Update on GPS Modernization for Space Operations & Science Missions

Progress on Enhancing the GPS Space Service Volume (SSV)

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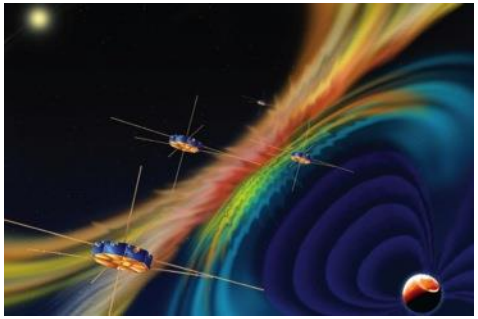
The Promise of using GPS for Real-Time Navigation in the Space Service Volume

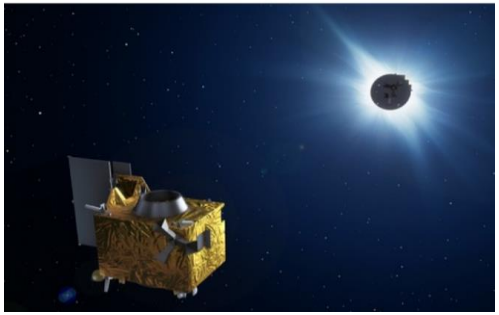
Benefits of GPS use in SSV:

- Significantly **improves real-time navigation performance** (from: km-class to: meter-class)
- Supports **quick trajectory maneuver recovery** (from: 5-10 hours to: minutes)
- GPS 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

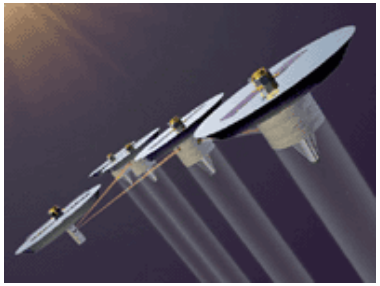


Space Weather Observations

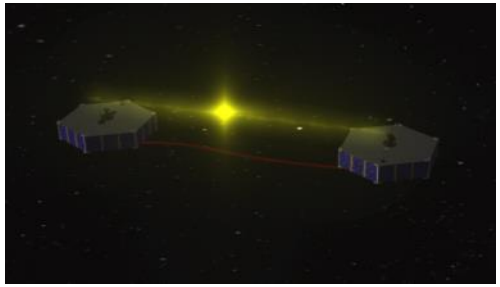


Precise Relative Positioning

Launch Vehicle Upper Stages & Beyond-GEO applications

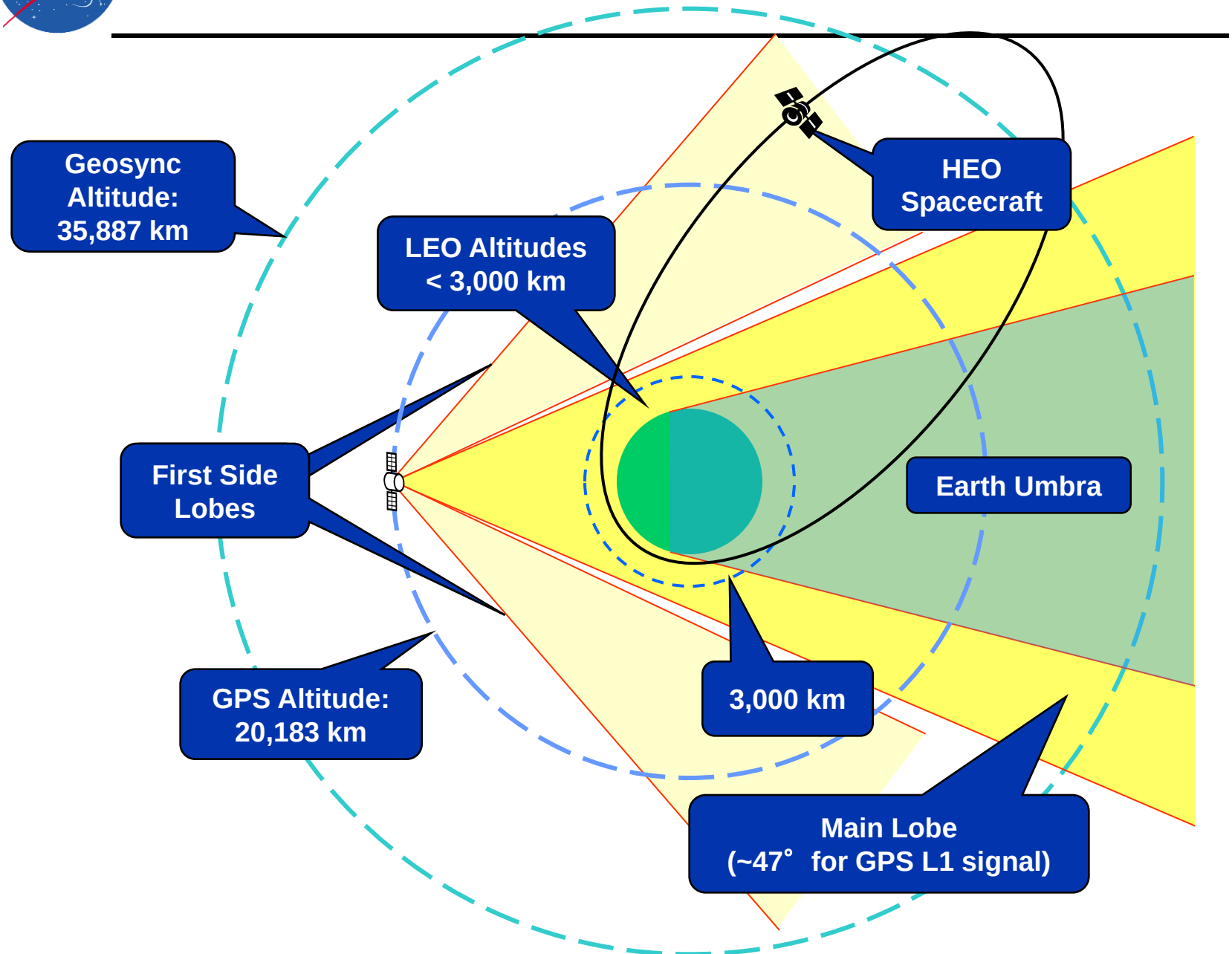


Formation Flying, SSA, ProxOps



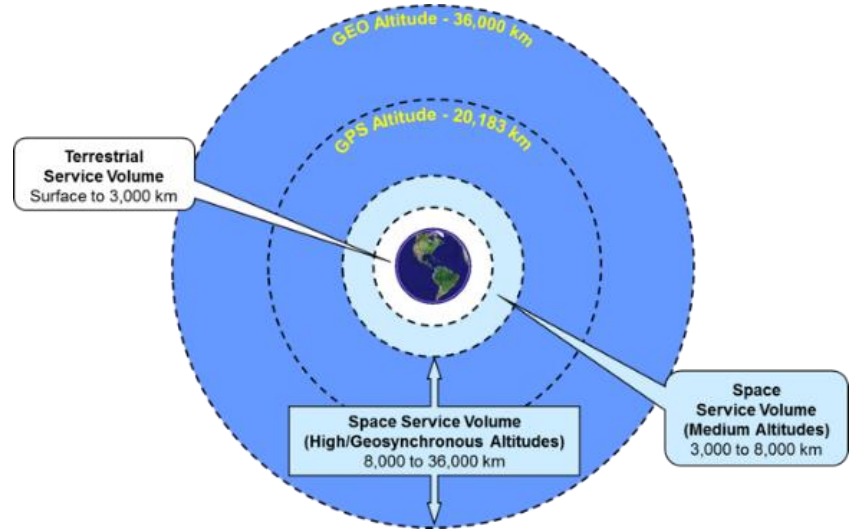
Precise Position Knowledge & Control at GEO

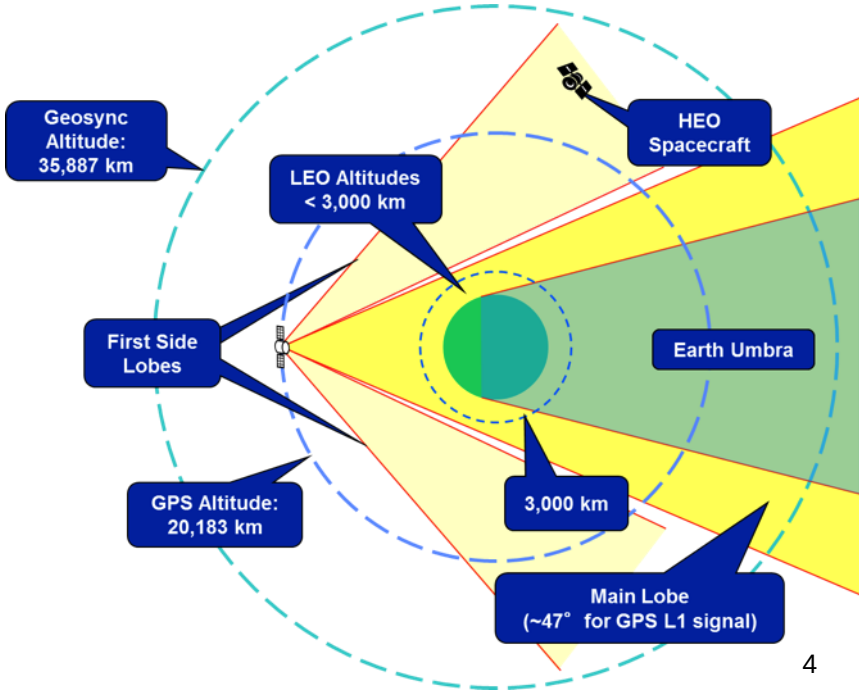
Reception Geometry for GPS Signals in Space



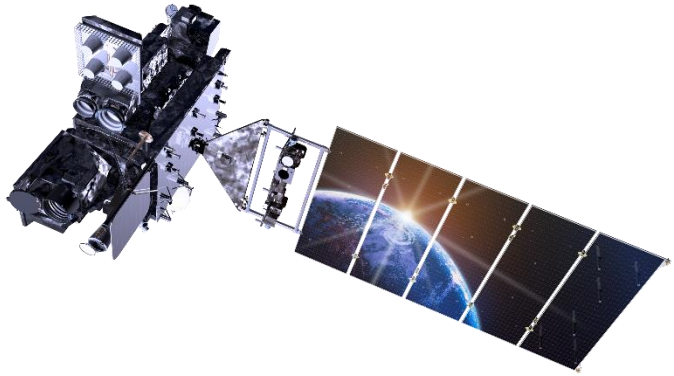
GPS Space Service Volume: Executive Summary

- Current SSV specifications, developed with limited on-orbit knowledge, only capture performance provided by signals transmitted within 23.5°(L1) or 26°(L2/L5) off-nadir angle.
- On-orbit data & lessons learned since spec development show **significant PNT performance improvements** when the full aggregate signal is used.
- **Numerous** Military & Civil operational missions in High & Geosynchronous Earth Orbit (HEO/GEO) **utilize** the full signal to enhance vehicle PNT performance
  - **Multiple** military & civil stakeholders **require** this enhanced PNT performance to meet mission requirements.
- **Failure to protect** aggregate signal performance in future GPS designs creates the risk of **significant loss of capability**, and **inability to further utilize performance** for civil and military space users in HEO/GEO
- Protecting GPS aggregate signal performance **ensures GPS preeminence** in a developing multi-GNSS SSV environment.





Key Civil Stakeholder: GOES-R

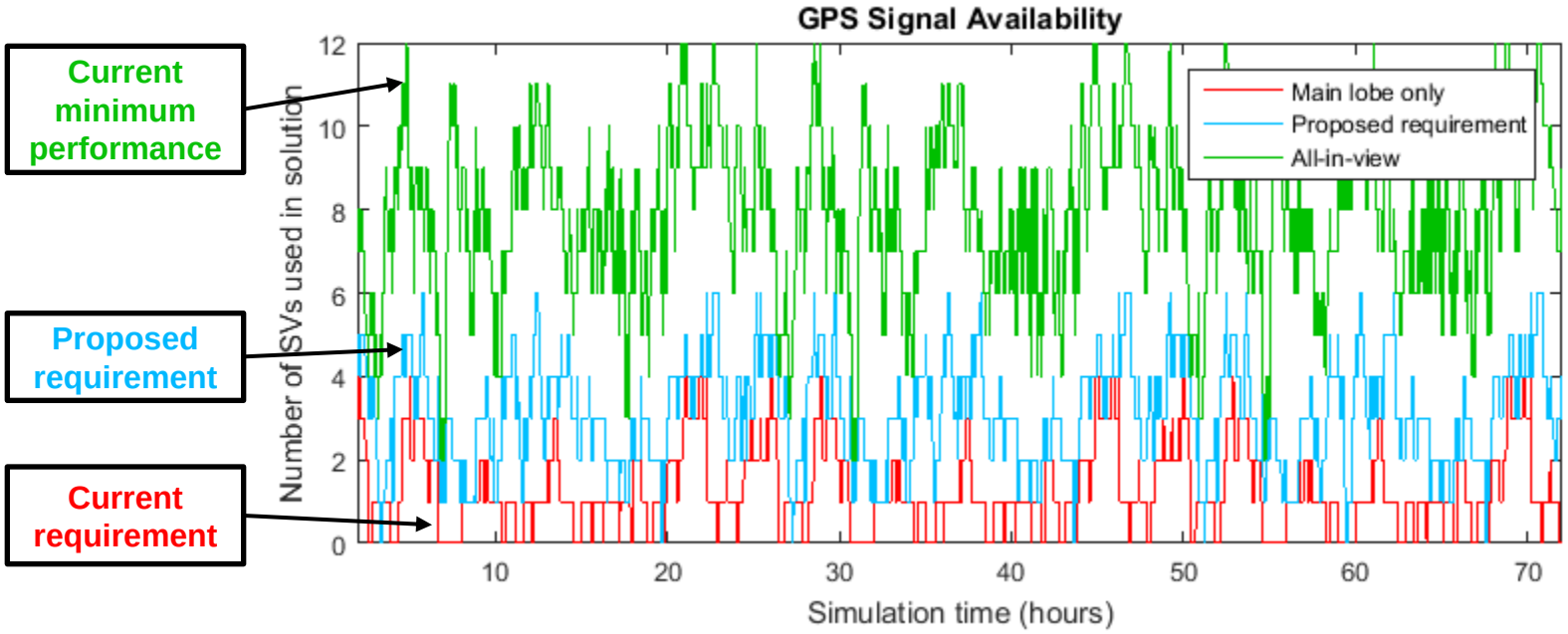


- GOES-R, -S, -T, -U: 4th generation NOAA operational weather satellites
- Launch: 2016, 20-year service life
  - Series operational through 2030s
- Driving requirements:
  - **Orbit position knowledge** requirement (right)
  - All performance requirements **applicable through maneuvers**, **<120 min/year** allowed exceedances
  - Stringent **navigation stability** requirements
  - Requirements unchanged for GOES-S, -T, -U

Parameter	Requirement (m, 1-sigma)
Radial	33
In-track	25
Cross-track	25

- GOES-R cannot meet stated mission requirements with SSV coverage as currently documented
- NASA-led interagency requirement formulated as minimum-impact solution to meet GOES-R performance needs

Proposed SSV Requirement



- **Current requirement is a "triad" of three interrelated components:**
  - Signal availability (% of time that 1 or 4 GPS signals are available; max outage time)
  - Minimum received signal power at GEO
  - Maximum pseudorange accuracy (equivalent to user range error)
- **Proposed requirement adds second tier of capability specifically for HEO/GEO users**
  - Increased signal availability to nearly continuous for at least 1 signal
  - Relaxed pseudorange accuracy from 0.8m RMS to 4m RMS
  - No change to minimum received signal power
  - Applies to all signals (L1/L2/L5), all codes

PR acc. (rms)	0.8 m	4m
1+ signal	≥ 80%	≥ 99%
4+ signals	≥ 1%	≥ 33%
Max outage	108 min	10 min

SSV L1 HEO/GEO availability

Progress Since Oct 2015 Advisory Board Meeting

- **Oct 2015–Feb 2016: NASA and Air Force coordinate through IFOR process**
  - Monthly IFOR WG meetings w/ NASA, AFSPC, SMC (Aerospace as “honest broker”)
  - Major deliverables provided by NASA:
    1. Requirement Language
    2. Statement of Need
    3. Analysis of Alternatives
  - NASA coordinating with interagency stakeholders for letters of support/commitment
- **9 Feb 2016: Final IFOR WG Meeting**
  - NASA delivers final products
  - SMC delivers ROM cost estimate for impact to GPS system
- **26 Feb 2016: Formal SMC/SY (Space Superiority) endorsement of NASA requirement**
- **22 Mar 2016: IFOR Co-Chair preliminary recommendation meeting**
  - SMC requests for clarification on AoA and forward plan leads to IFOR-requested HPT
- **12–13 Apr 2016: NASA/AFSPC/SMC HPT**
  - Drafting of USAF/NASA MoA
  - Clarification of AoA items
  - Agreement on forward engagement in SV11+ procurement process
- **19 Apr 2016: Formal NOAA endorsement of NASA requirement**
- **June 2016: Final IFOR Co-Chair recommendation meeting**

Key Endorsements

USAF SMC/SY (Space Superiority Systems)

- Letter of endorsement signed by Col Garrant, 26 Feb 2016.
- SMC/SY has documented program requirement.
- Requirement is unfunded at this time.
- SY currently performing analyses to document their actual required capability levels as compared to NASA's proposed IFOR requirement.

NOAA

- Letter of endorsement from VADM Manson Brown (NOAA Deputy Administrator) to Gen Hyten & Maj Gen Thompson, 19 Apr 2016
- Confirms that GOES-R is reliant on GPS signals as captured in NASA's proposed IFOR requirement
- Additionally, identifies EUMETSAT (EU) and Japanese weather satellites as reliant on increased signal availability

Progress on Key Issues

- **NASA & USAF partnership on implementation**
  - Joint NASA/USAF Memorandum of Agreement in coordination
  - Defines roles & responsibilities for NASA and USAF through requirements definition and acquisition process

- **Ensuring navigation resiliency**
  - NASA-proposed requirement is intended to protect use of critical GPS capabilities for space users in HEO/GEO
  - Effort is not intended to establish GPS as a space user's only navigation solution
  - Resiliency is ensured through space vehicle applications of complementary PNT solutions – RF, optical, INS, etc.

Way Ahead

- **Complete IFOR process:**
  - **June 2016**: IFOR Co-chair decision meeting
  - **Summer 2016**: Gen Hyten decision confirmation brief
  - **Late 2016–2017**: CDD with SSV requirement enters JCIDS process for implementation

- **Implement NASA/USAF MoA:**
  - **Current status**: Coordination on MOA terms
  - **Summer 2016**: Staffing and MOA approval by agency signatories
  - **Late 2016**: Initiation of formal coordination with USAF on requirement implementation

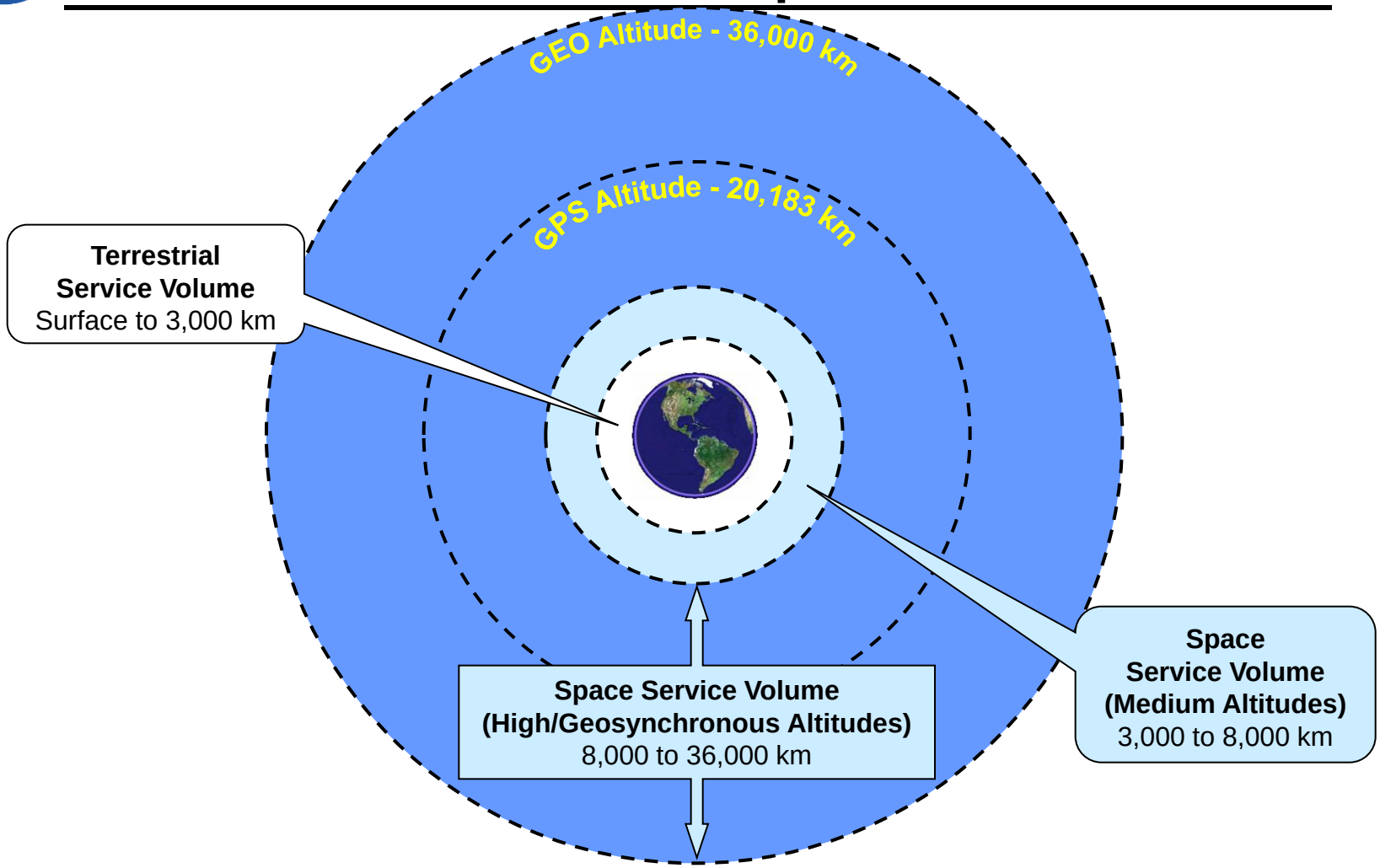
Closing Remarks

- **Civil and military space users rely on GPS as a critical space navigation utility over an expanding range of orbital regimes**
- **Missions using GPS in HEO/GEO orbits are vulnerable to GPS constellation design changes because availability provided by sidelobe signals is critically important and not specified**
- **NASA has developed a proposed requirement based on documented mission needs that will benefit entire Space Enterprise**
- **NASA is working through formal IFOR process for implementation into the GPS III SV11+ CDD.**
- **CDD & requirements update for HEO/GEO SSV users will:**
  - Maintain critical capabilities employed by users in HEO/GEO
  - Provides a green-light for civil and military space missions considering future operational use of GPS beyond LEO

Protection of GPS Side Lobe Signals through Specification is Critically Important for Current and Future Users in the SSV

Backup Charts

What is a Space Service Volume (SSV)?
Current SSV Specification



Specification of SSV, Signal Strength and Availability Crucial for Reliable Space User Mission Designs

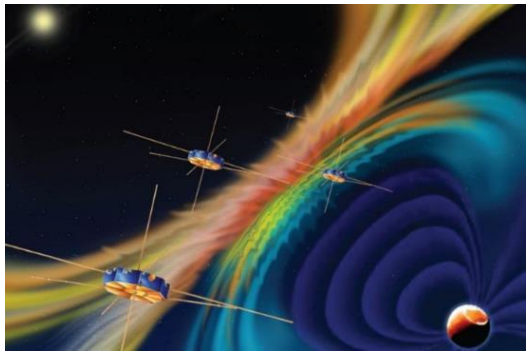
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

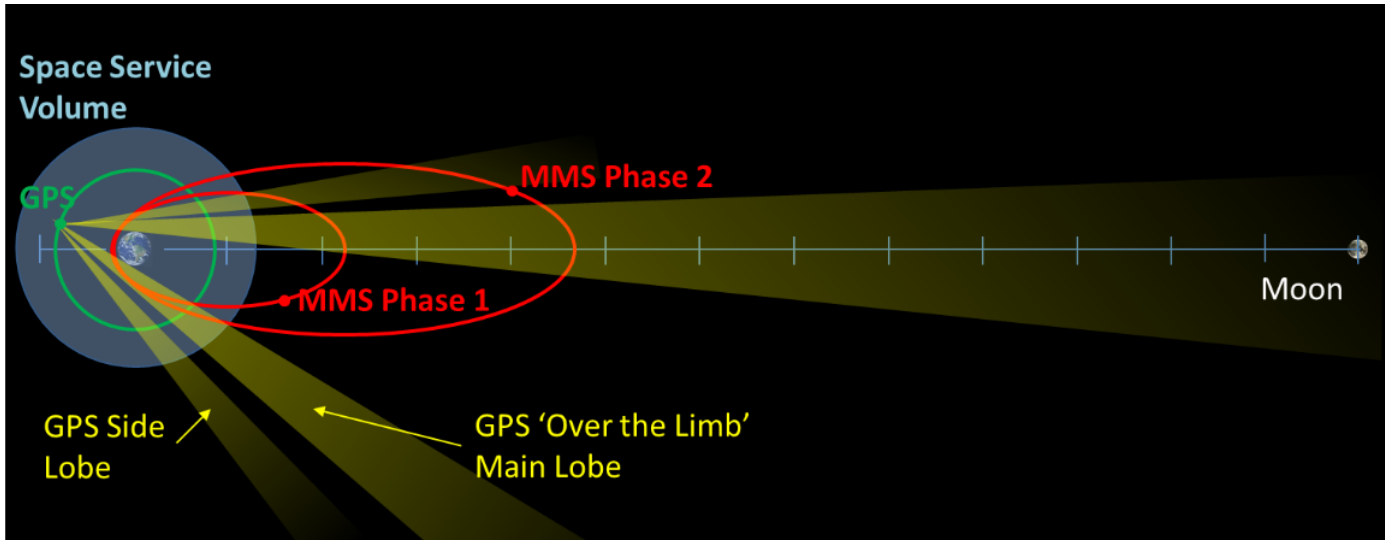
Magnetospheric Multi-Scale (MMS)

- **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)

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 a 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 a record as the fastest operational GPS receiver in space, at velocities over 35,000 km/h**



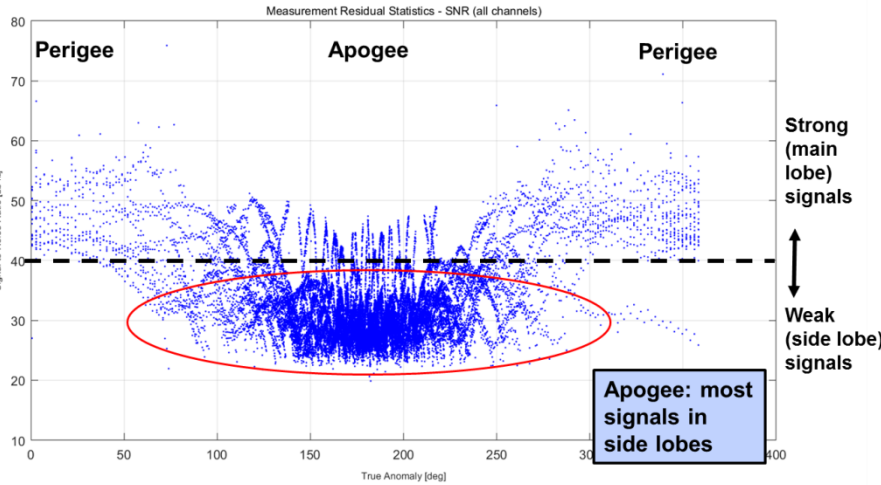


Measured Performance of MMS with Side Lobe Signal Availability

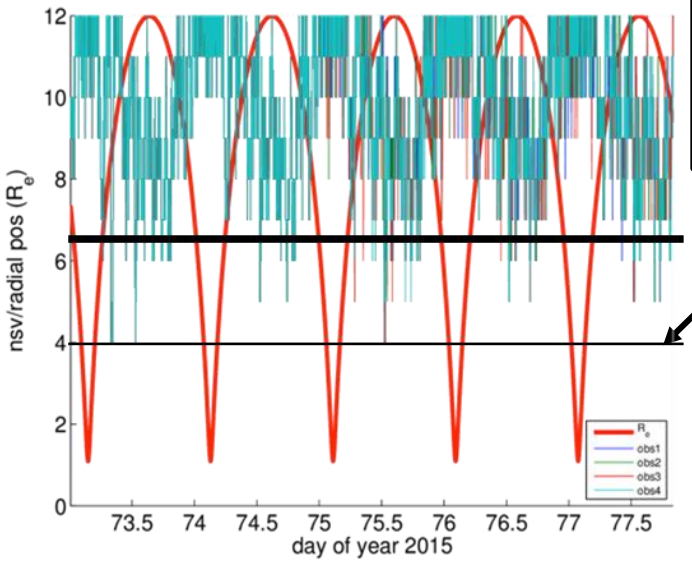
Signal Availability Contributed by Side Lobes (Assumes 24 Satellite Constellation)		
L1 Signal Availability	**Main Lobe Only**	**Main and Side Lobes**
4 or More SVs Visible	**Never**	**99%**
1 or More SVs Visible	59%	100%
No SVs Visible	41%	Never

Current Spec: L1 Signal Availability→4 or more SVs visible: >1%

Recent Flight Data From Magnetosphere Multi-Scale (MMS) Mission



Signal strength (C/N0) vs. position in orbit



Current spec: Four or more PRs shall be available more than or equal to 1% of the time

MMS is seeing **100%**

GPS Space Service Volume Specification History

- **Mid-1990s**—efforts started to develop a formal Space Service Volume
  - –Discussion/debate about requiring “backside” antennas for space users
  - –Use of main lobe/side-lobe signals entertained as a no cost alternative
- **1997-Present**—Several space flight experiments, particularly the AMSAT-OSCAR-40 experiment demonstrated critical need to enhance space user requirements and SSV
- **February 2000**—GPS Operational Requirements Document (ORD), released with first space user requirements and description of SSV
  - –Shortcomings
    - Did not cover mid-altitude users (above LEO but below GPS)
    - Did not cover users outside of the GEO equatorial plane
    - Only specified reqts on L1 signals (L2 and L5 have wider beam-width and therefore, better coverage)
- **2000-2006**—NASA/DoD team coordinated updated Space User reqmnts
  - – Worked with SMC/GPE, Aerospace support staff & AFSPACE to assess impacts of proposed requirements to GPS-III
  - – Government System Spec (SS-SYS-800) includes threshold & objective reqmnts
  - – Shortcomings:
    - Developed with limited on-orbit experiment data & minimal understanding of GPS satellite antenna patterns
    - **Only specifies the main lobe signals, does not address side lobe signals**