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GNSS Space Service Volume Update—ICG WG-B

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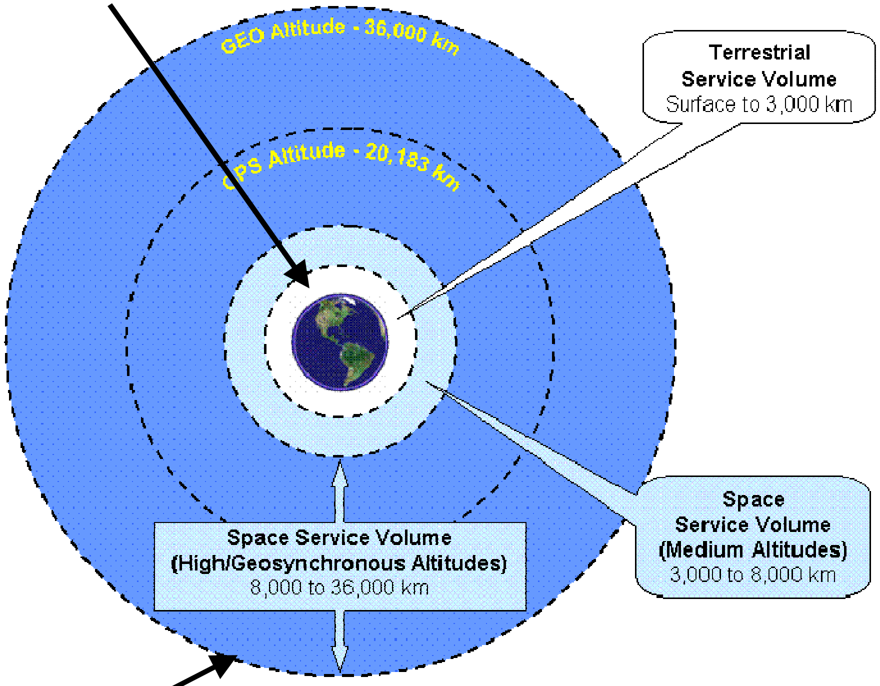
Expanding the GPS Space Service Volume (SSV) into a multi-GNSS SSV

- At least four GNSS satellites in line-of-sight are needed for on-board real-time autonomous navigation
  - GPS currently provides this up to 3,000 km altitude
  - Enables better than 1-meter position accuracy in real-time
- At Geosynchronous altitude, only one GPS satellite will be available at any given time.
  - GPS-only positioning still possible with on-board filtering, but only up to approx. 100-meter absolute position accuracy.
  - GPS + Galileo combined would enable 2-3 GNSS sats in-view at all times.
  - GPS + Galileo + GLONASS would enable at least 4 GNSS sats in-view at all times.
  - GPS + Galileo + GLONASS + Beidou would enable > 4 GNSS sats in view at all times. This provides best accuracy and, also, on-board integrity.
- However, this requires:
  - Interoperability among these the GNSS constellations; and
  - Common definitions/specifications for use of GNSS signals within the Space Service Volume (3,000 km to Geosynchronous altitude)

≥ 4 GPS satellites in line-of-sight here (surface to 3000 km)



Only 1-2 GPS satellites in line-of-sight at Geosynchronous orbit altitude

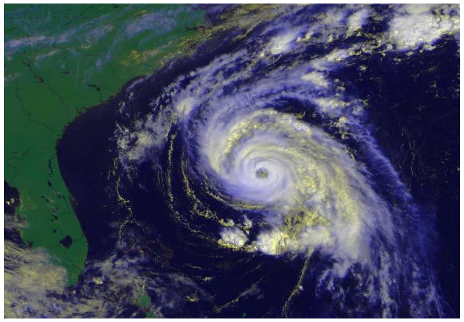
... but, if interoperable, then GPS + Galileo + GLONASS + Beidou provide > 4 GNSS sats in line-of-sight at Geosynchronous orbit altitude.

Why is an interoperable Space Service Volume important?

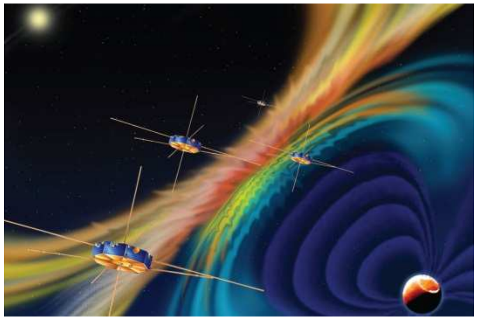
Global, interoperable Space Service Volume specifications are crucial for real-time GNSS navigation solutions in high Earth orbit

•Supports increased satellite autonomy for high Earth orbit missions, lowering mission operations costs

- **Enables new/enhanced mission capabilities for High Earth orbit and geostationary orbit missions of the future, such as:**



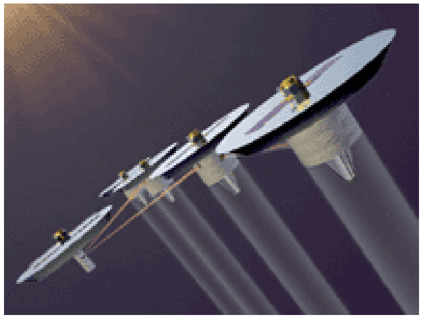
Improved Weather Prediction using Advanced Weather Satellites



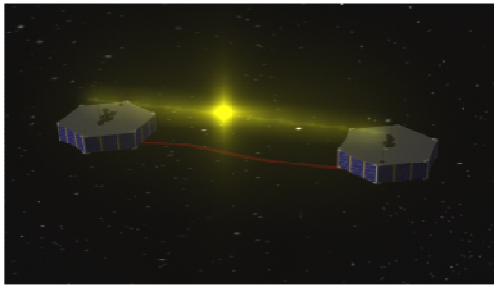
Space Weather Observations

Astrophysics Observations

En-route Lunar Navigation Support

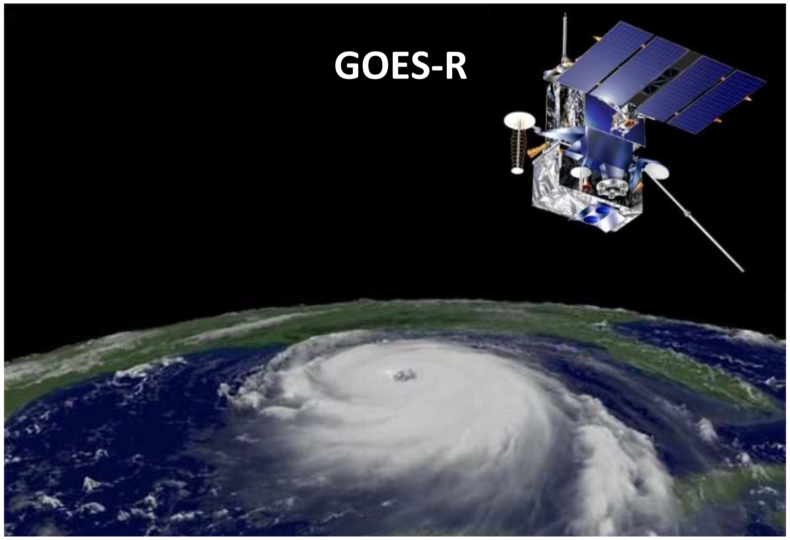


Formation Flying & Constellation Missions



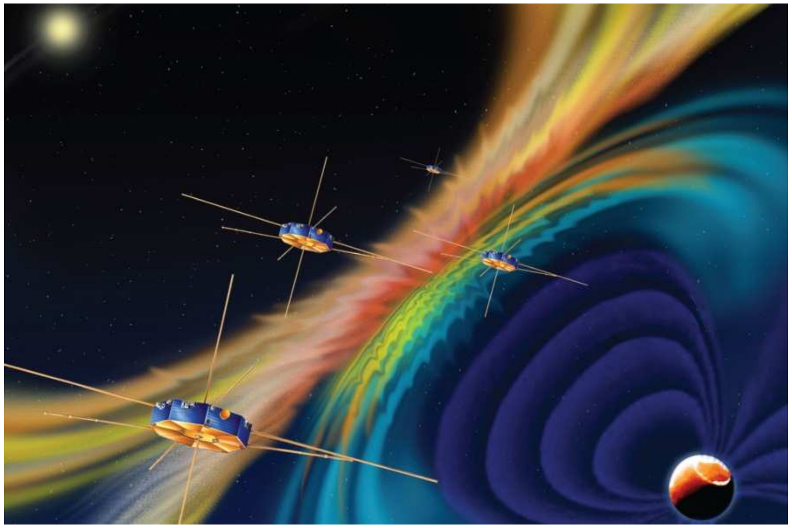
Closer Spacing of Satellites in Geostationary Arc

Current U.S. Missions using GPS above the GPS Constellation



GOES-R Weather Satellite Series

- First operational use of GPS above the constellation
- Improves navigation performance for GOES-R
- Station-keeping operations on current GOES N-Q constellation require relaxation of Image Navigation Registration for several hours
- GPS supports GOES-R breaking large station-keeping maneuvers into smaller, more frequent ones
  - Quicker Recovery
  - Minimal impact on weather science

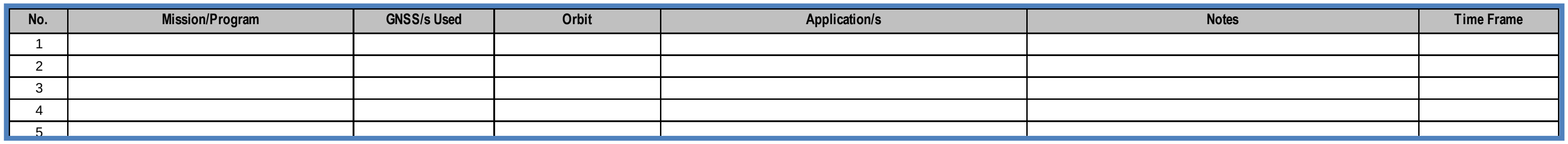


Magnetospheric Multi-Scale (MMS) Mission

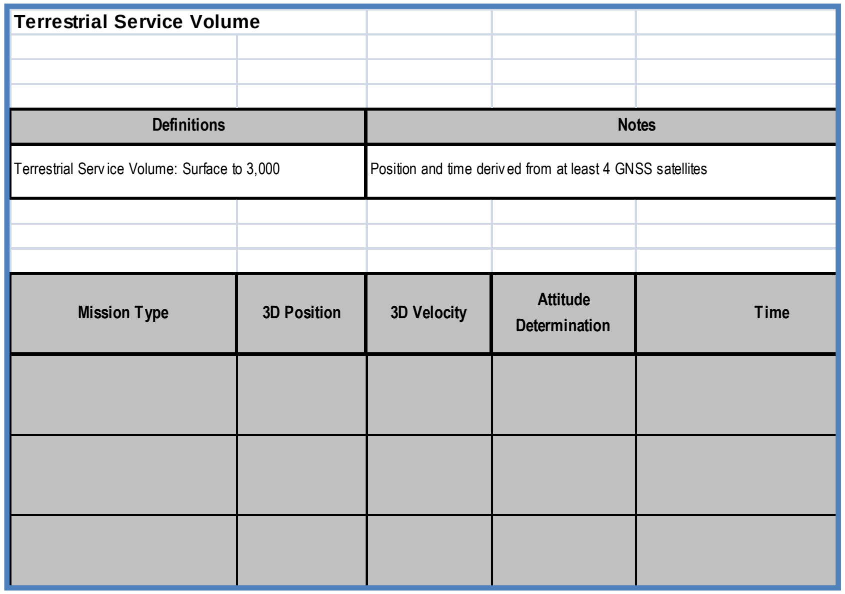
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Starts in 1.2 x 12 Re orbit (7600 km x 76,000 km)
- GPS enables onboard (autonomous) navigation and potentially autonomous station-keeping

GNSS Space Service Volume Templates

- GNSS space user performance templates have been distributed to the ICG WG-B and to the Interagency Operational Advisory Group (IOAG), these include
  - A list of space missions using GNSS for navigation and/or science applications
  - Performance characteristics for the Terrestrial Service Volume (surface to 3000 km altitude)
  - Performance characteristics for the Space Service Volume (3000 km to geosynchronous altitude)



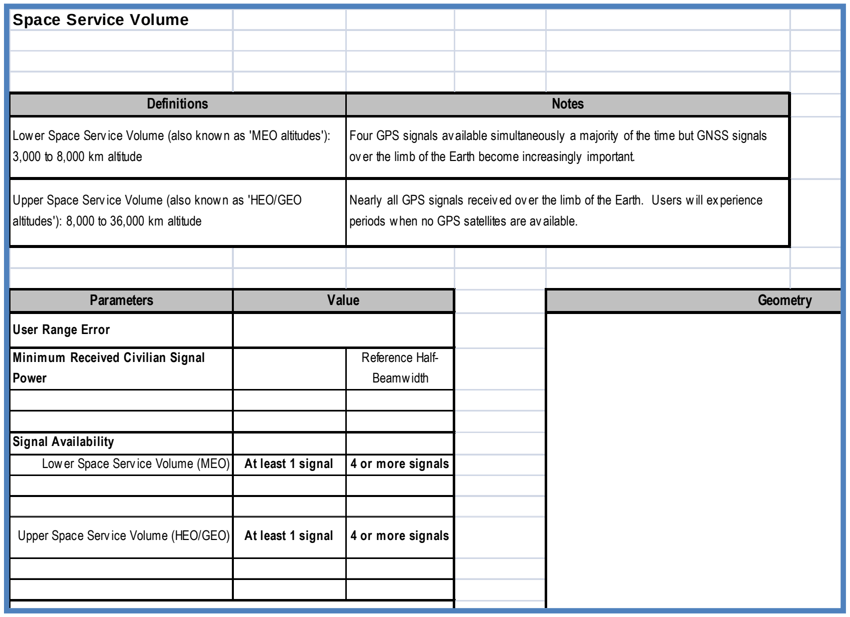
No.	Mission/Program	GNSS/s Used	Orbit	Application/s	Notes	Time Frame
1						
2						
3						
4						
5						



Terrestrial Service Volume

Definitions	Notes
Terrestrial Service Volume: Surface to 3,000	Position and time derived from at least 4 GNSS satellites

Mission Type	3D Position	3D Velocity	Attitude Determination	Time



Space Service Volume

Definitions	Notes
Lower Space Service Volume (also known as 'MEO altitudes'): 3,000 to 8,000 km altitude	Four GPS signals available simultaneously a majority of the time but GNSS signals over the limb of the Earth become increasingly important.
Upper Space Service Volume (also known as 'HEO/GEO altitudes'): 8,000 to 36,000 km altitude	Nearly all GPS signals received over the limb of the Earth. Users will experience periods when no GPS satellites are available.

Parameters	Value	
User Range Error		
Minimum Received Civilian Signal Power		Reference Half-Beamwidth
Signal Availability		
Lower Space Service Volume (MEO)	**At least 1 signal**	**4 or more signals**
Upper Space Service Volume (HEO/GEO)	**At least 1 signal**	**4 or more signals**

Geometry

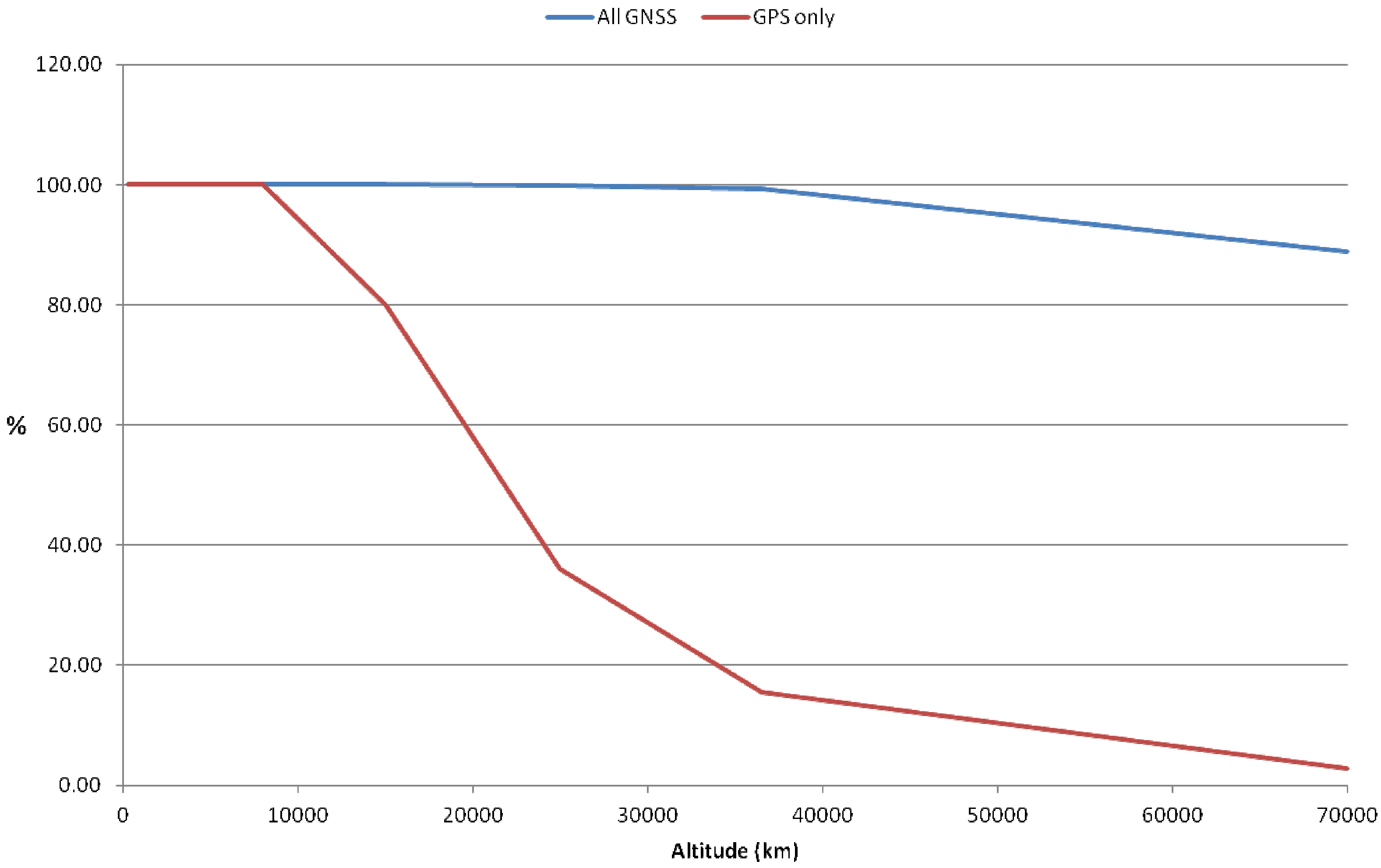
Realizing the Space Service Volume Vision
The LONG and Winding Road

- Mid-1990s—efforts started to develop a formal Space Service Volume (SSV) with accompanying GPS signal and availability specification
- February 2000—GPS Operational Requirements Document (ORD), released, included first space user requirements and description of SSV
- 1997-Present—Several space flight experiments, particularly the AMSAT-OSCAR-40 experiment, provided data to enhance space user requirements and SSV
- 2000-2010—NASA/DoD team coordinated set of updated Space User requirements to meet existing and future PNT needs
  - Team worked with SMC/GPE, Aerospace support staff and AFSPACE to assess impacts of proposed requirements to GPS-III and to incorporate appropriate language into GPS-III Capabilities Description Document (CDD)
  - Threshold requirements correspond to performance from current constellation (do no harm to space users)
  - Future space user needs included as Objective requirements
  - Continual Joint Program Office "zero impact" push back on CDD levels to GPS-III baseline (Objective requirements)
  - Agreed to perform NASA/DoD study further as constellation design matures with emphasis on moving towards Objective requirements
  - Government System Spec (SS-SYS-800) includes CDD threshold & objective performance

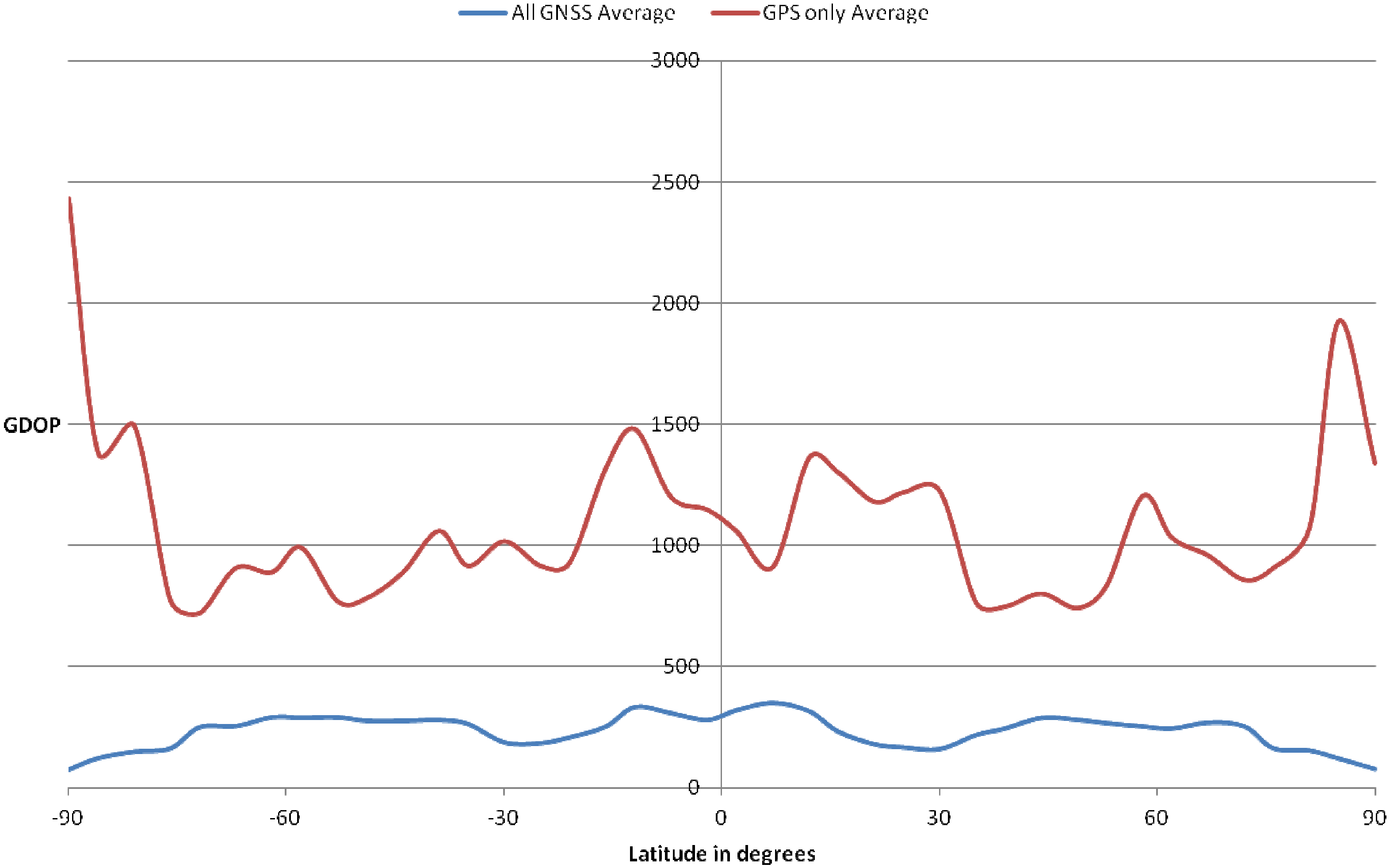
Navigation Improvements Resulting from an Interoperable SSV

- Analysis performed to understand effects of augmenting GPS SSV signals with interoperable GNSS and SBAS
- Configuration analyzed:
  - GPS: 24 + 3 configuration
  - Galileo: 27 satellite configuration
  - GLONASS: 24 satellite configuration
  - Beidou: 27 MEO, 5 GEO, 3 IGSO
  - SBAS: 3 satellites for WAAS, EGNOS, SDCM (planned), QZSS(planned); GAGAN: first satellite launched
- Benefits observed:
  - >4 satellites observed 100% of time w/ all GNSS constellations & augmentations
  - Factor of ~2-5 improvement in geometric dilution of precision (GDOP) when all constellations included
- **Global, interoperable Space Service Volume specifications are crucial for real-time GNSS navigation solutions in high Earth orbit**

Navigation Coverage, 4+ Satellites in View GNSS Constellations + SBAS



Geometric Dilution of Precision, 36500 km



Acknowledgements

- Sincere thanks to all in the U.S. that have helped realize the Space Service Volume vision:
  - USAF SMC GPS Program Office
  - NASA
  - Frank Bauer
  - Stephan Esterhuizen
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  - Mike Moreau
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  - Park Temple
  - Larry Young

- Acknowledging, in advance, all outside the U.S. that recognize the in-space advantages of the Space Service Volume specification and provide leadership in developing a Space Service Volume specification for their GNSS constellation

Scientific Applications & Actions from Vienna 2013

Scientific Applications & Actions from Vienna 2013

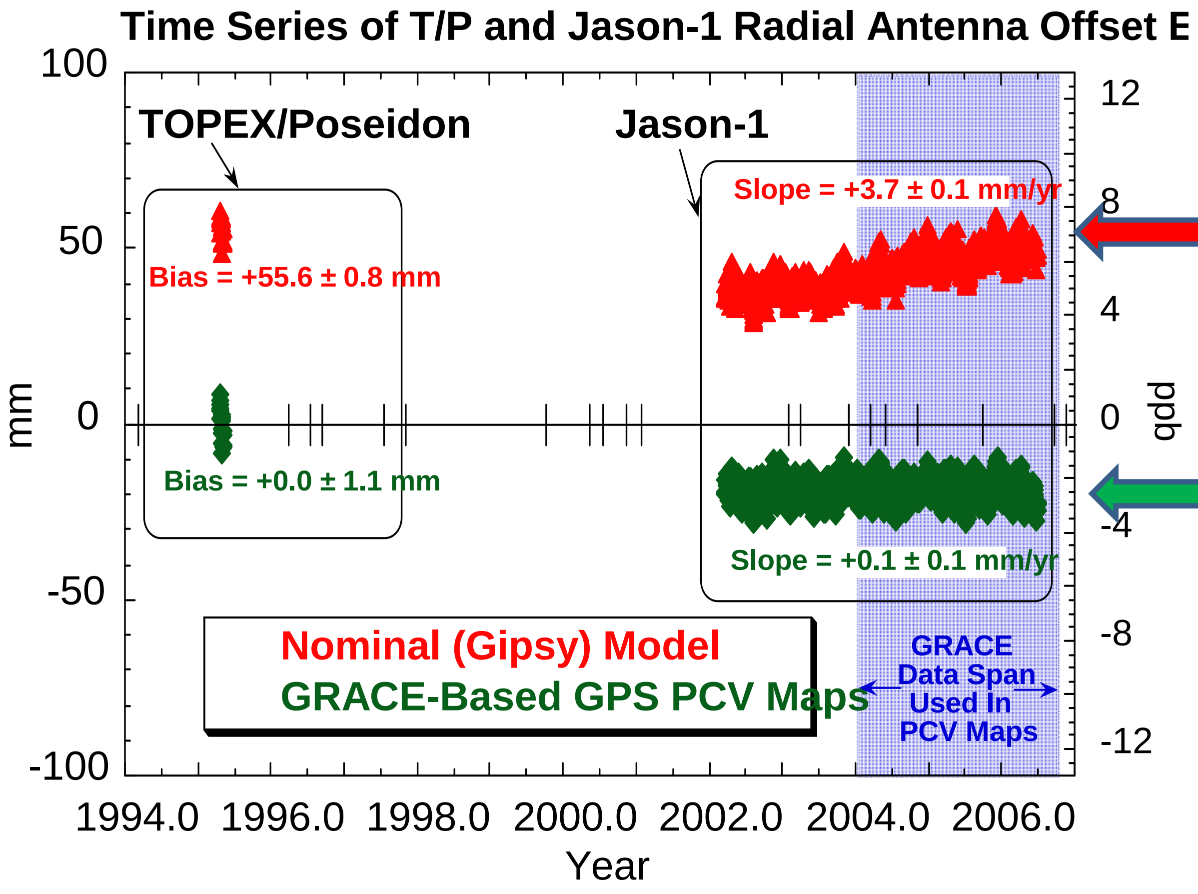
- Applications: Ocean Altimetry and Terrestrial Reference Frame
- How to create: GPS Transmit Antenna Maps (group delay and phase vs. angle)
- Variation of antenna patterns between spacecraft and between blocks
- Recommendations from the Scientific Community

Application: Ocean Altimetry

(Bruce Haines et al)

Uncertainties in GPS transmit antenna phase variations are among the limiting sources of error in global, GPS-based geodesy. Apparent root cause of:

- **Bias in Topex GPS antenna position**
- **Drift in Jason GPS antenna position**

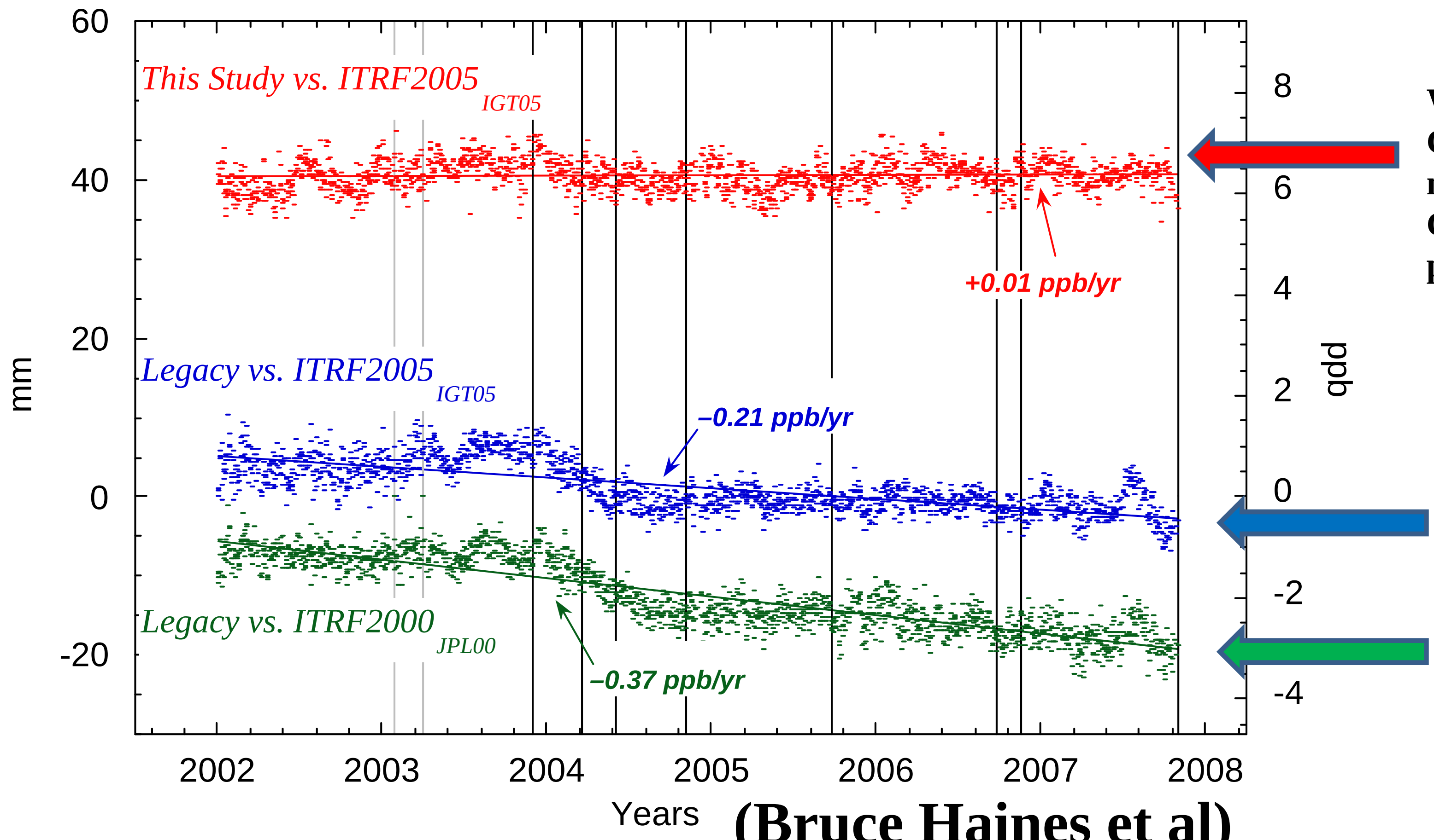


With antenna phase-center offset only

With GRACE-measured GPS antenna phase maps

Application: Reference Frame

Terrestrial Reference Frame Scale from GPS Alone (2002–2007): Agreement with ITRF2005



With GRACE-measured GPS antenna phase maps

With antenna phase-center offset only

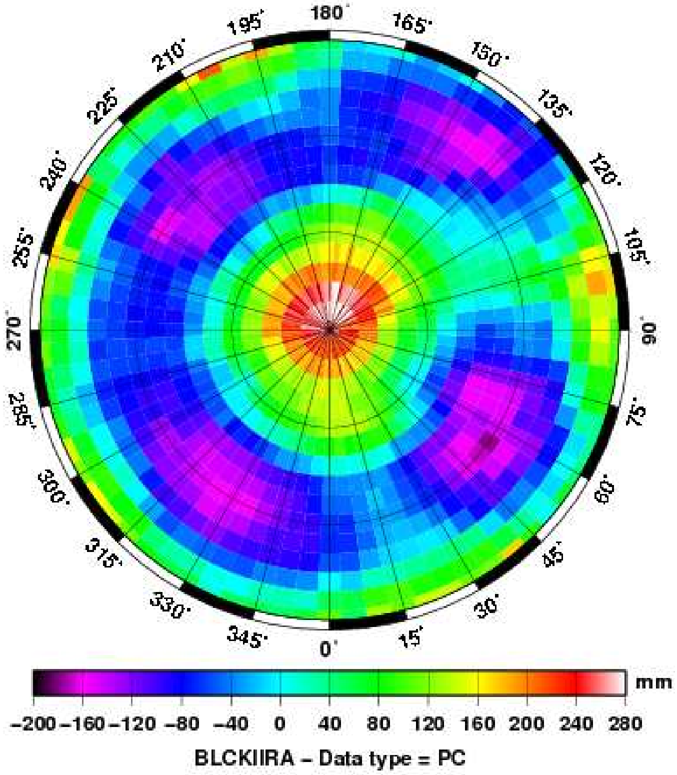
(Bruce Haines et al)

GPS Transmit Antenna Maps

- **Maps are made from 0° to 15° off nadir**
- **Ionosphere-free GPS L1/L2 measurements**

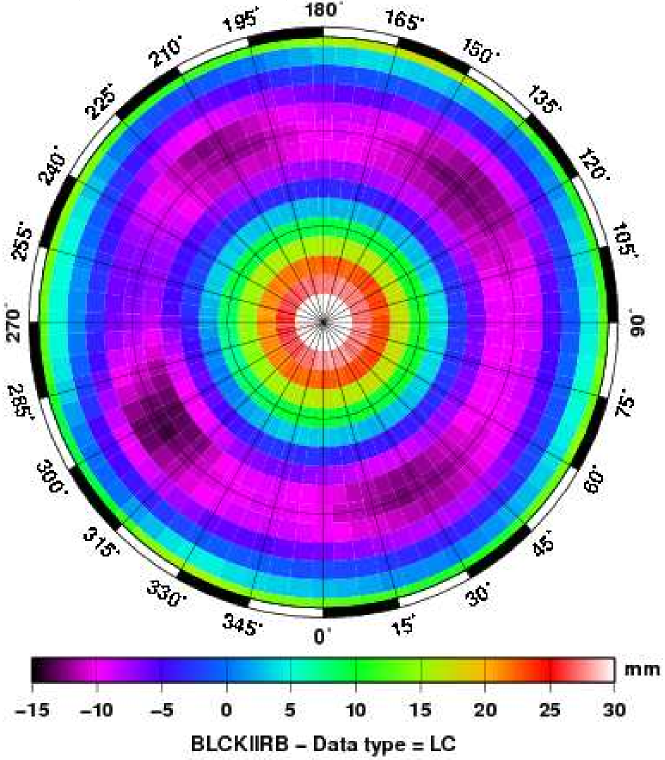
BK IIR-A Group Delay vs Angle

(Shailen Desai et al)



BK IIR-M Phase Variations

(Bar-Sever et al)

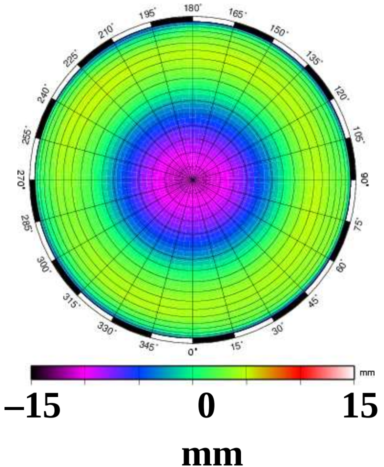


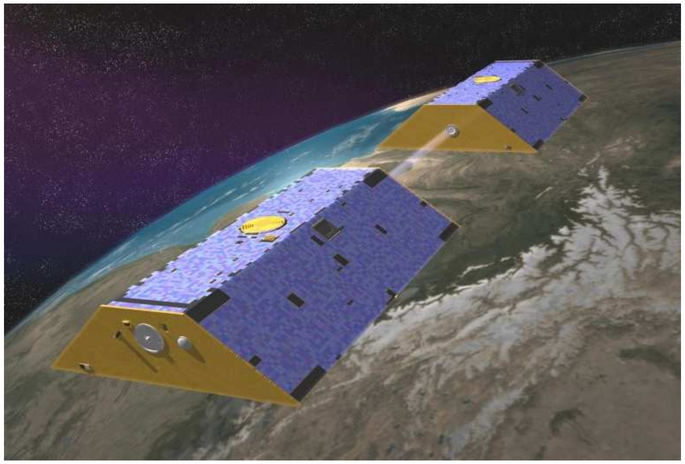
GPS Antenna Maps Created from Orbit

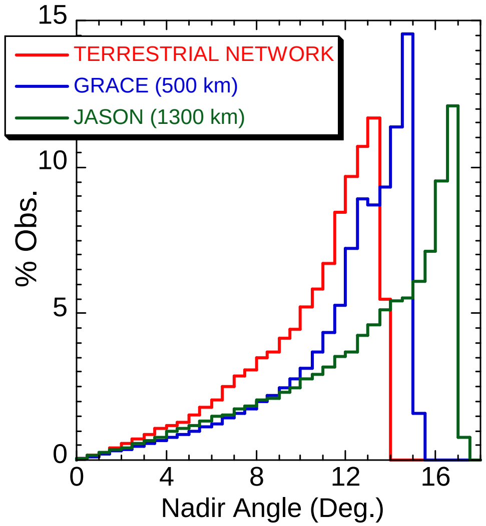
Maps created from stacked post-fit POD residuals:

- Iterative approach
- A priori GRACE antenna model from pre-launch anechoic measurements
- Estimates for all PRNs flying Oct. 2006–Nov. 2009
- Includes group delay (Ionosphere-free pseudorange, *PC*)

GRACE *a priori* antenna phase variation model from anechoic chamber



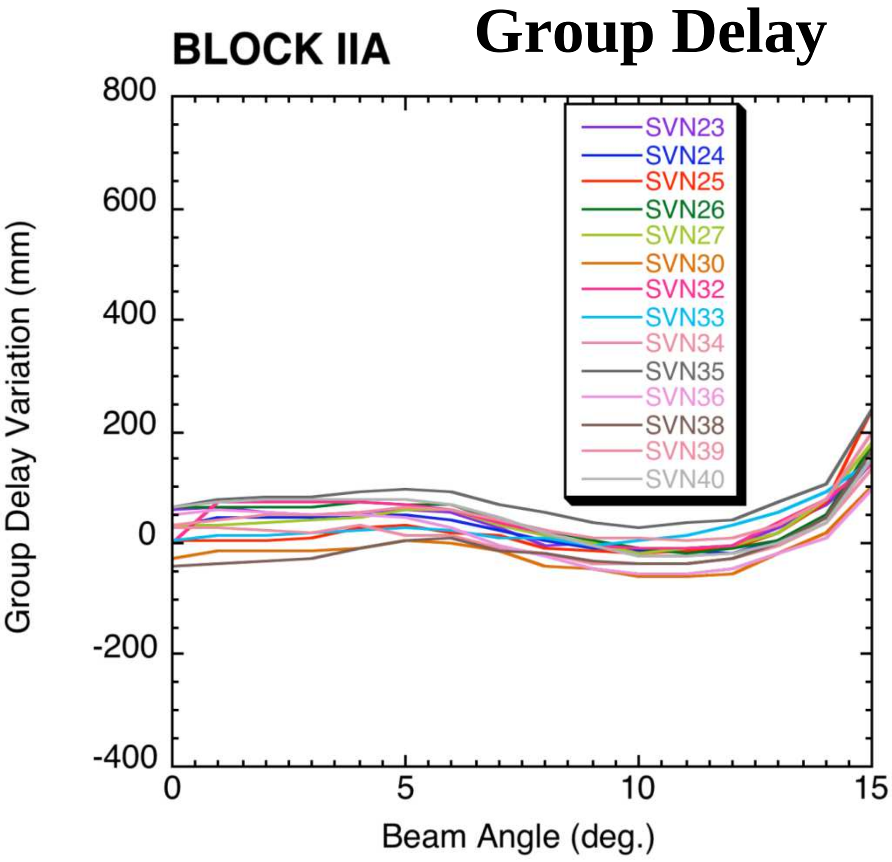


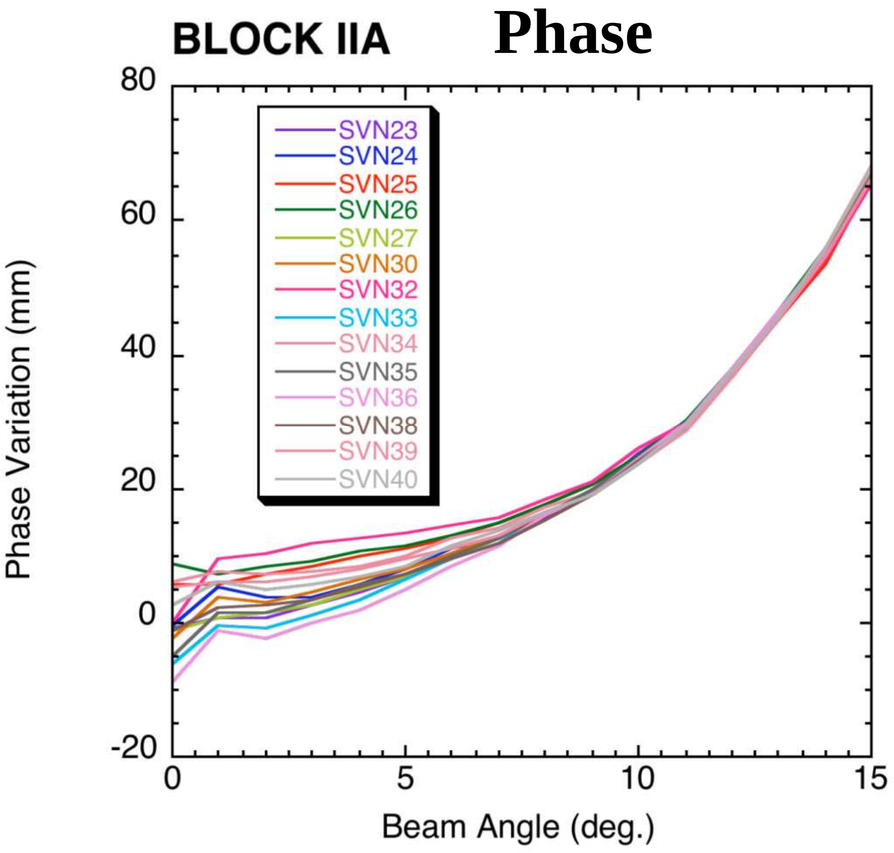


(Bruce Haines et al)

Off-nadir angle vs. percentage of observations

GPS Block IIA Transmit Antenna

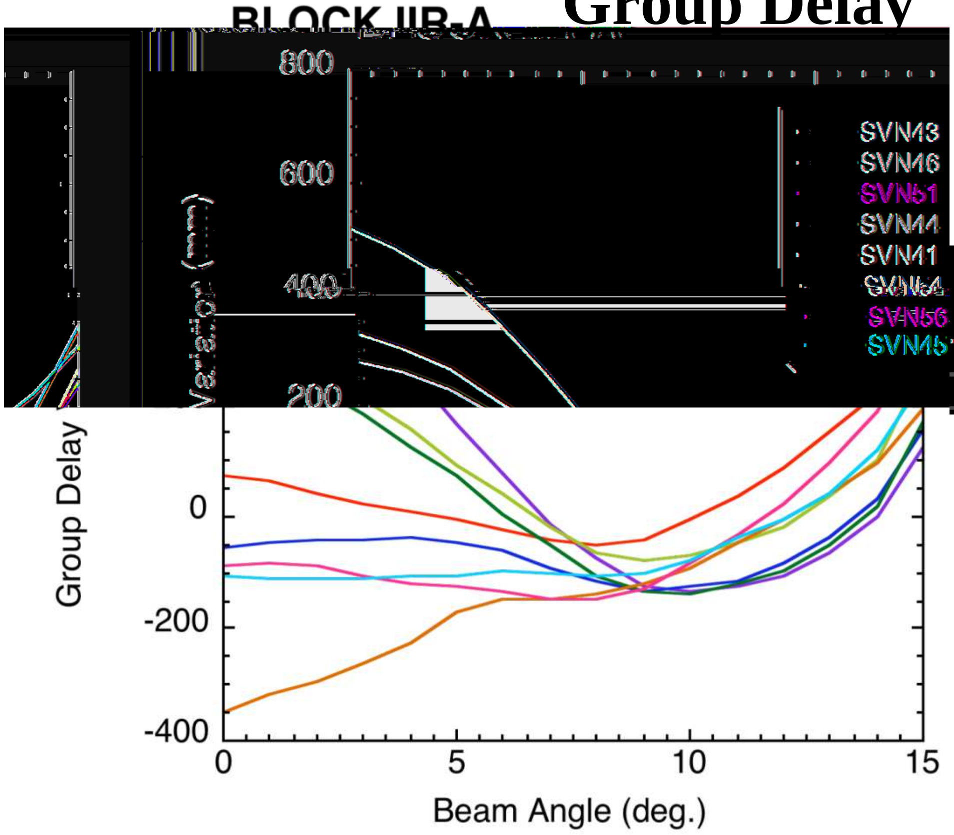

Group Delay


Phase

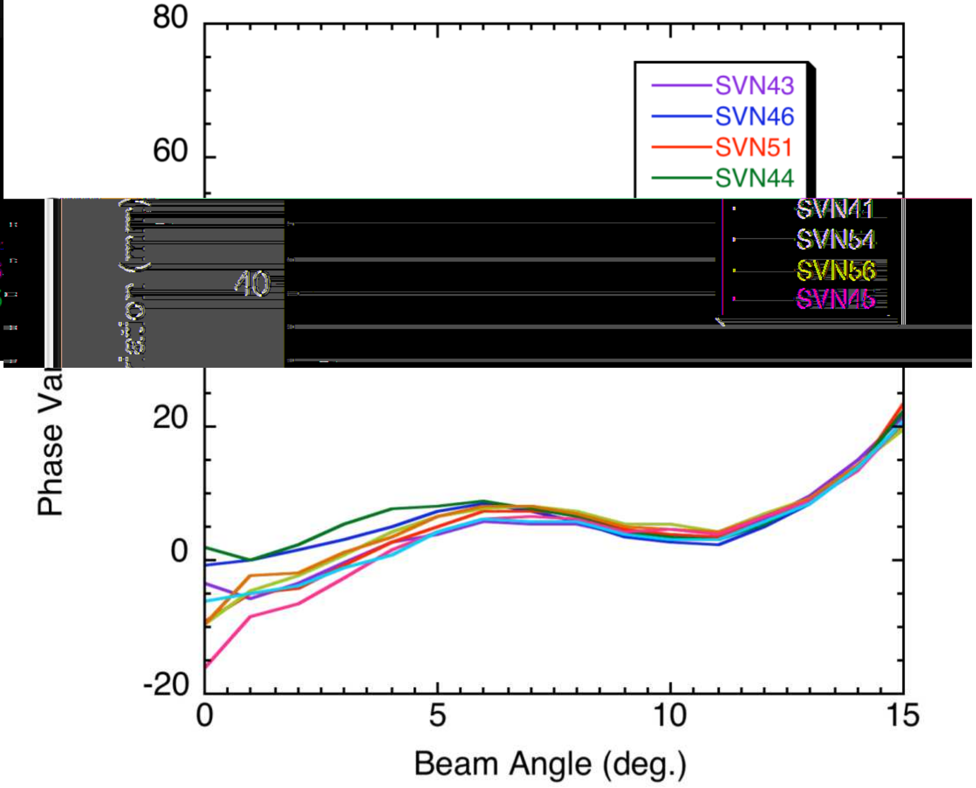
(Bruce Haines et al)

GPS Block IIR-A Transmit Antenna

Group Delay



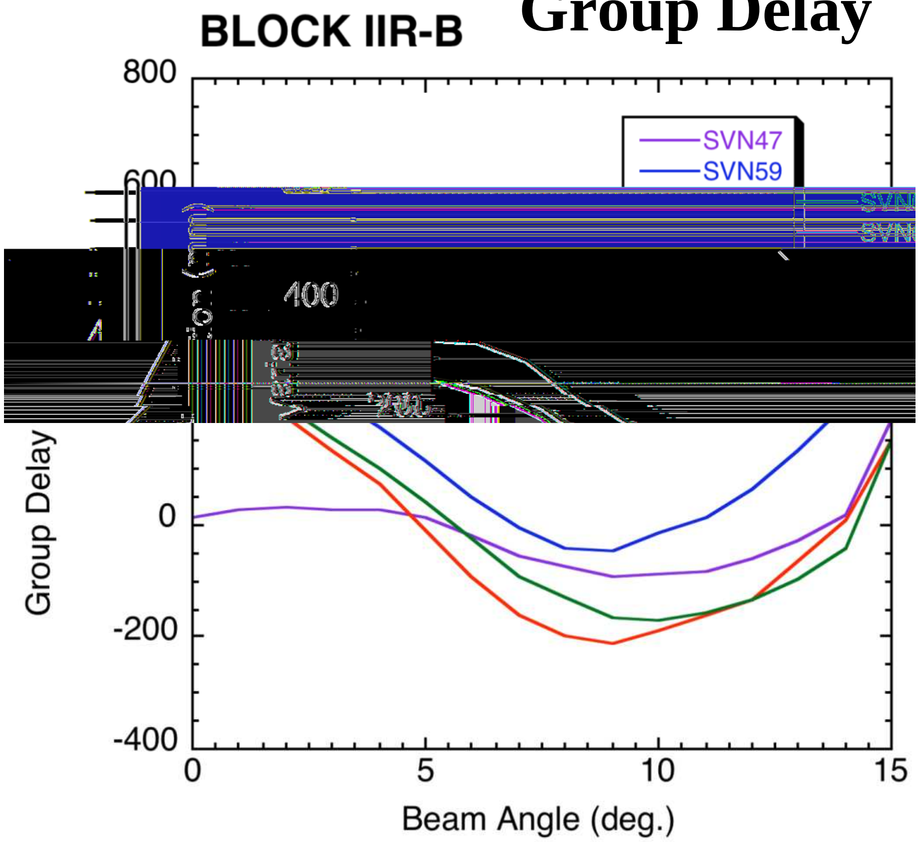
Phase



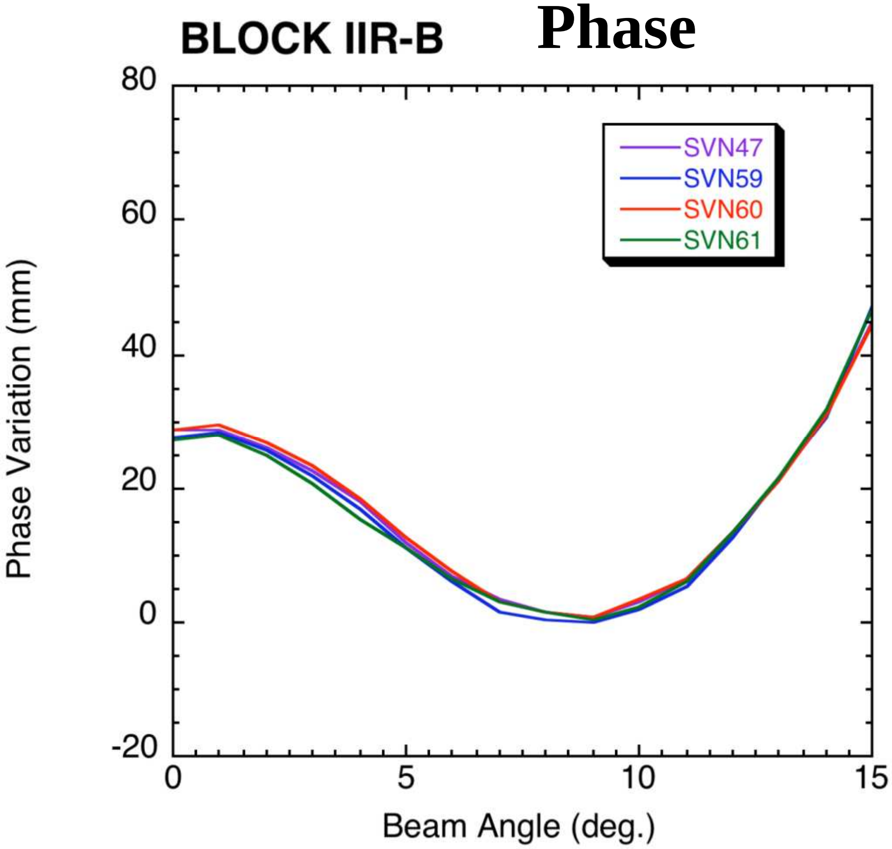
(Bruce Haines et al)

GPS Block IIR-B Transmit Antenna

Group Delay



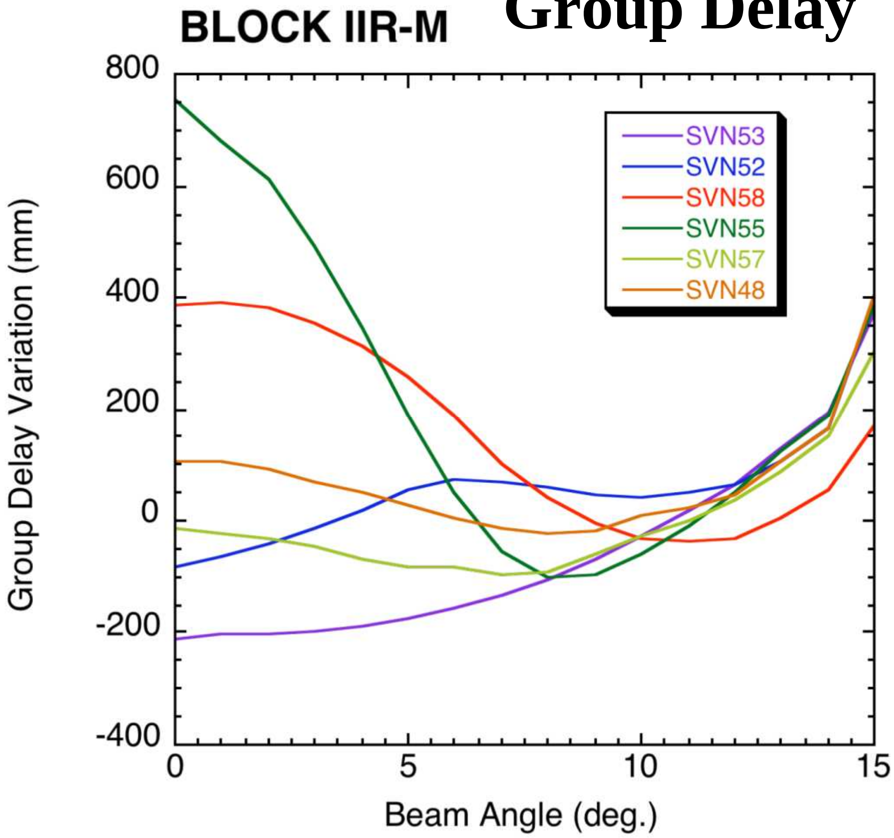
Phase



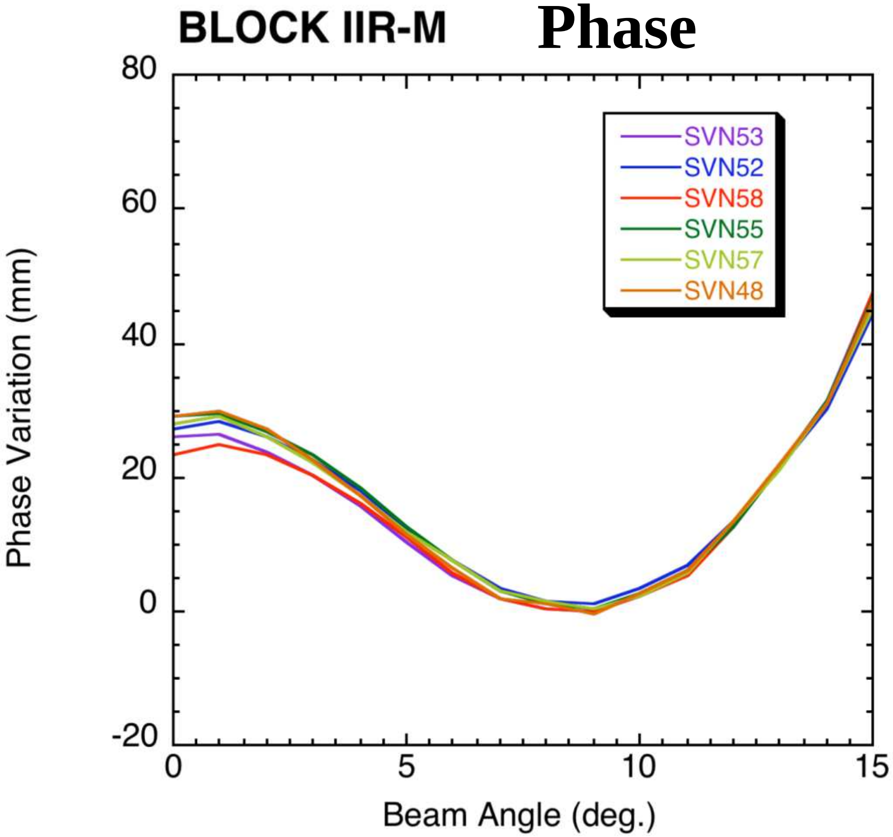
(Bruce Haines et al)

GPS Block IIR-M Transmit Antenna

Group Delay



Phase



(Bruce Haines et al)

Recommendations for GNSS Transmit Antennas–Delay and Phase Variation vs. angle

Recommendation	Variation	Knowledge of variation	Notes
Minimize group delay (pseudorange) **variation** with angle	**<1 ns** (0.3 m)	**0.1 ns** (30 mm) (accurate to 0.1ns with 95% probability)	L1: 0° to 23.5° off boresight L2: 0° to 26° off boresight
Minimize phase variation with angle	**<0.01 ns** (3mm)	**0.001 ns** (0.3 mm) (accurate to 1ps with 95% probability)	L1: 0° to 23.5° off boresight L2: 0° to 26° off boresight

Recommendations for GNSS Transmit Antennas – Delay & Phase Centers

Recommendation	Accuracy	Notes
Group delay (pseudorange) **center**	**0.1 ns** (30 mm) with 95% probability	95% probability
Phase center	**0.1 ps** (0.03 mm)	95% probability. Antenna range measurement precision < 0.03mm

The **best-fit group-and-phase delay center** is defined to be the least-squares solution for the center of a sphere of constant delay, with observations weighted equally by solid angle, from 0 to 14 degrees off boresight

Relative Group Delay & Phase Offsets: Antenna + Electronics vs. Time

Recommendation	Coherence	Notes
Relative group delay offset (coherence among codes)	**< 10 ns (3 m)**	Delay between transitions of signals shall not exceed 10ns (inter-signal, inter-frequency)
Relative phase offset (coherence among carriers)	**< 10 milliradians** (1 ps or 0.3 mm at GPS L1)	Aside from a constant bias, any pair of carriers may not deviate between each other by more than 10 milliradians
Group delay vs. phase coherence	**< 0.030 ns (9 mm)** over 6 hour period	Application: Smoothing of pseudorange with carrier phase.

Conclusion

- For the scientific community to realize the full potential of a satellite navigation system, it is crucial to provide a precise and stable system.
- Care must be taken when designing transmit antennas and spacecraft electronics due to variations between products.
- Tables of recommendations were provided, relating to designing of transmit antennas and satellite electronics.

Backups

Specifications (1): Received Signal Power

Signal	Terrestrial Minimum Power (dBW)	SSV Minimum Power (dBW)*	Reference Half-beamwidth
L1 C/A	-158.5	-184.0	23.5
L1C	-157.0	-182.5	23.5
L2C	-158.5	-183.0	26
L5	-157.0	-182.0	26

(*) SSV Minimum power from a 0 dBiC antenna at GEO

- SSV minimum power levels were specified based on the worst-case (minimum) gain across the Block IIA, IIR, IIR-M, and IIF satellites
- Some signals have several dB margin with respect to these specifications at reference off-nadir point

Specifications (2): Pseudorange Accuracy

- In the Terrestrial Service Volume, a position accuracy is specified. In the Space Service Volume, pseudorange accuracy is specified.
- Position accuracy within the space service volume is dependent on many mission specific factors, which are unique to this class of user, such as user spacecraft orbit, CONOPS, navigation algorithm, and User Equipment.
- Specification: The space service volume pseudorange accuracy shall be ≤ 0.8 m (rms) (**Threshold**); and ≤ 0.2 m (rms) (**Objective**).
- In order for GPS to meet the SSV accuracy requirement, additional data must be provided to users:
  - The group delay differential parameters for the radiated signal with respect to the Earth Coverage

Specifications (3): Signal Availability

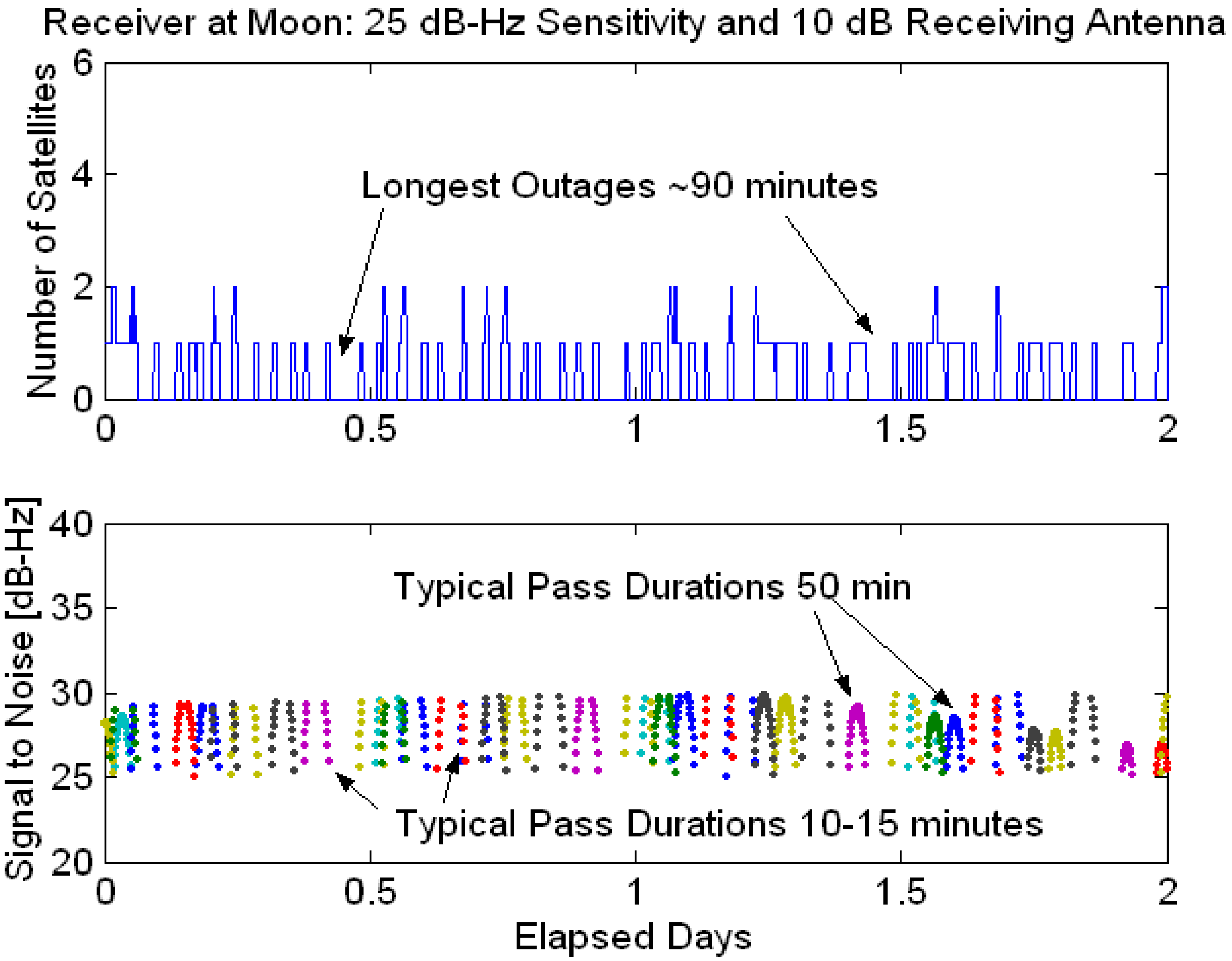
- Assuming a nominal, optimized GPS constellation and no GPS spacecraft failures, signal availability at 95% of the areas at a specific altitude within the specified SSV should be as follows:

	MEO SSV		**HEO/GEO SSV**	
	at least 1 signal	4 or more signals	at least 1 signal	4 or more signals
L1	100%	≥ 97%	≥ 80% [1]	≥ 1%
L2, L5	100%	100%	≥ 92% [2]	≥ 6.5%

1. With less than 108 minutes of continuous outage time.
2. With less than 84 minutes of continuous outage time.

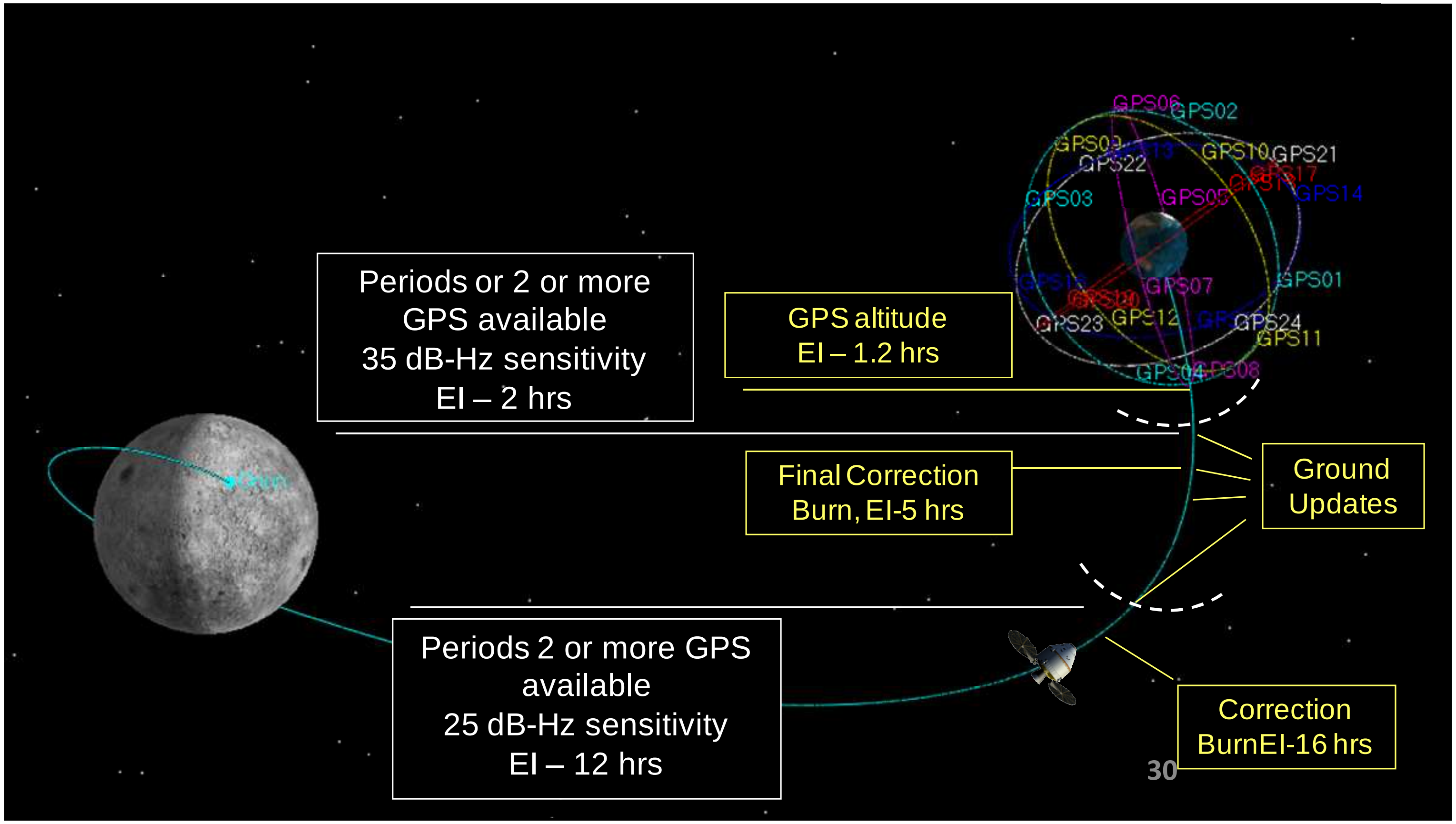
- Objective:
  - MEO SSV: 4 GPS satellites always in view
  - HEO/GEO SSV: at least 1 GPS satellite always in view

Signals Present for 25 dB-Hz Sensitivity GPS Receiver at Moon



GPS Use in Cislunar Space

- Weak GPS signal tracking technology enables tracking signals up to approximately ½ the distance to the Moon
- For example, a spacecraft returning from the Moon could start using GPS data 16 hours before Earth Insertion (EI) for trajectory determination



Periods or 2 or more GPS available
35 dB-Hz sensitivity
EI – 2 hrs

GPS altitude
EI – 1.2 hrs

Final Correction Burn, EI-5 hrs

Ground Updates

Periods 2 or more GPS available
25 dB-Hz sensitivity
EI – 12 hrs

Correction BurnEI-16 hrs