NASA Update on GPS/GNSS Initiatives for Enhanced Space Operations and Science

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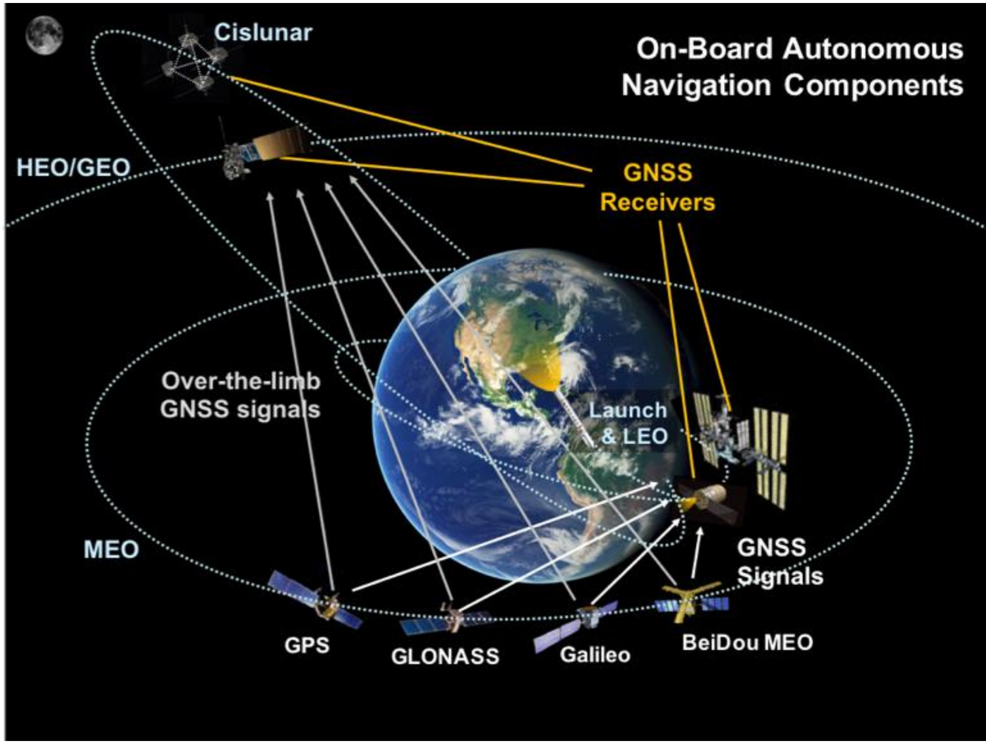
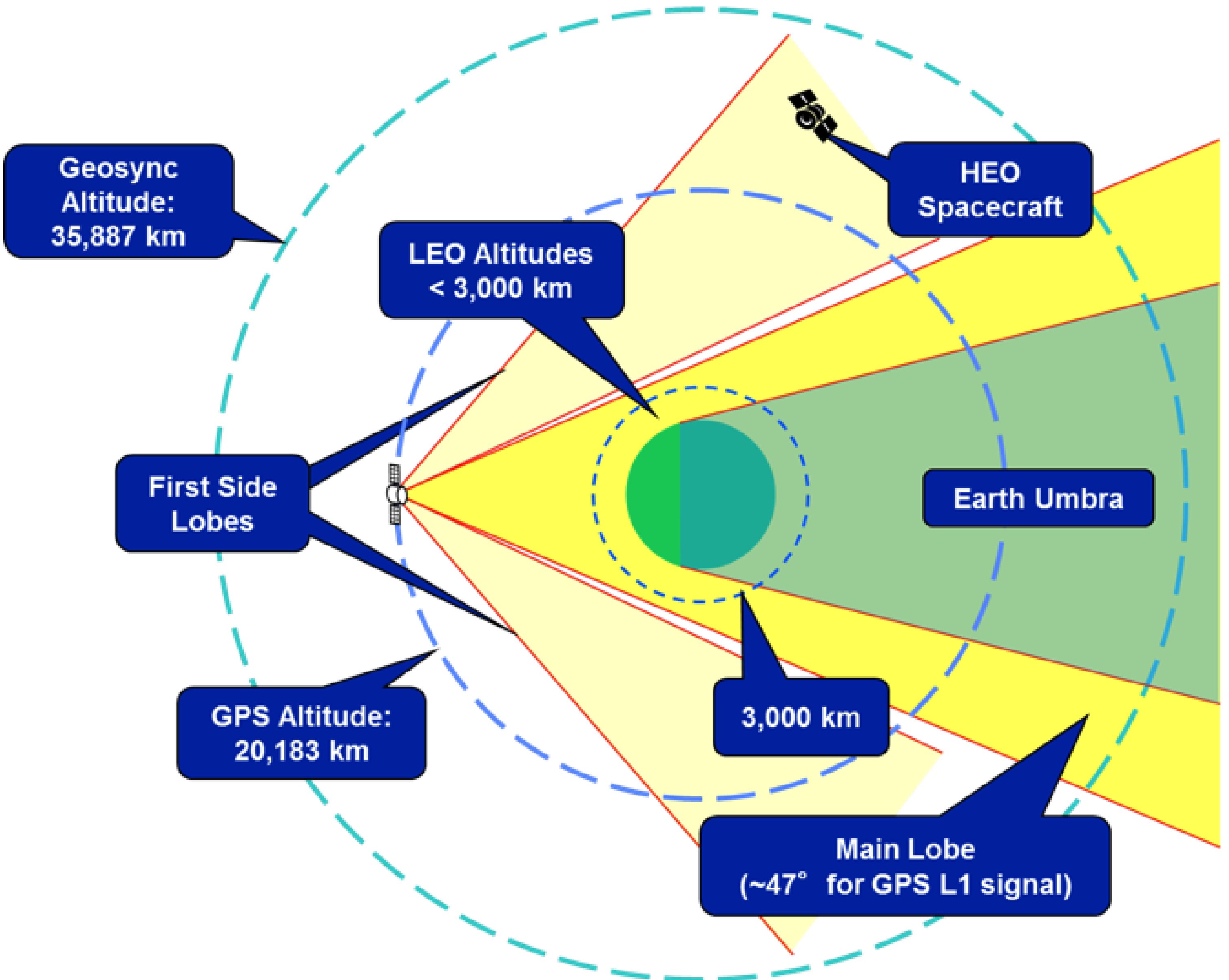
Space Uses of Global Navigation Satellite Systems (GNSS)

- **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:** 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
- **Launch Vehicle Range Operations:** Employs GPS to support launch vehicle flight termination function, providing safety net to people/property during launch failures & enabling higher cadence launch facility use
- **Attitude Determination:** 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

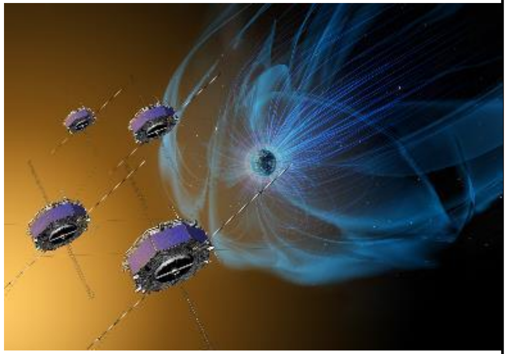
Reception Geometry for GPS Signals in Space



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

Operational Users

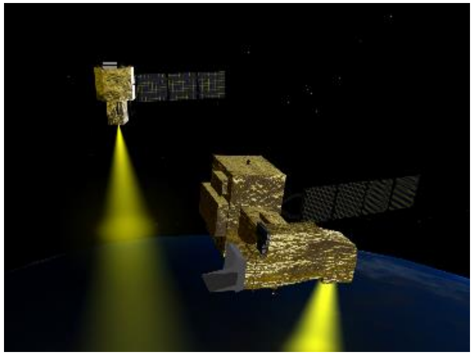
- MMS
- GOES-R, S, T, U
- EM-1 (Lunar en-route)
- Satellite Servicing



Operational Use Demonstrates Future Need

Space Flight Experiments

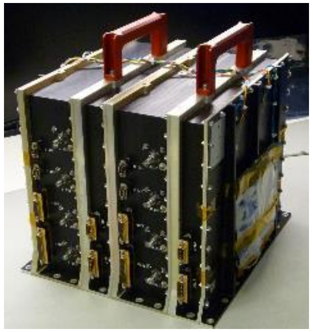
- Falcon Gold
- EO-1
- AO-40
- GPS ACE
- EM-1 (Lunar vicinity)



Breakthroughs in Understanding; Supports Policy Changes; Enables Operational Missions

SSV Receivers, Software & Algorithms

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



Develop & Nurture Robust GNSS Pipeline

SSV Policy & Specifications

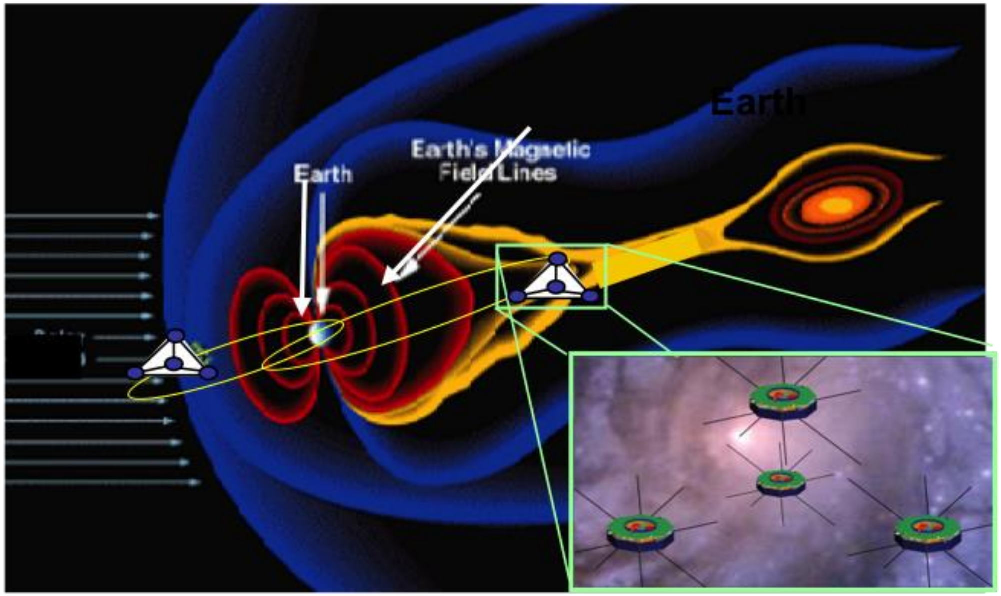
- SSV definition (GPS IIF)
- SSV specification (GPS III)
- ICG Multi-GNSS SSV common definitions & analyses

Operational Guarantees Through Definition & Specification

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

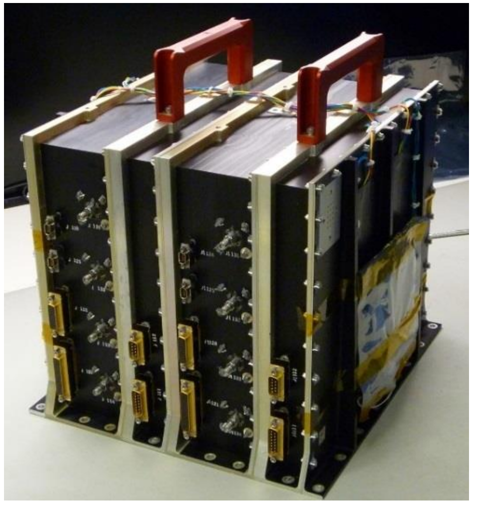
NASA's Magnetospheric MultiScale (MMS) Mission

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



MMS Navigator GPS Receiver

- **Navigator**
  - Single freq C/A code Rx ~10m level onboard accuracy for LEO/GEO/HEO
  - Performance for high altitude applications enabled by
    - Weak signal acquisition and tracking (25 dB-Hz)
    - Integrated on-board navigation filter (GEONS)



- **MMS Results**
  - Once powered, receiver began acquiring weak signals and forming point solutions
  - Long term trend shows average of >8 signals tracked above $8R_E$
  - GPS enables onboard (autonomous) navigation and near autonomous station-keeping

Records are Meant to be Broken

- Oct 20, 2016: Guinness World Record awarded to MMS 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
- Session B3: The Navigation of Satellites
  - *New High-Altitude GPS Navigation Results from the Magnetospheric Multiscale Spacecraft and Simulations at Lunar Distances*: Winternitz et. al.

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.

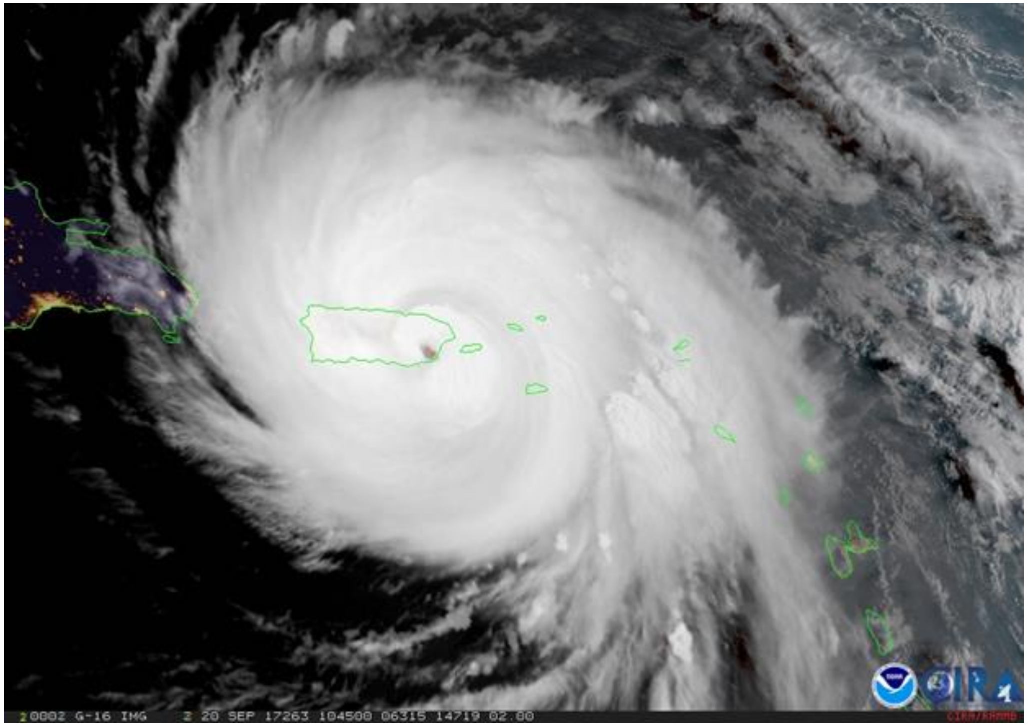
4X BETTER RESOLUTION

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.

GPS is an Enabling Technology for Weather Forecasting



GOES-16 GeoColor image of Hurricane Maria over Puerto Rico as it made landfall on September 20, 2017. Credit: CIRA

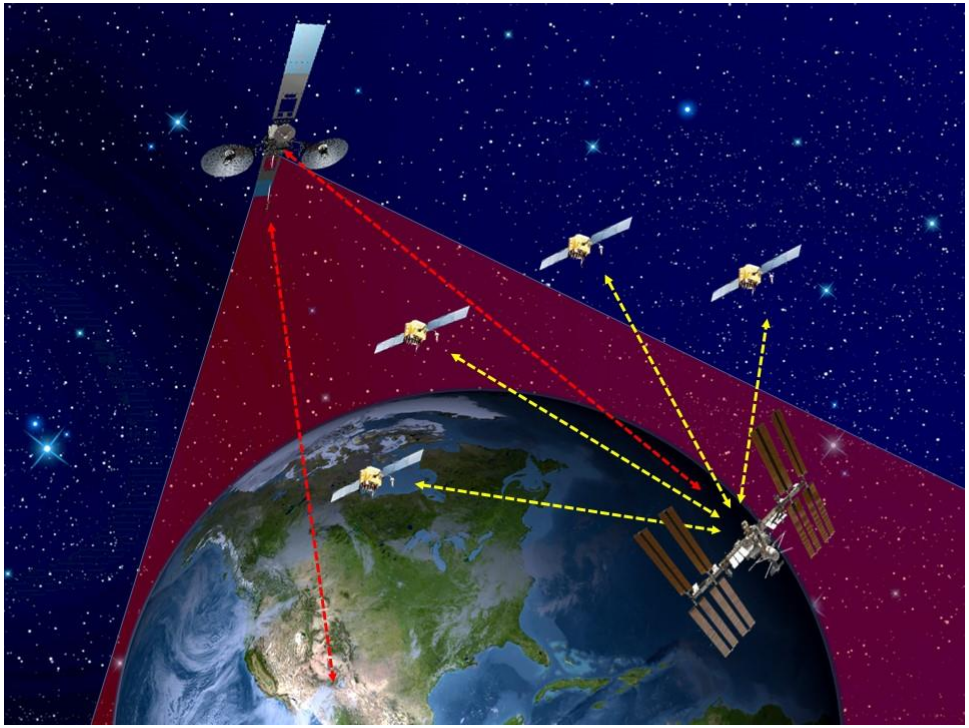
- GOES-16 is able to scan a targeted area of severe weather as often as every 30 seconds, a capability not available with current GOES. This rapid scanning rate is allowing forecasters to analyze cloud patterns and track Maria in real time.
- GPS based orbit determination is required for onboard orbit motion compensation (OMC) in the primary instrument, the Advanced Baseline Imager (ABI) and for image navigation registration (INR), aka geolocation, on the ground.

International Committee on GNSS (ICG) Multi-GNSS SSV Summary

- Interoperable, Multi-GNSS SSV coordination is accomplished as part of **ICG Working Group B (WG-B): Enhancement of GNSS Performance, New Services and Capabilities**
- ICG WG-B discussions have encouraged **GNSS providers** to characterize performance for space users to GEO
- **2016 ICG meeting** was held Nov. 6-11, in Sochi, Russia, Participating members are finalizing a guidance booklet on GNSS SSV & are jointly conducting analyses to characterize interoperability
  - Expected to be endorsed December 2017 at ICG-12 in Kyoto, Japan
  - SSV Booklet Publication early of 2018
  - SSV video being produced by NASA/GRC

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**

NGBS: Benefits to Current and Future Users

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

- **Many of NASA’s current and future science missions study transient phenomena (gamma-ray burst, gravitational waves)**
  - Investigation of these events requires coordinated observations between ground and space-based assets. **Fast communication between observatories is essential.**

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

Conclusions

- NASA is engaged in numerous GNSS technology initiatives that enable our science mission

- The recent successes of the MMS and GOES-R/GOES-16 missions demonstrate the positive impact of technology and policy investments in the GPS Space Service Volume

- NASA technology development activities show strong investment in a robust autonomous PNT solution for civil space users
  - The Next Generation Broadcast Service (NGBS) is an emerging concept to further improve PNT resiliency for space users

- NASA would like to thank the US Air Force for their collaboration and continued support of the civil space community