Autonomous Spacecraft Navigation Using Above-the-Constellation GPS Signals
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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 enable 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

- **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)

Results from GIOVE-A
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
GPS SIGNALS AT HIGH ALTITUDE
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.
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:
  - Quantifies antenna characteristics, including main & side lobe gain, enabling improved simulation.
- On-orbit experience with MMS.
- ACE project.
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

- 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.
GPS NAVIGATION FOR THE MMS MISSION
Magnetospheric MultiScale Mission (MMS)

- 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
GSFC in-house design based on 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)
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.

![Graphs showing signal tracking performance](image)
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.
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
  - More here: http://www.emergentspace.com/resources/related-works/