations**
- **TDRSS performance**
- **GPS and TDRSS onboard navigation users**
- **Conjunction Assessment Risk Analysis**
- **Capabilities consistent with the modern GNSS architecture**

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

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

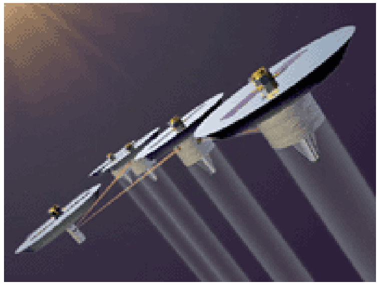
Earth Weather Prediction using Advanced Weather Satellites



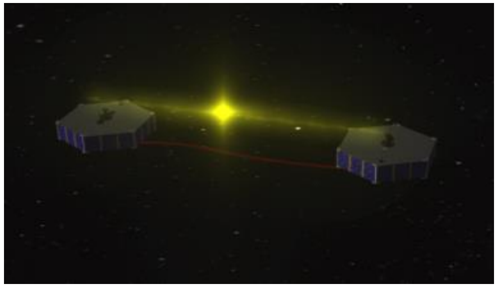
Space Weather Observations

Precise Relative Positioning

Launch Vehicle Upper Stages and Beyond-GEO applications



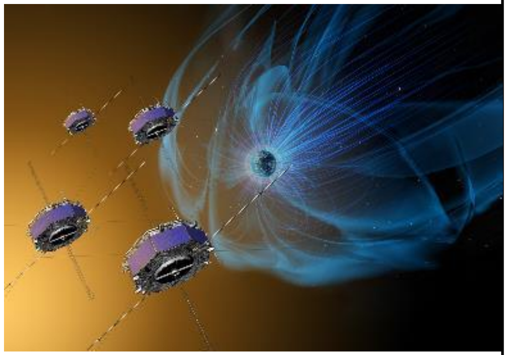
Formation Flying, Space Situational Awareness, Proximity Operations



Precise Position Knowledge and Control at GEO

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

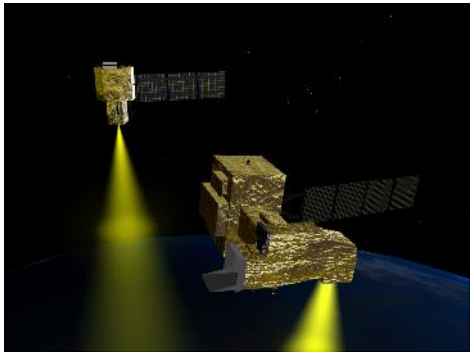
Operational Users



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

Operational Use Demonstrates Future Need

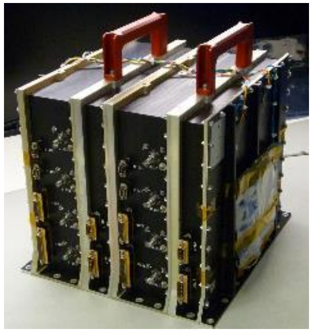
Space Flight Experiments



- 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

GOES-R THE FUTURE OF FORECASTING

3X MORE CHANNELS

Improves every product from current GOES Imager and will offer new products for severe weather forecasting, fire and smoke monitoring, volcanic ash advisories, and more.

4X BETTER RESOLUTION

The GOES-R series of satellites will offer images with greater clarity and 4x better resolution than earlier GOES satellites.

5X FASTER SCANS

Faster scans every 30 seconds of severe weather events and can scan the entire full disk of the Earth 5x faster than before.

GOES-R Navigation Needs

- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- Launch: 19 Nov 2016, 15-year life
- Driving requirements:
  - **Orbit position knowledge** requirement (right)
  - All performance requirements **applicable through maneuvers**, **<120 min/year** allowed exceedances
  - Stringent **navigation stability** requirements
  - Requirements unchanged for GOES-S, -T, -U

Parameter	Requirement (m, 3-sigma)
Radial	100
In-track	75
Cross-track	75

- GOES-R **cannot** meet stated mission requirements with basic SSV coverage as currently documented.
- Like other high-altitude users, relies on existing beyond-spec GPS sidelobe signals to increase SSV performance.
- NOAA also identifies **EUMETSAT (EU) and Japanese weather satellites** as reliant on increased GNSS signal availability in the SSV.

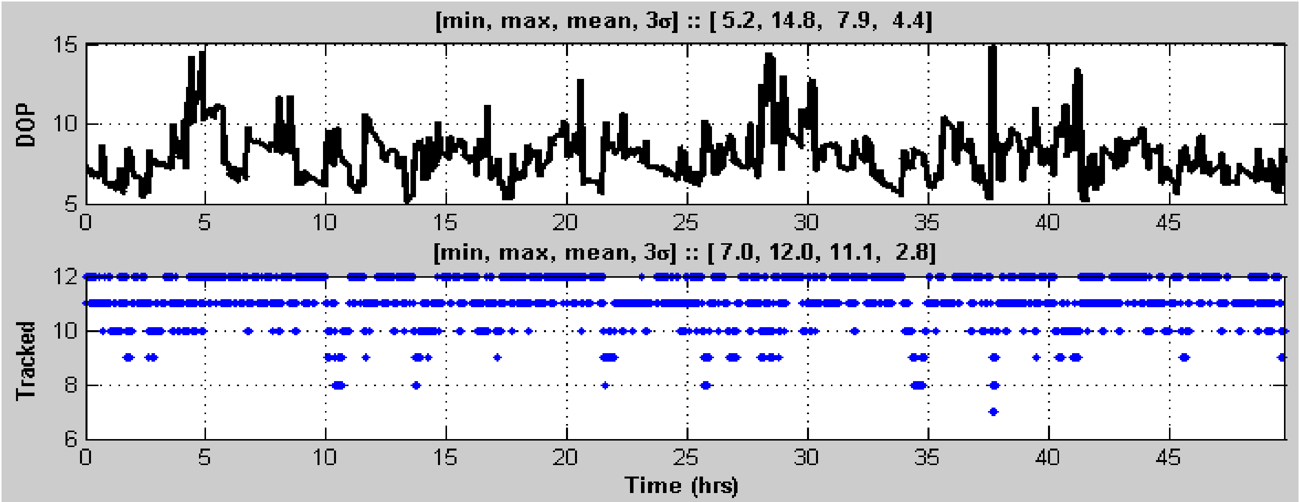
GOES-R In-Flight Performance

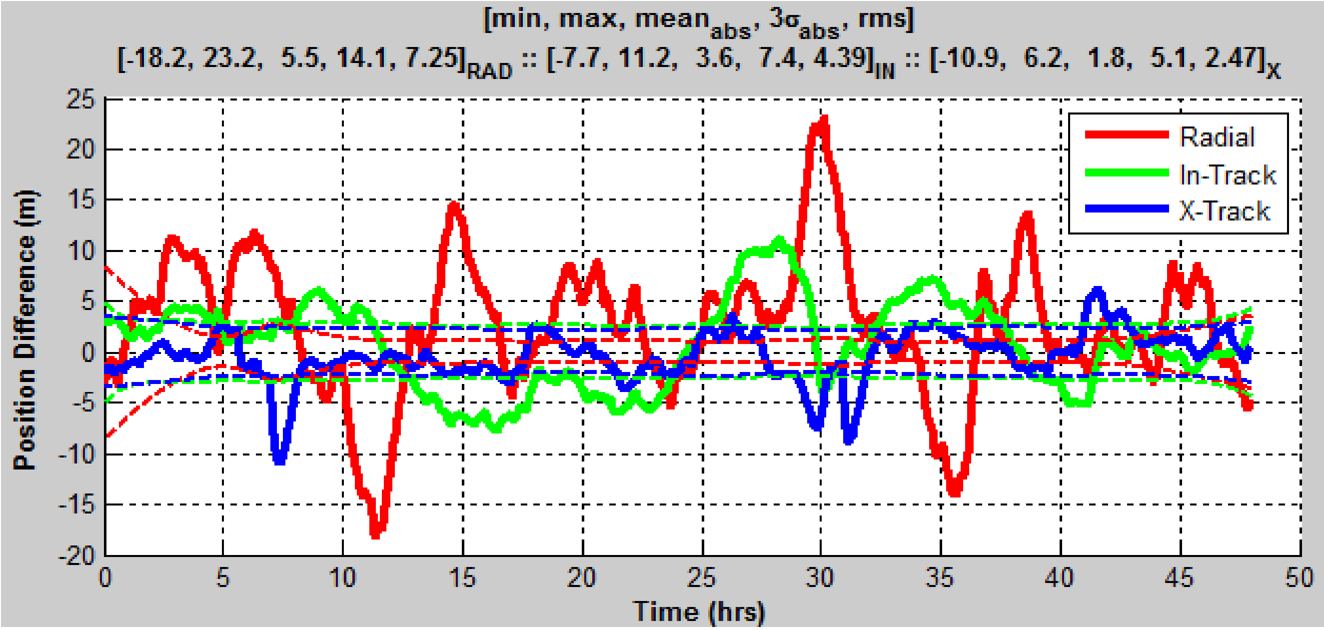
GPS Visibility

- 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

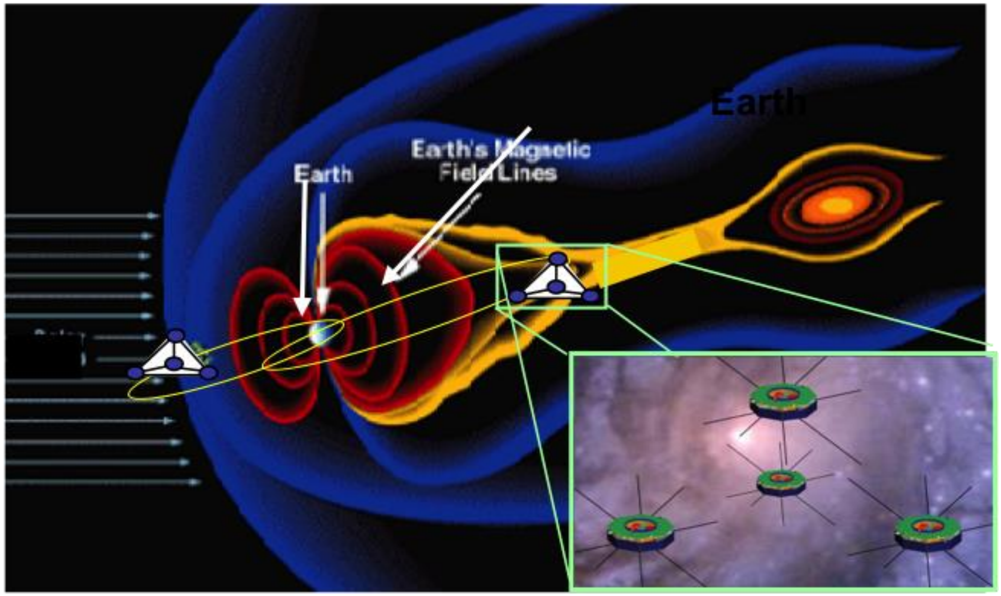




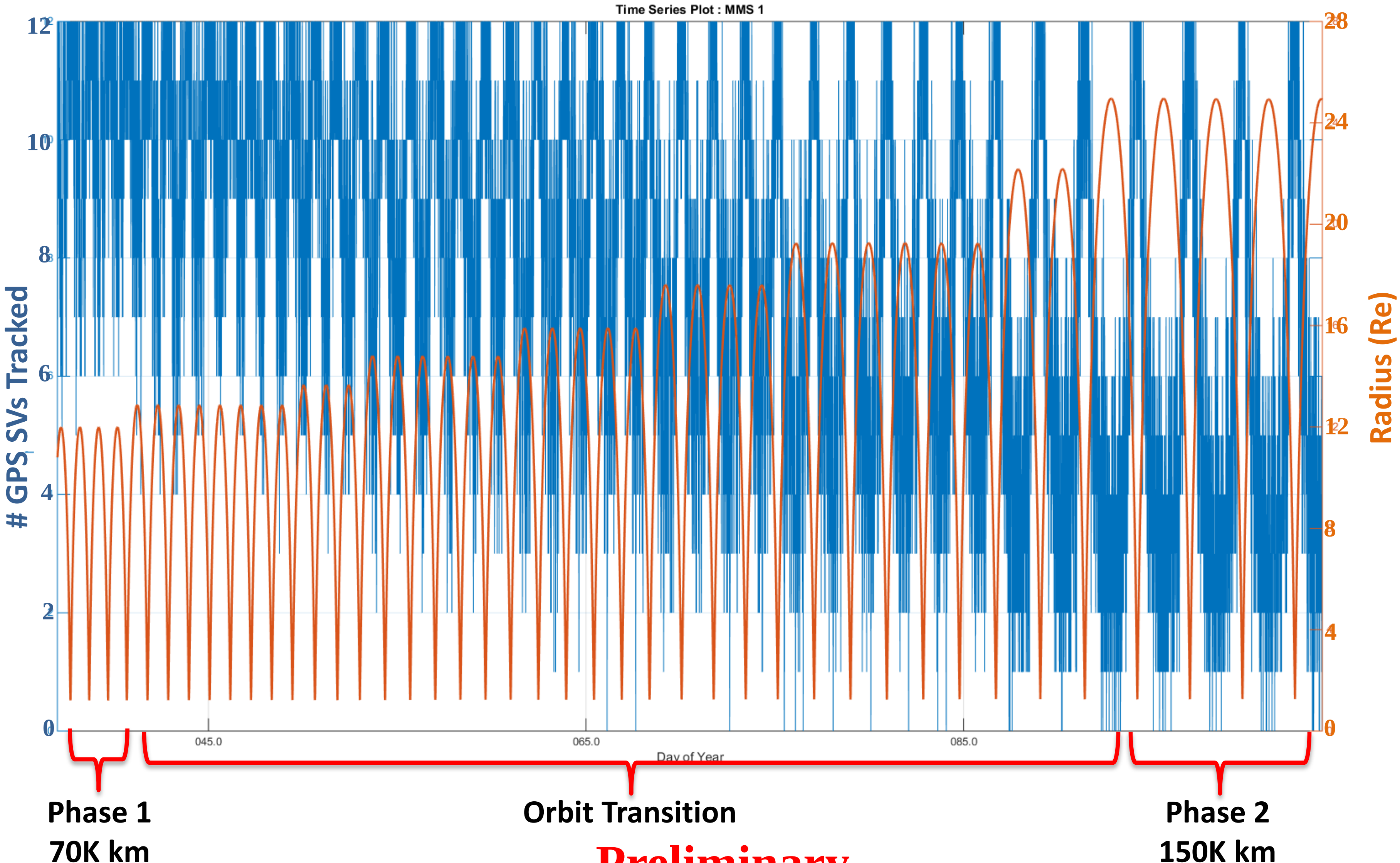
Source: Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," ESA GNC 2017, 29 May-2 Jun 2017, Salzburg, Austria.

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



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



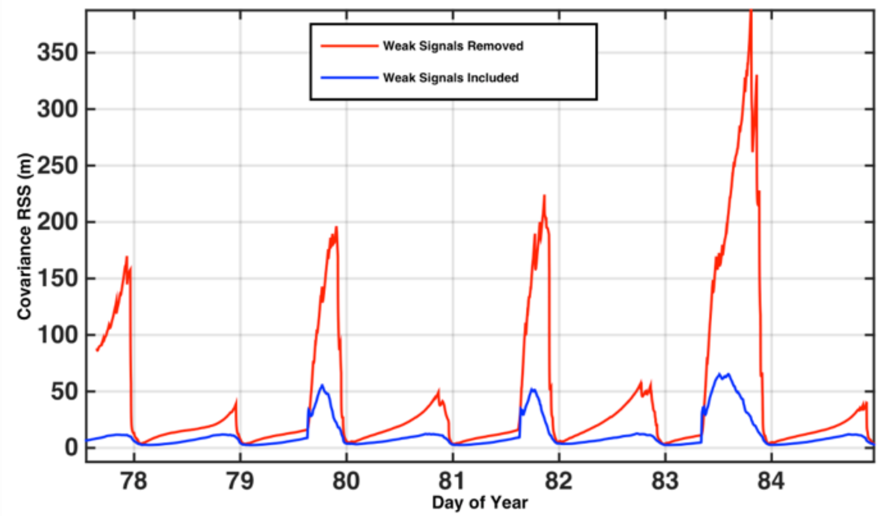
Preliminary

Records are Meant to be Broken

- Oct 20, 2016: Guinness World Record awarded to NASA's Magnetospheric MultiScale (MMS) mission for the highest-altitude GPS fix ever recorded: 70,135 km (2x geostationary altitude)
- 2017: MMS apogee raise to 150,000 km
  - GPS navigation solutions achieved at 24.4 Re
  - Now ~40% of the way to the moon at apogee
  - New record to follow?

GOES-R & 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)

Conclusions

- NASA finds multi-GNSS Space Service Volume critical to supporting advanced uses of GNSS at high altitude, as compared to single constellation use
  - MMS and GOES-R demonstrate the positive impact of technology and policy investments in the SSV.
  - NASA is strongly supportive of WG-B SSV analysis and publication activities.
- NASA technology development activities show strong investment in multi-GNSS future for civil space users
  - NASA activities (e.g. GARISS) represent outstanding USA/international partnerships that will extend our GNSS understanding and signal utility
  - The Next Generation Broadcast Service (NGBS) introduces a critical level of resiliency to GNSS and augments data and signals to further improve PNT
  - The Automatic Flight Termination System (AFTS) improves Launch Range use, reduces launch costs and improves the safety of people and property
- We encourage GNSS providers to consider and report on these ideas and others to further enhance global support and utility of the interoperable GNSS in space