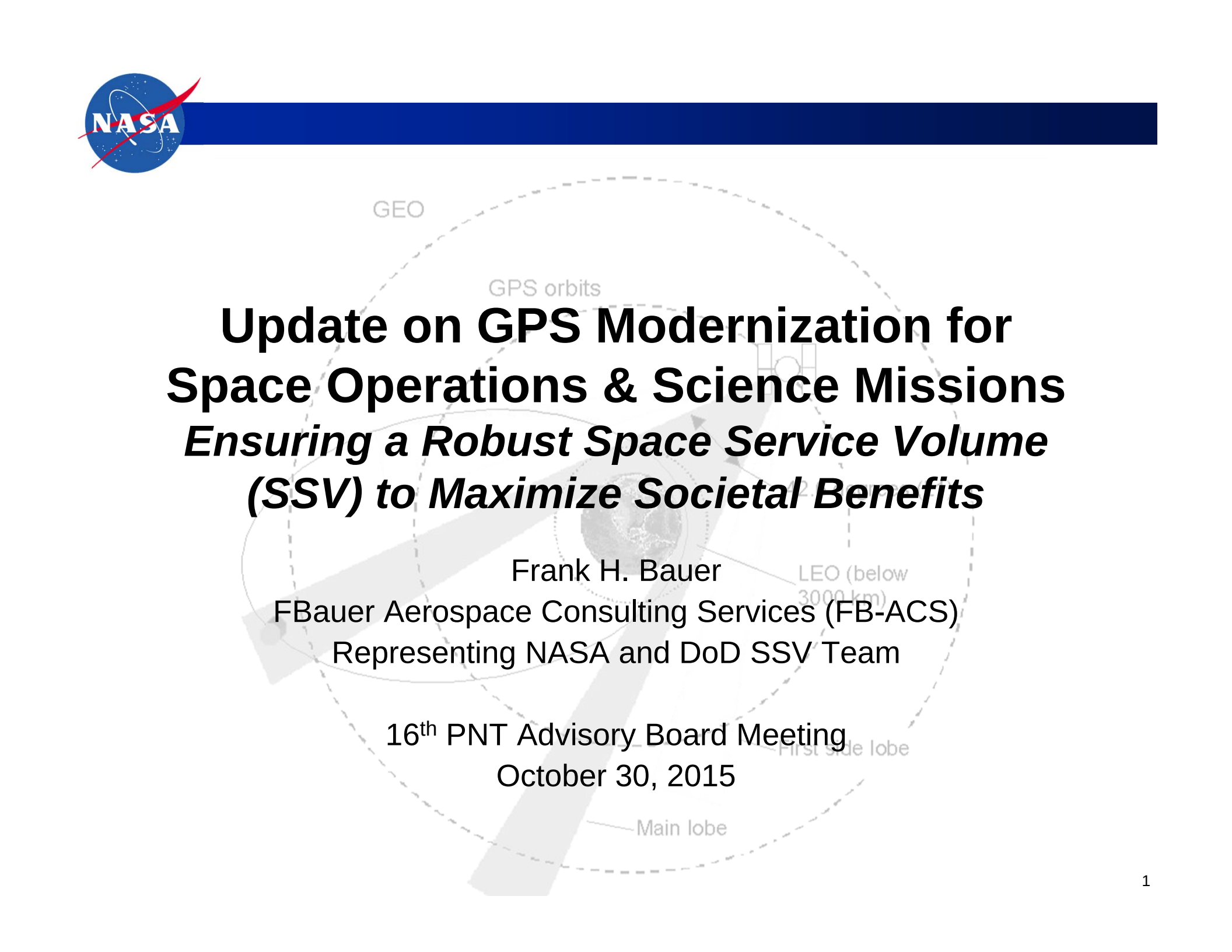


Update on GPS Modernization for Space Operations & Science Missions

Ensuring a Robust Space Service Volume (SSV) to Maximize Societal Benefits

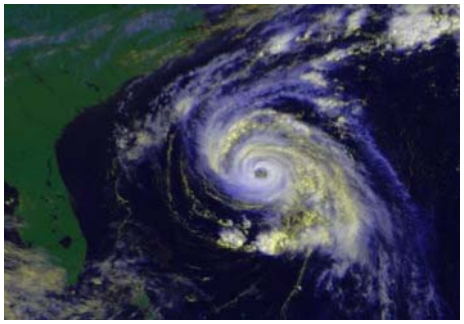
Frank H. Bauer
FBauer Aerospace Consulting Services (FB-ACS)
Representing NASA and DoD SSV Team

16th PNT Advisory Board Meeting
October 30, 2015

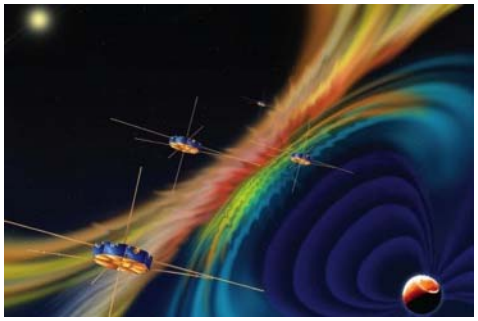
The Promise of using GPS for Real-Time Navigation in the Space Service Volume

SSV specifications are crucial for all space users, providing real-time navigation solutions in Low, Medium & High Earth Orbit & Beyond!

- **Supports increased satellite autonomy for missions, lowering mission operations costs**
- **Significantly improves vehicle navigation performance in these orbits**
- **Supports quick mission recovery after spacecraft trajectory maneuvers**
- **Enables new/enhanced capabilities and better performance for HEO and GEO/GSO missions, such as:**



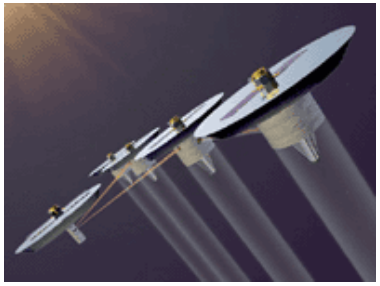
Improved Weather Prediction using Advanced Weather Satellites



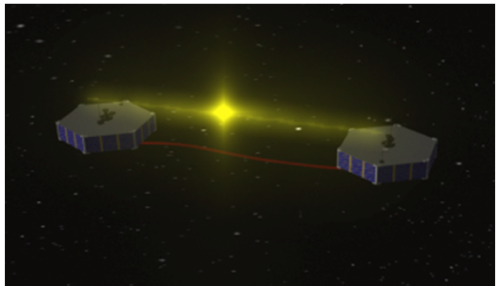
Space Weather Observations

Solar Occultation Observations

En-route Lunar Navigation Support

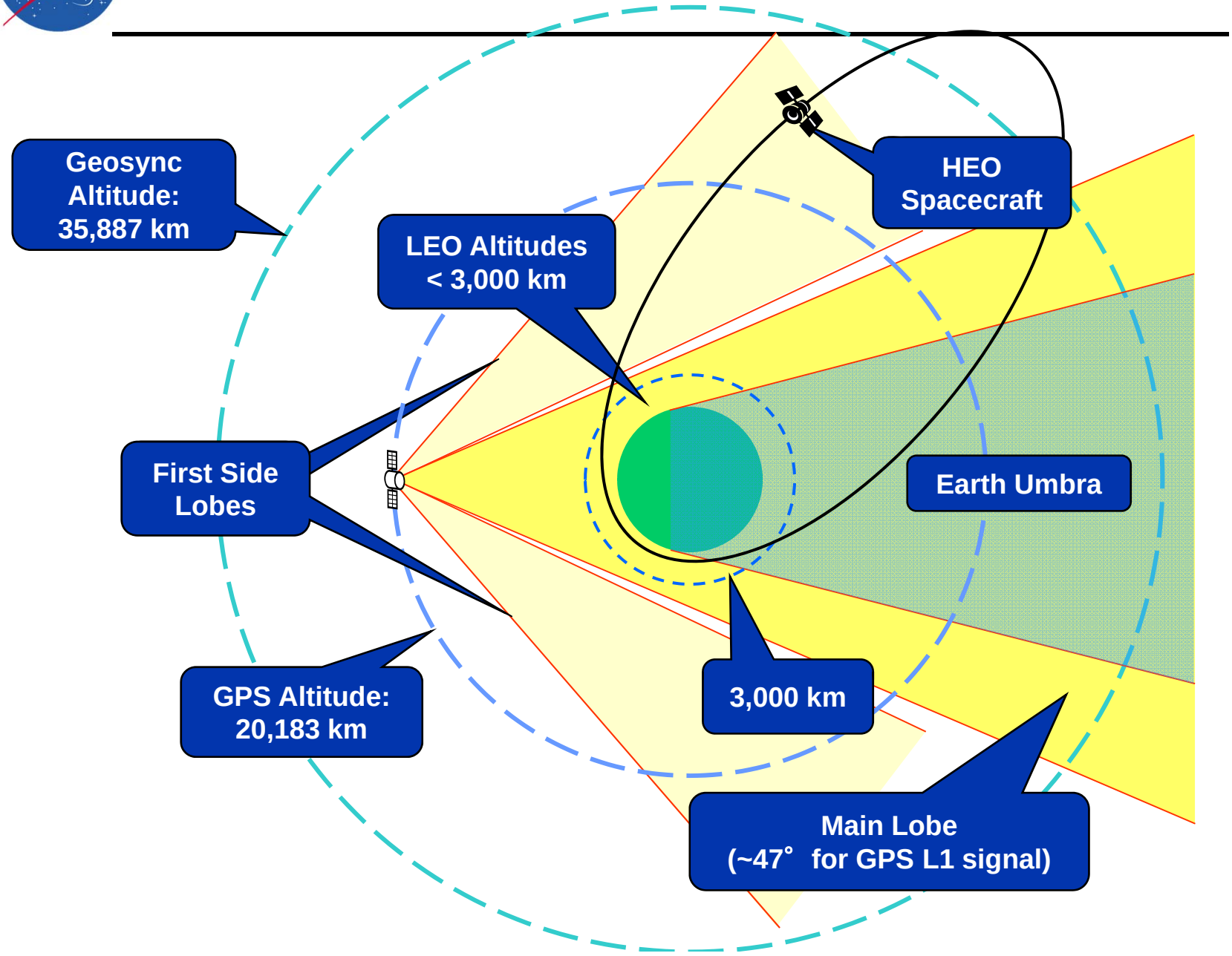


Formation Flying & Constellation Missions



Closer Spacing of Satellites in Geostationary Arc

Reception Geometry for GPS Signals in Space



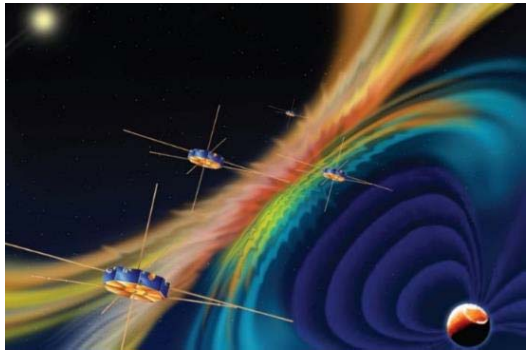
Using GPS above the GPS Constellation: NASA GSFC MMS Mission

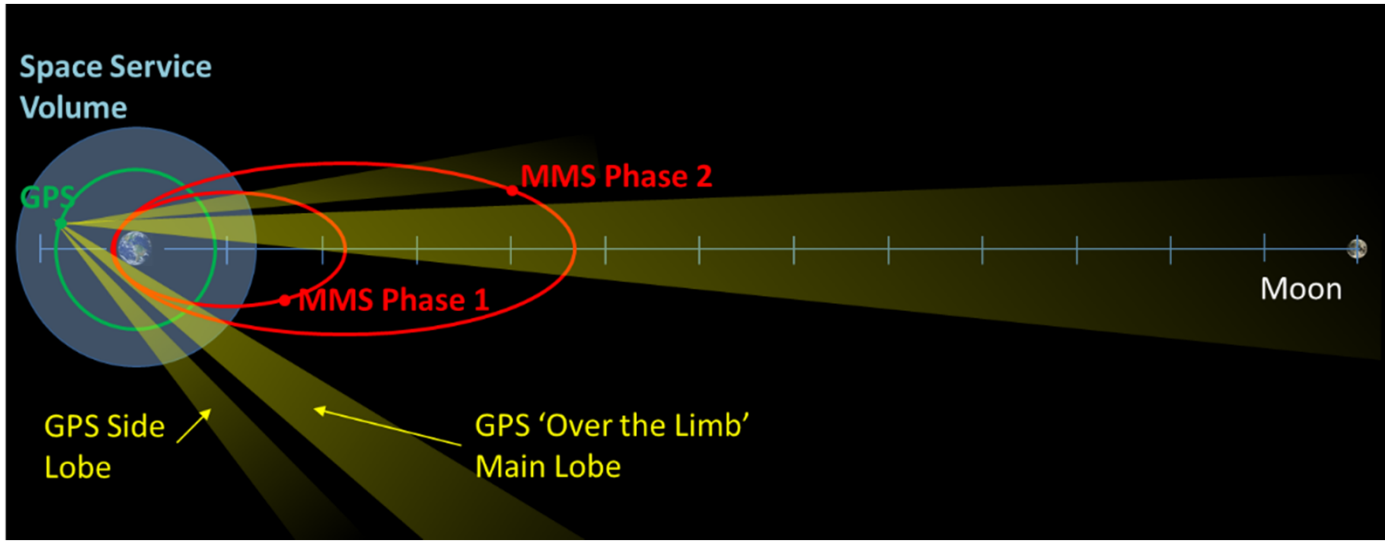
Magnetospheric Multi-Scale (MMS)

- **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**



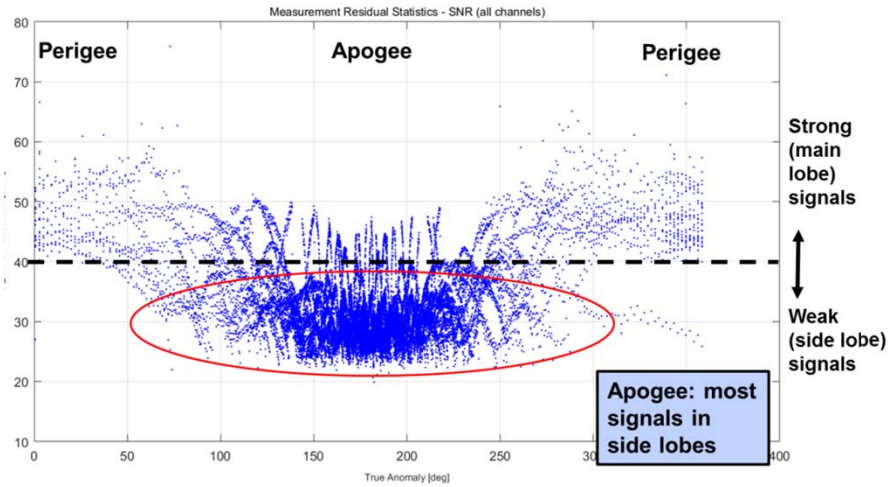


Measured Performance of MMS with Side Lobe Signal Availability

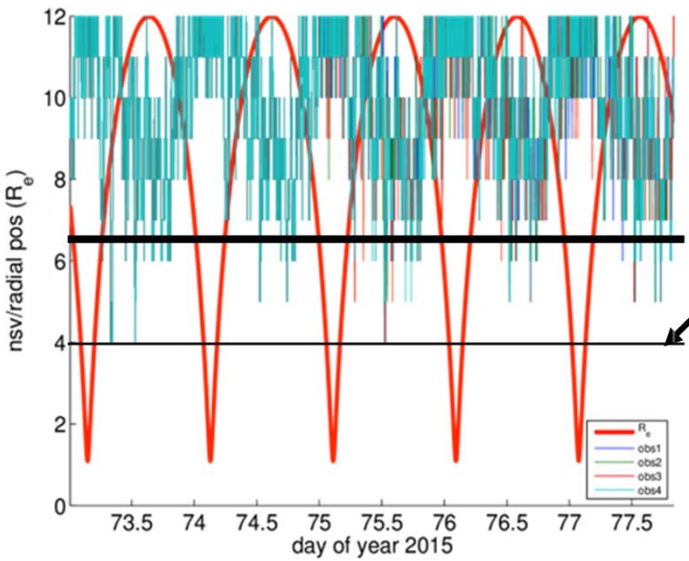
Signal Availability Contributed by Side Lobes (Assumes 24 Satellite Constellation)		
L1 Signal Availability	**Main Lobe Only**	**Main and Side Lobes**
4 or More SVs Visible	**Never**	**99%**
1 or More SVs Visible	59%	Always
No SVs Visible	41%	Never

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

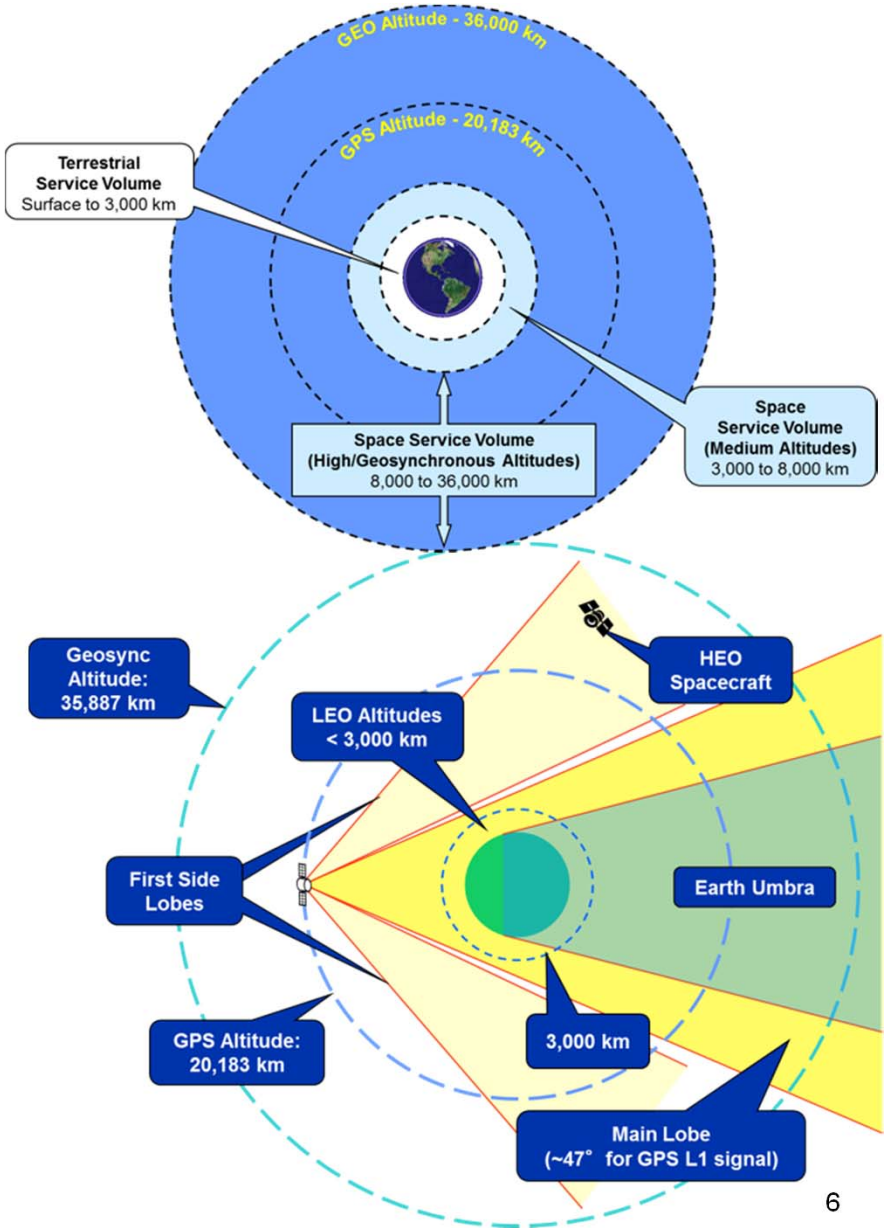


Current spec: Four or more PRs shall be available more than or equal to 1% of the time

MMS is seeing **100%**

GPS SSV Status & Lessons Learned: Executive Summary

- Current SSV specifications, developed with limited on-orbit knowledge, employ only the GPS main lobe signal
- On-orbit data & lessons learned since spec development show significant PNT performance improvements when main lobe and side lobes are employed together
  - Side lobe signals make significant contributions to PNT performance, enabled by modern weak signal tracking GPS receivers
- Numerous operational missions in High & Geosynchronous Earth Orbit (HEO/GEO) employ GPS side lobes to enhance vehicle PNT performance; many other missions in development
- Space user community is **vulnerable** to GPS constellation design changes if side lobe signal performance parameters not formally recognized
- **Failure to protect** GPS side lobe signals can result in **significant loss of capability** for space users in HEO/GEO orbits and should be preserved for on-board PNT in the 2025-2040 timeframe



Progress Since June 2015 Advisory Board Meeting

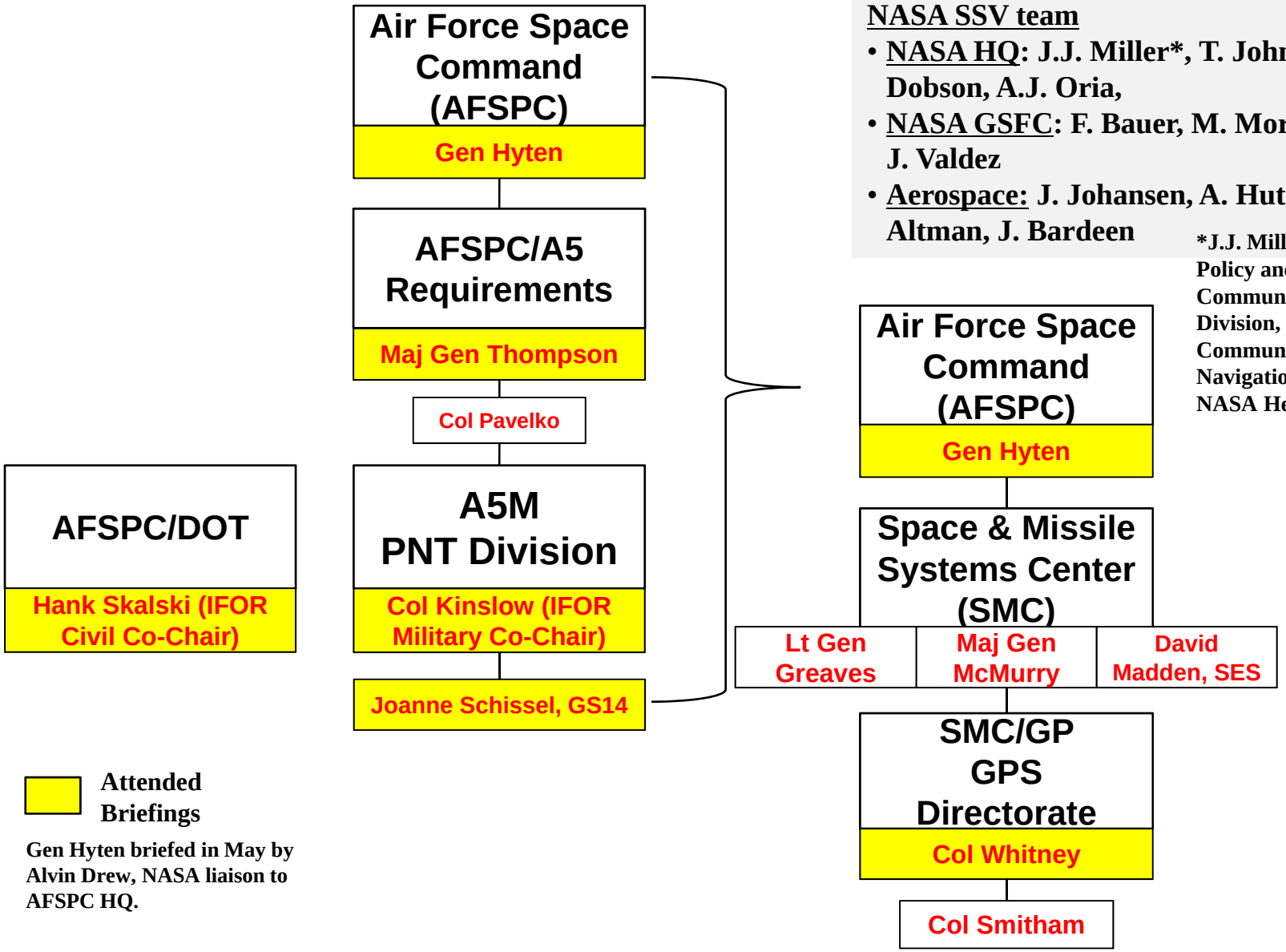
- **Significant interagency coordination & socialization accomplished**
  - Support from stakeholders in NASA, USAF, OGAs
- **NASA/DoD team is working through the USAF-DOT IFOR* process to add requirement**
  - Modification to minimum availability requirement in current Capability Development Document (CDD)
  - Also addressing sidelobe signal strength and accuracy
- **Entering critical coordination phase with SMC/GP**
  - Sep–Jan timeframe to complete analysis, requirements language coordination, analysis of alternatives, cost/impact assessments
  - Initial feedback from SMC: direction to focus on user mission requirements
  - Working with stakeholders for access to GPS-III program data to complete analyses
- **Working toward IFOR final deadline: 1 March 2016**

*IFOR: Interagency Forum for Operational Requirements

SSV Update
Socialization Status

- **Socialization Summary—May 2015-Present**
  - 5/5 NASA PNT Team
  - 6/11 National Space-Based PNT Advisory Board (Brad Parkinson, Col Whitney)
  - 6/29 AFSPC A5, SMC/GPV, SMC/GPE
  - 7/16 SMC/GP (Col Whitney, Col Kinslow)
  - 8/12 HANU-GPS Quarterly
  - 8/18 AFSPC (Maj Gen Thompson)
  - 9/10 AFRL & SMC (Col Goldstein)
  - 9/11 Interagency Operations Advisory Group (IOAG)
  - 9/14 Civil GPS Service Interface Committee (CGSIC) at ION GNSS 2015+
  - 9/21 Pentagon (D. Loverro)
  - 10/14 FAA GPS QPMR
  - 10/16 NASA Goddard Space Flight Center Director Chris Scolese
  - 10/30 National Space-Based PNT Advisory Board (Brad Parkinson, Maj Gen Thompson, Col Brennan)
  - AFSPC/SMC socialization – see next chart

AFSPC and SMC Leadership SSV Socialization Accomplished



NASA SSV team

- **NASA HQ: J.J. Miller*, T. Johnson, C. Dobson, A.J. Oria,**
- **NASA GSFC: F. Bauer, M. Moreau, J. Parker, J. Valdez**
- **Aerospace: J. Johansen, A. Hutchinson, M. Altman, J. Bardeen**

***J.J. Miller is Deputy Director, Policy and Strategic Communications (PSC) Division, Space Communications and Navigation (SCaN) Program, NASA Headquarters**

Gen Hyten briefed in May by Alvin Drew, NASA liaison to AFSPC HQ.

IFOR Status & Future Planning

Date	Milestone
23 Sep 2015	IFOR WG kickoff
30 Sep 2015	NASA formal submission of Form 1, endorsement letter
22 Oct 2015	IFOR WG status #1
9–10 Nov 2015	IFOR WG status #2 – face-to-face
1 Dec 2015	JROC HPT – TBR-level CDD language due
14 Dec 2015	*IFOR WG status #3 – face-to-face
11 Jan 2016	*IFOR WG status #4 – face-to-face
18 Jan 2016	Goal for CDD language finalization
1 Mar 2016	IFOR completion deadline

Current milestone

IFOR process milestones

*proposed

HEO/GEO SSV
Signal Protection Requirement Concepts

Primary goals

1) Protect current signals so new constellation builds maintain current PNT performance for HEO/GEO users

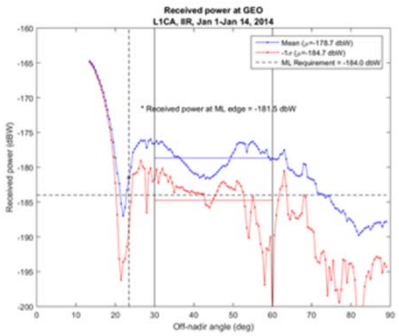
2) Specify smartly to not drive design

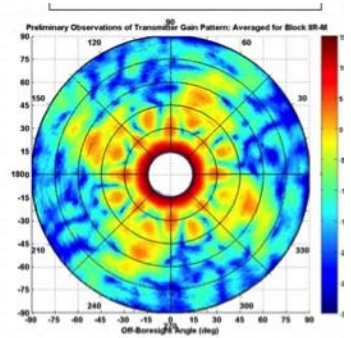
3) Similar to or minor changes to current SSV specification

4) No better than current system

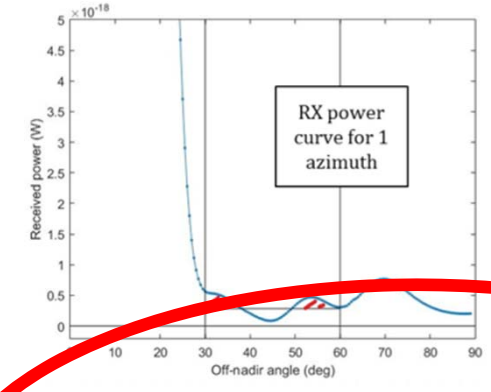
- Assumes 24+3 satellite constellation
- Analyses use constellation build with worst case signals in space

3 Concepts Currently Considered





Mean Received Side Lobe Power



Total Received Signal Power

	MEO SSV (unchanged from current requirement)		HEO/GEO SSV	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	100%	≥ 99%
L2, L5	100%	100%	100%	≥ 77%

Signal Availability above Threshold Power

Work in Progress/Tentative Ideas

Way Ahead

- **Continue socialization activities. Next up:**
  - NOAA (GOES-R)
  - USAF/OGAs
- **Continue IFOR process toward USAF milestones:**
  - 1 Dec 2015: Draft CDD language for USAF High Performance Team (HPT)
  - 1 Mar 2016: Last possible date for IFOR completion
- **Work with GPS Directorate (SMC/GP) during three-month coordination & analysis period**
  - Conduct monthly formal status meetings – F2F Nov 9-10
  - Goal for CDD language finalization – 18 Jan 2016
- **Complete analyses**
  - Performance-based analysis from current GPS performance ("what is provided")
  - User-based analysis from user mission requirements ("what is necessary")

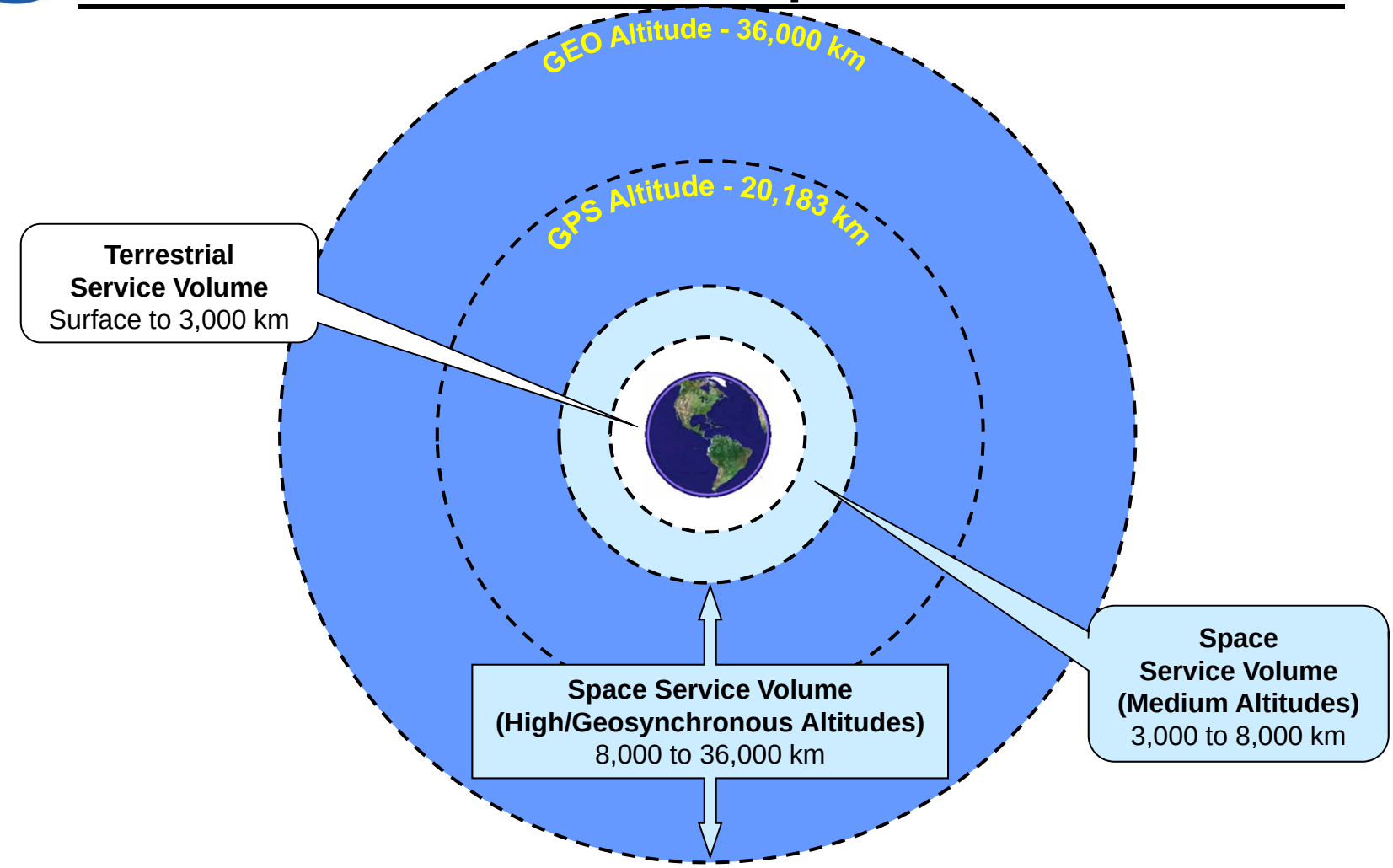
Closing Remarks

- **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 side lobe signals are critically important and not specified**
- **Several concepts are being worked to specify and protect GPS signal availability/signal strength in these orbit regimes**
- **CDD & requirements update for HEO/GEO SSV users will:**
  - Maintain capabilities employed in HEO/GEO with current constellation
  - Provides a green-light for civil and military space missions considering future operational use of GPS beyond LEO
- **Interoperability for all space users will be enhanced if other PNT service providers such as Galileo also implement similar requirements/operational capabilities.**
  - This issue has been actively worked as part of ICG meetings since 2011

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

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**