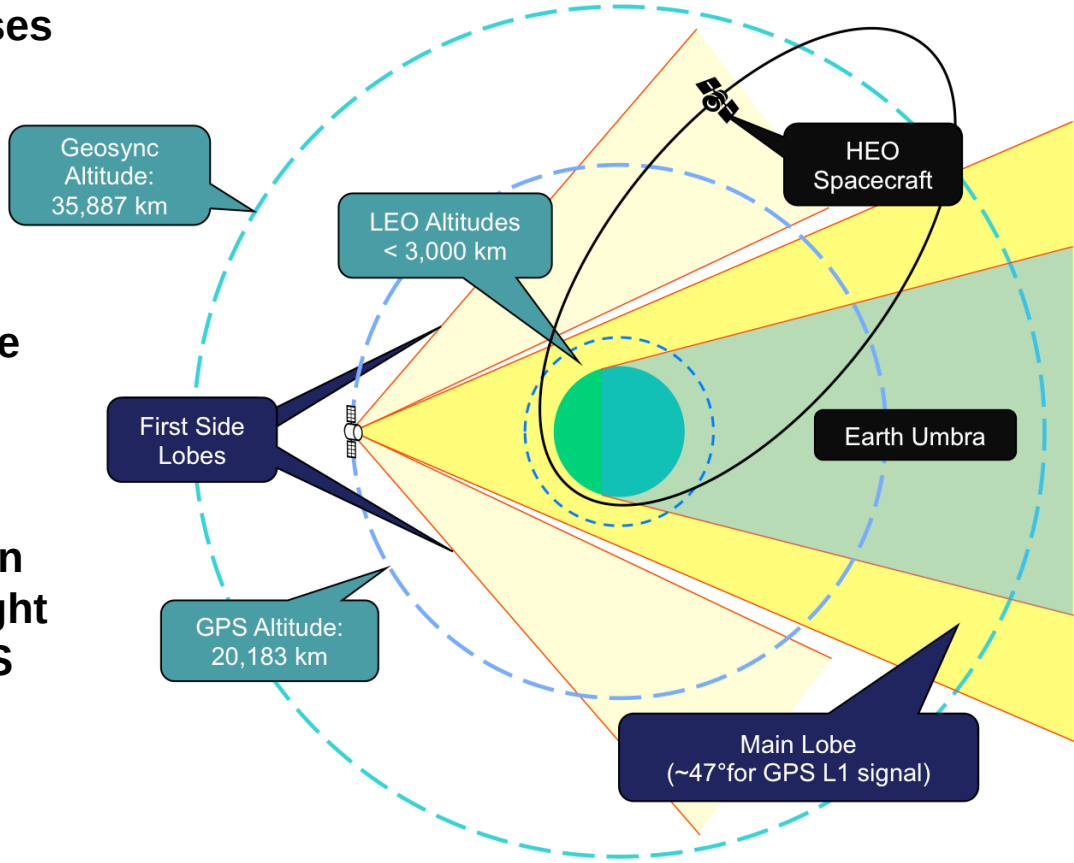
Autonomous Spacecraft Navigation Using Above-the-Constellation GPS Signals

Dr. Luke Winternitz, NASA Goddard Space Flight Center

SCaN Navigation Workshop February 16, 2017

Reception Geometry for GPS Signals in Space

- GPS based satellite navigation above the GPS constellation poses challenges
- Advances in GPS receiver technology and a better understanding of the signals transmitted by the GPS constellation will enabled or save cost for numerous current and upcoming operational HEO missions
- NASA GSFC has been involved in technology development and flight tests related to high altitude GPS applications since 1990's

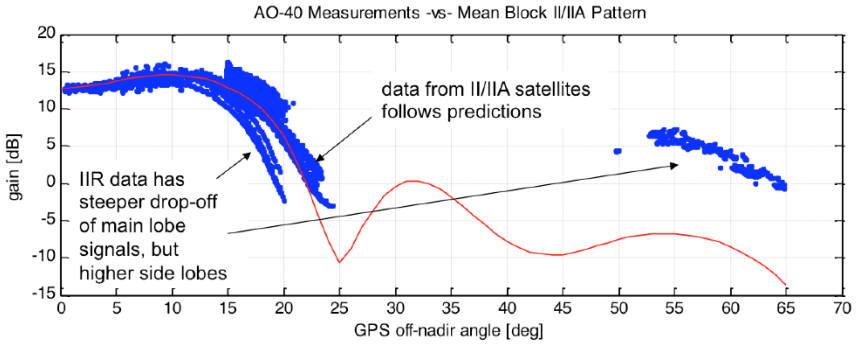


Outline

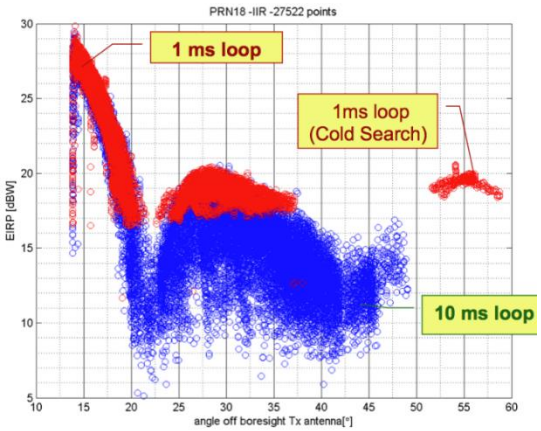
- **Past, Recent, and Planned Missions**
  - High altitude GPS experiments
  - Current and future missions
- **GPS Signals in Space at HEO**
  - Space Service Volume
  - GPS Antenna Characterization Experiment (GPS ACE)
- **GPS Navigation for the MMS mission**
  - MMS background
  - Navigation system
  - Performance results from MMS Phase 1
- **Summary**

RECENT AND PLANNED HIGH ALTITUDE GNSS MISSIONS

High Earth Orbit GPS Experiments



- **Falcon Gold, 1997**
  - Mounted on Centaur upper stage, GTO
- **TEAMSAT, 1997**
  - GTO, ESA experiment
- **EQUATOR-S, 1998**
  - GTO, German research satellite, side-lobe tracking
- **NASA GSFC / AMSAT OSCAR-40, 2000**
  - 1,000 x 59,000 km orbit, spin stabilized
  - Returned most significant measurement of side lobes to date
  - Observed variations between GPS satellite blocks and supported development of current GPS Space Service Volume requirements on GPS III performance



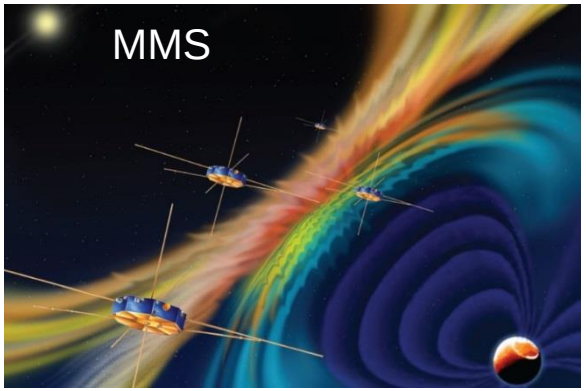
Results from GIOVE-A

- **Airbus/Astrium LION Navigator GNSS receiver for operations in HEO/GEO**
  - Performed 2011 study on Galileo SSV
- **Surrey Satellite (SSTL)**
  - GIOVE-A SGR-GEO experiment (2013) which carried 12 channel L1 C/A code GPS Receiver and operated in circular orbit at 23,200 km (3,200 km above GPS)

Operational HEO Missions

MMS (NASA) (March 2015)

- Operational on-board GPS navigation of 4-satellite formation
- Very high altitude, sparse, weak-signal environment
- NASA Navigator GPS receiver and GEONS filter software

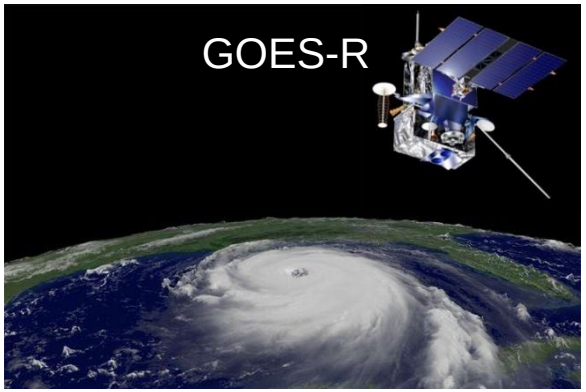


ANGELS (AFRL, ~July 2014)

- GEO mission
- BroadReach HEO receiver (now Moog BroadReach)

SBIRS

- Constellation of satellites at HEO and GEO
- General Dynamics (GD) Monarch receiver at GEO, tracks main lobes only, manual GPS satellite selection



GOES-R Weather Satellite (NOAA/NASA, Nov 2016)

- Operational use of GPS at GEO
- GPS supports efficient station-keeping maneuvers, improves image registration leading to improved science
- General Dynamics Viceroy-4 receiver

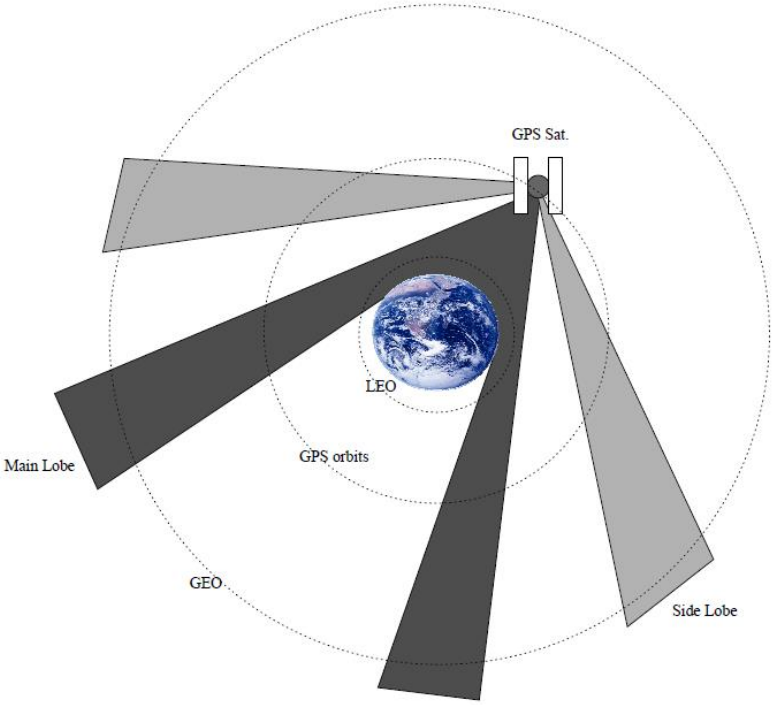
Many more coming

- AFRL EAGLE (2017, MBR NavSBR), GOES-S (2017, GD Viceroy4), ORION EM1 (2018, Honeywell Rx), ESA Proba-3 (2018, RUAG Podrix Rx) …

GPS SIGNALS AT HIGH ALTITUDE

HEO GPS Signals in Space

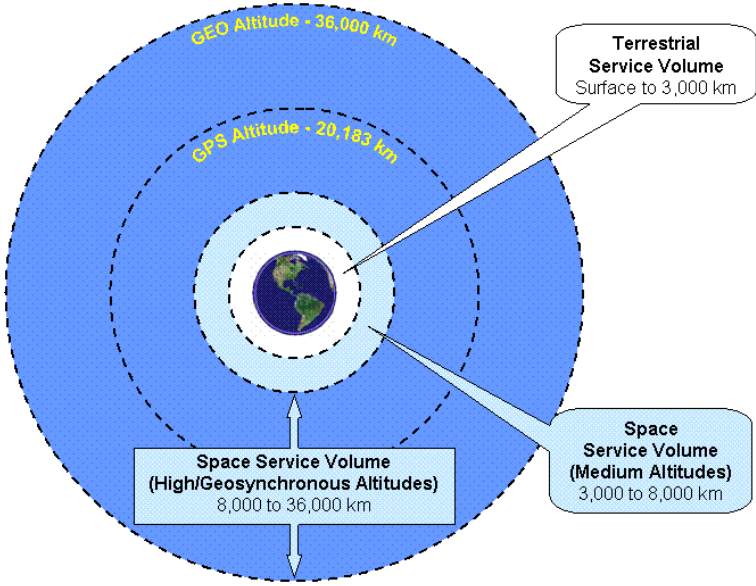
- **Side-lobe signals, can significantly boost GPS signal availability for users above the constellation**
- **Challenges for HEO GPS users include**
  - Main lobe signal availability greatly reduced. Side-lobe signals are weaker.
  - Signal strength and pseudorange accuracy in the side-lobes was also not well known, not specified – are the side-lobe signals useful for navigation?
  - At very high altitudes the GPS constellation no longer has ideal geometry
  - Elliptical HEO orbits can have challenging dynamics for signal acquisition and tracking



Many of these concerns have been mitigated by recent technology demonstrations and operational use.

Space Service Volume (SSV) and Signal Characterization

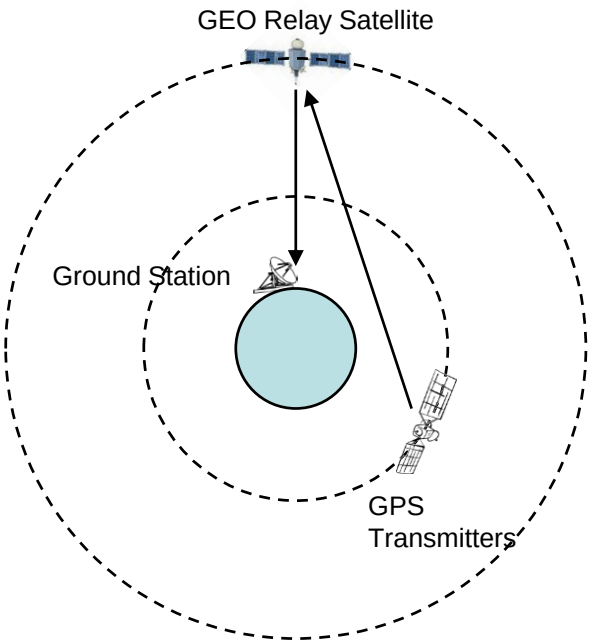
- **GSFC has led the effort to define the Space Service Volume for Space users beyond LEO**
- **Working to continue to develop SSV along two lines**
  - Extend GPS SSV requirements to capture emerging users
  - Define interoperable multi-GNSS SSV with foreign providers.
  - Much more in Joel Parker's talk.



- **Characterization of signals:**
  - Public release of Lockheed Martin data on GPS Block IIR & IIR(M) antenna patterns on www.gps.gov (2015)
    - Quantifies antenna characteristics, including main & side lobe gain, enabling improved simulation
  - On-orbit experience with MMS
  - ACE project

ACE: GPS Antenna Characterization Experiment

- **Goal: Characterize GPS transmitter gain patterns and pseudorange performance in the side lobes**
  - Allow future HEO missions to precisely model expected performance
  - Confirm GPS performance against requirements for the GPS Space Service Volume (SSV)
- **Project is a collaboration between Aerospace Corp. and NASA Goddard Space Flight Center (GSFC)**
  - Represent common interests of DoD and civil space users of GPS



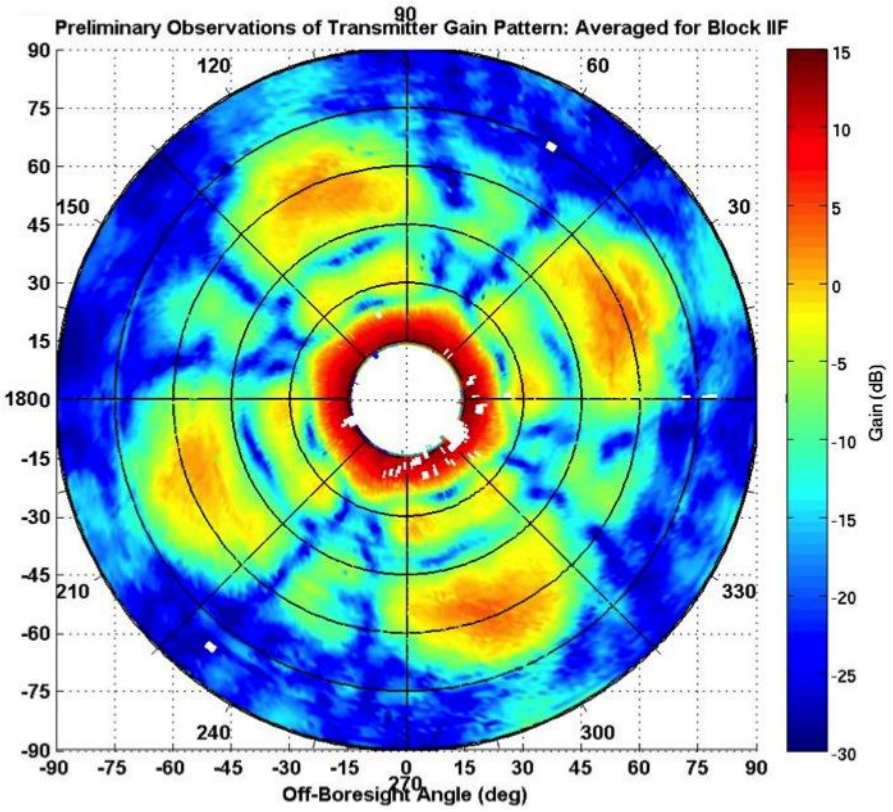
- **Process "bent-pipe" GPS signals received by GEO vehicle and transmitted to ground site**
- **Results:**
  - Unprecedented new knowledge of complete "as-flown" GPS transmit antenna patterns including side lobes
  - Initial pseudorange accuracy characterization indicates side-lobes of "navigation quality"
  - Real-time, autonomous orbit determination experiment at GEO using GSFC Navigator development receiver and GEONS

GPS ACE Results: Block IIR-M and IIF

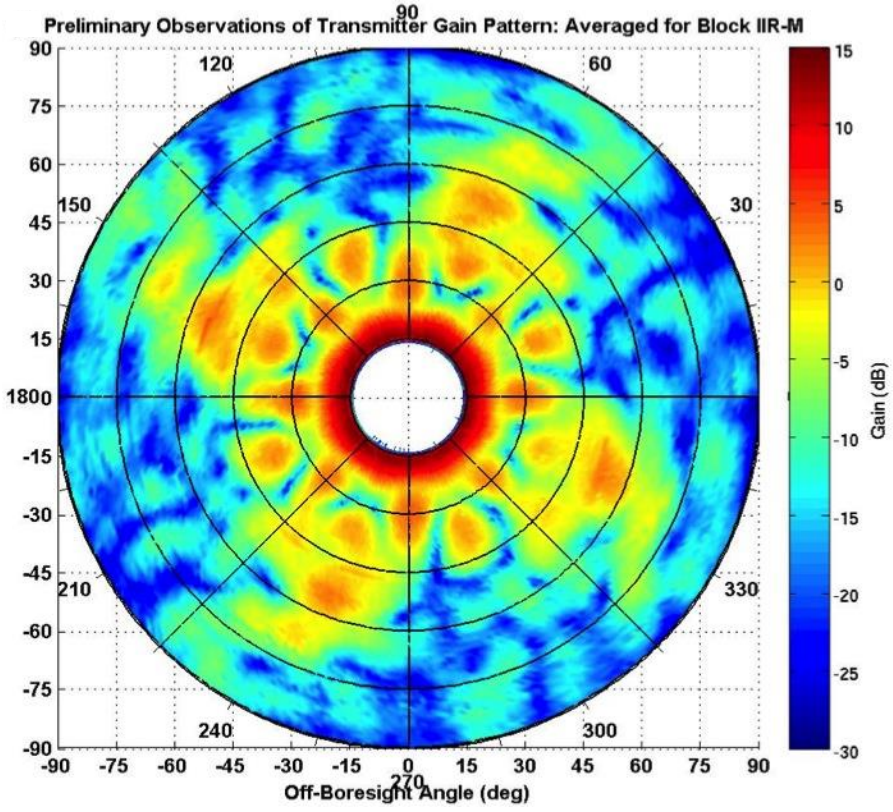
Goddard Space Flight Center

- **Side lobe signal strength and availability changes between GPS blocks**
- **Goal of GPS ACE project is to provide results and analysis to user community to enable navigation improvements over a wide range of high-altitude missions.**

In-Flight Measurement Average from IIF SVs



In-Flight Measurement Average from IIR-M* SVs

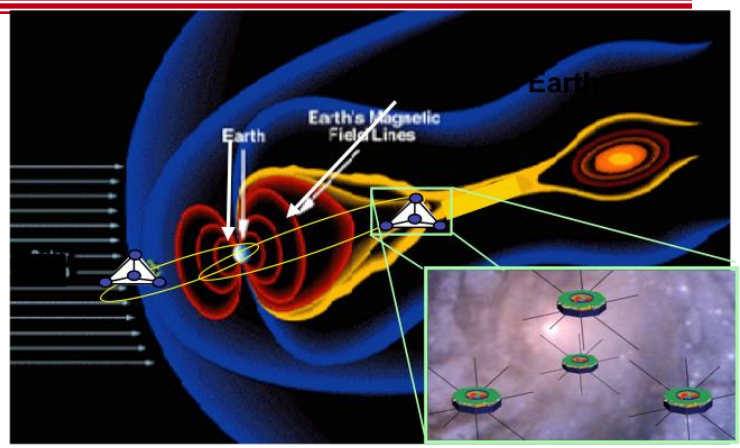


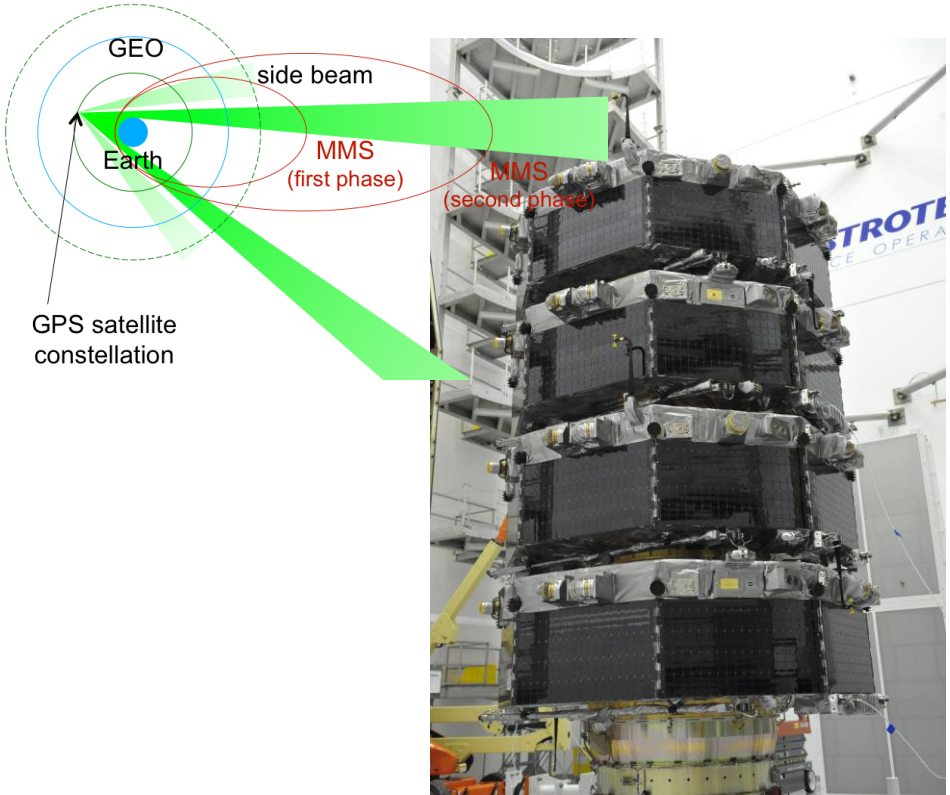
GPS NAVIGATION FOR THE MMS MISSION

Magnetospheric MultiScale Mission (MMS)

Goddard Space Flight Center

- **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 7km**
- **Flying in two highly elliptic orbits in two mission phases**
  - Phase 1 1.2x12 R_E (magnetopause)
  - Phase 2B 1.2x25 R_E (magnetotail)
- **GPS only Navigation using Navigator weak signal GPSR and GEONS filter software**
  - Highest altitude operational GPS navigation mission
- **Trade vs. Ground OD (2005)**
  - Estimated >$2.4M lifecycle savings over ground-based OD.
  - Enhanced flexibility wrt maneuver support
  - Quicker return to science after maneuvers





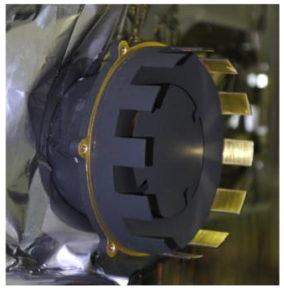
MMS Navigator GPS revceiver

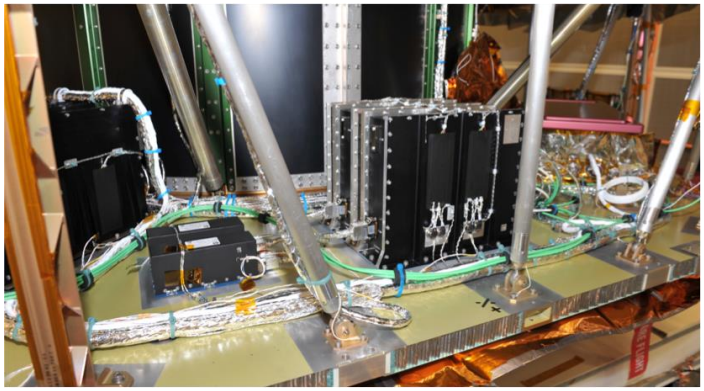
- GSFC in-house design based on based heritage Rx used on GPM, HSM4, EFT1
- L1C/A code receiver designed for high altitude: fast, unaided weak signal acquisition and tracking (<25 dB-Hz)
- High heritage on-board navigation filter software (GEONS)
- Radiation hard
- FEI Ultra-stable XO
- Four antennas each Rx evenly spaced around s/c perimeter to allow continuous tracking while spinning (handoff)

Ultra Stable Osc.

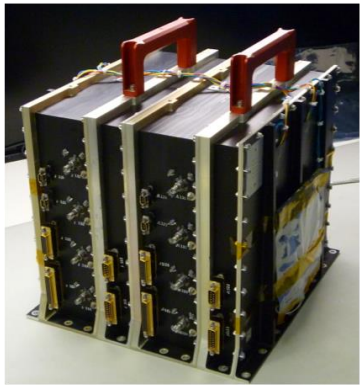
Front end electronics assembly

GPS antenna





Receiver and USO on spacecraft deck

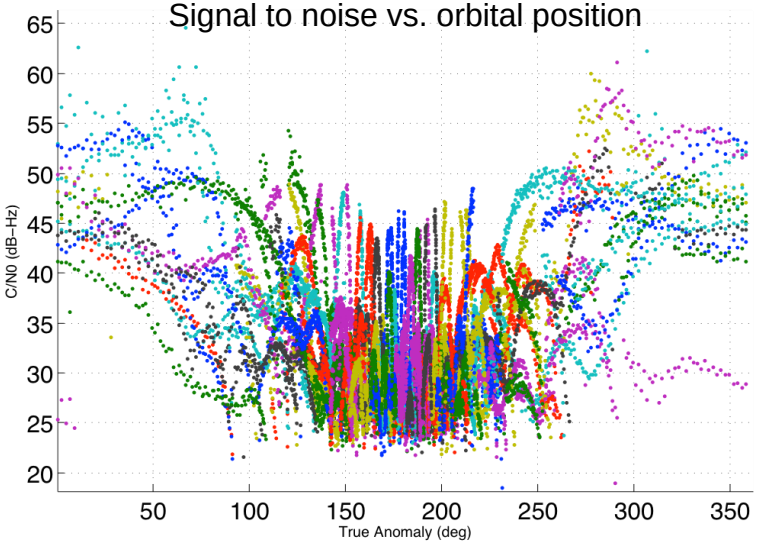


Redundant receiver electronics

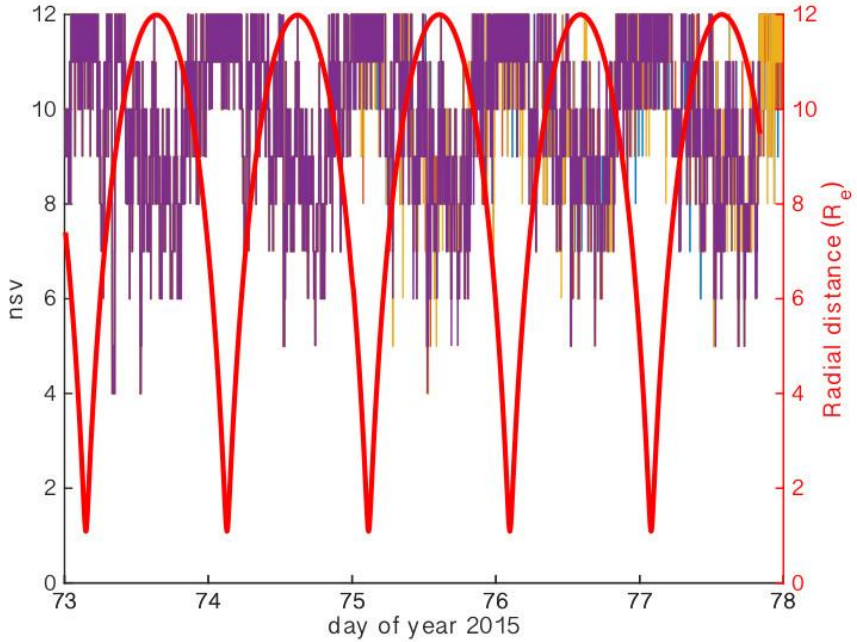
Phase 1 Performance: signal tracking

- **Almost as soon as the receiver turned on, it began acquiring weak signals and forming point solutions**
- **Long term trend shows average of >8 signals tracked above $8R_E$**
- **Above GPS constellation, vast majority of these are sidelobe signals**
- **Visibility exceeded preflight expectations**

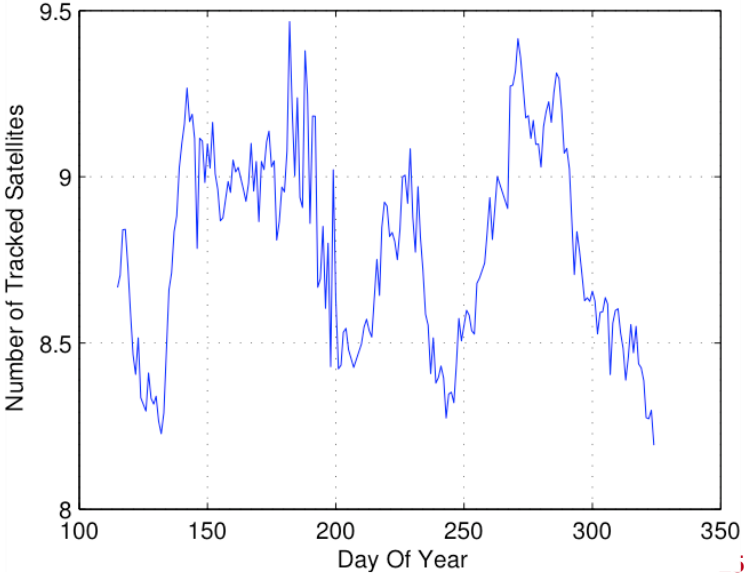
Signal to noise vs. orbital position



Signals tracked during first few orbits

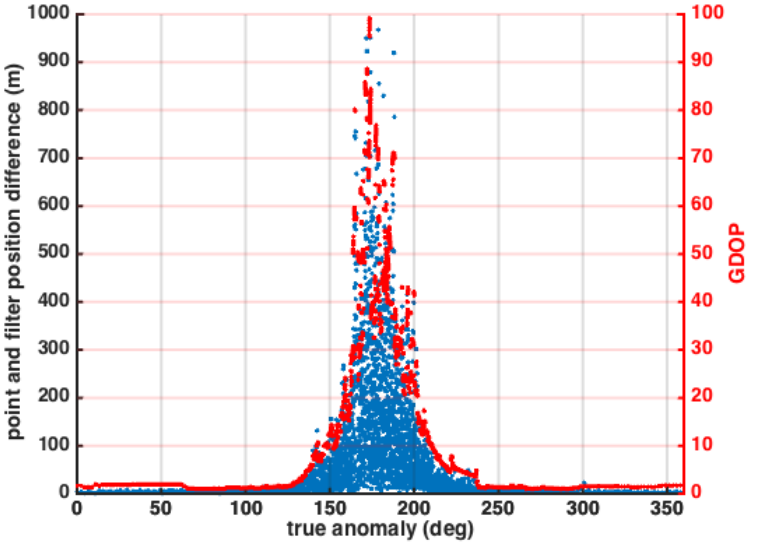


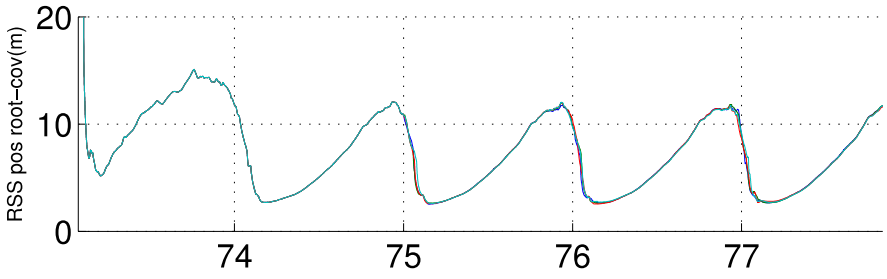
Average Number of Satellites Tracked With Radius > 8 Re

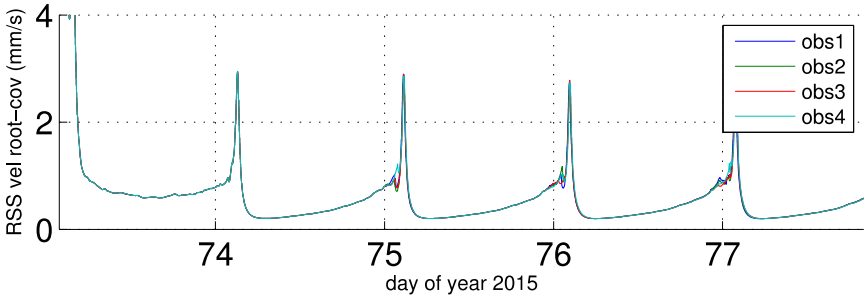


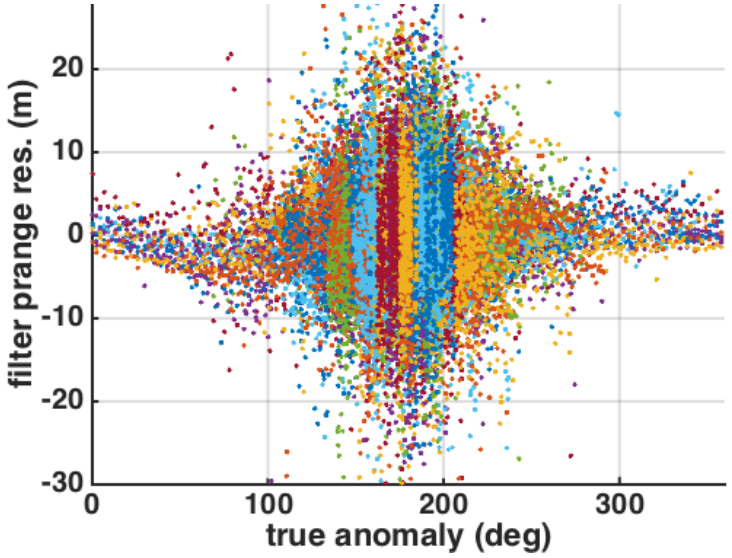
Phase 1 results: measurement and navigation performance

- GEONS filter RSS 1-sigma formal errors reach maximum of 12m and 3mm/s (typically <1mm/s)
- Although geometry becomes seriously degraded at apogee, point solutions almost continuously available
- Measurement residuals are zero mean, of expected variation. Suggests sidelobe measurements are of high quality.









Summary

- **High altitude GPS is now a proven technology that can reduce operations costs and even enable missions**
- **Recently several receivers have become available for above the GPS constellation applications**
- **GSFC has been working on aspects of high-altitude GPS navigation for 2 decades**
  - Developing specialized receivers and OD software
  - Performing analyses and simulation studies
  - Leading efforts to characterize and protect signals
- **MMS mission currently in Phase 1 orbit at 12Re (twice GEO distance) navigating onboard with GPS using Navigator+GEONS**
  - Onboard navigation significantly exceeding requirements
  - Signal visibility in Phase 1 is excellent
  - Sidelobe signals are of “navigation” quality
  - Promising for MMS Phase 2B with 25Re apogee
  - Promising for future missions perhaps to lunar distance

Credits & References

- **These slides borrowed liberally from**
  - Valdez Draper Symposium Talk 2015
  - Carpenter, Winternitz SCaN Noontime Talk June 2015
  - MMS GPS Navigation papers at 2016 AAS GNC, Breckenridge CO, to appear in *ION Navigation*
- **Credit to GSFC PNT group and MMS-Navigator and Flight Dynamics team**

- **Selected References**
  - F.H. Bauer, M.C. Moreau, M.E. Dahle-Melsaether, W.P. Petrofski, B.J. Stanton, S. Thomason, G.A Harris, R.P. Sena, L. Parker Temple III, The GPS Space Service Volume, ION GNSS, September 2006.
  - P.Martzen, D.E.Highsmith, J.E.Valdez, J.J.Parker, and M.C.Moreau,“GPS Antenna Characterization Experiment (ACE): Receiver Design and Initial Results,” *Proceedings of the Institute of Navigation Joint Navigation Conference*, June 2015.
  - L.Winternitz, W.Bamford, S.Price, R. Carpenter, A. Long, M.Farahmand, ”GPS Navigation above 76000km for the MMS Mission", To appear in *ION Navigation*
  - More here: http://www.emergentspace.com/resources/related-works/