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GNSS Space Service Volume Update—ICG WG-B

Frank H. Bauer, Emergent Space Technologies for SCaN Program

Stephan Esterhuizen, JPL for SCaN Program

Human Exploration and Operations Mission Directorate (HEOMD), NASA

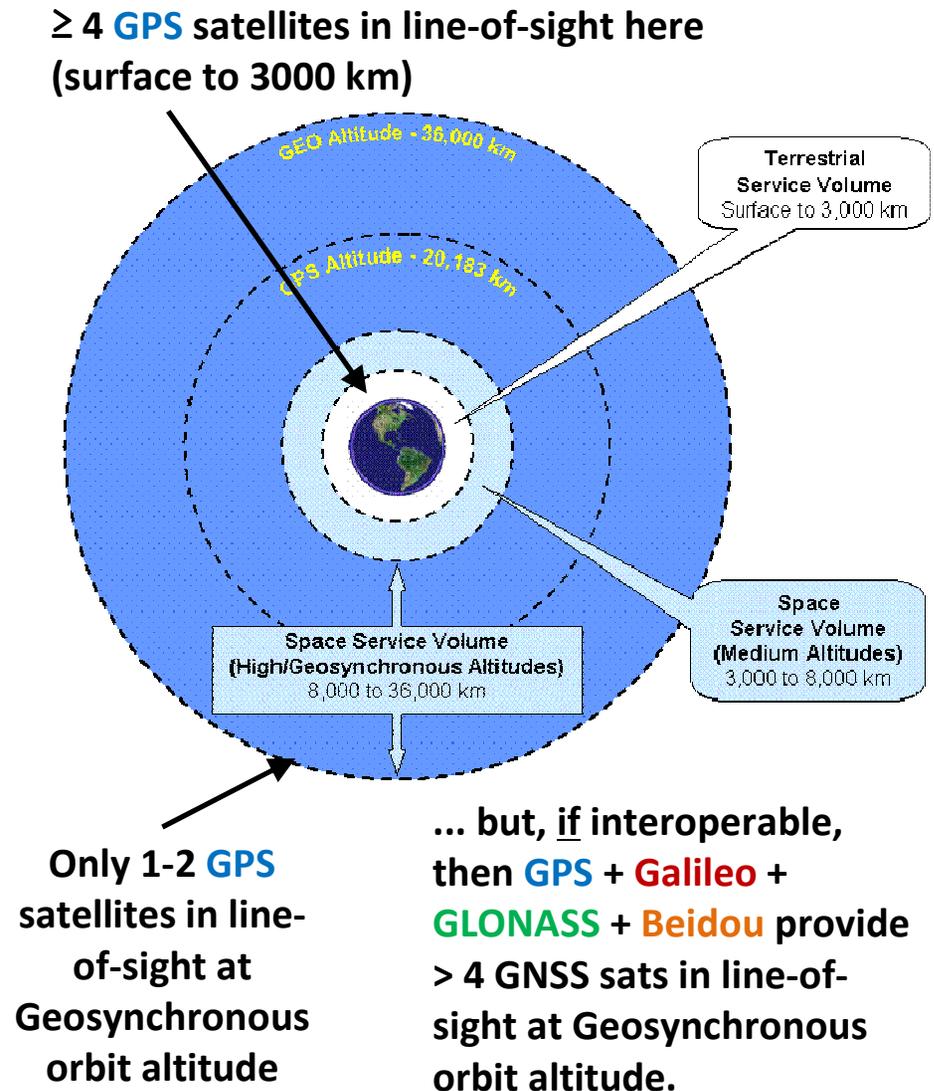
ICG-8, Dubai, UAE, November 12, 2013



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)





Why is an interoperable Space Service Volume important?

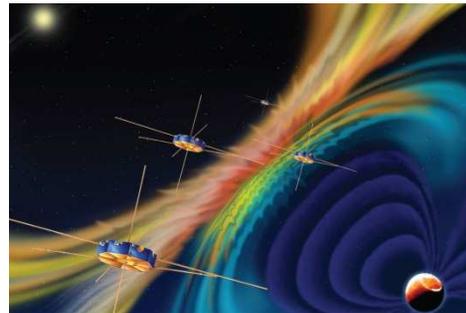


Global, interoperable Space Service Volume specifications are crucial for real-time GNSS navigation solutions in high Earth orbit

- 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



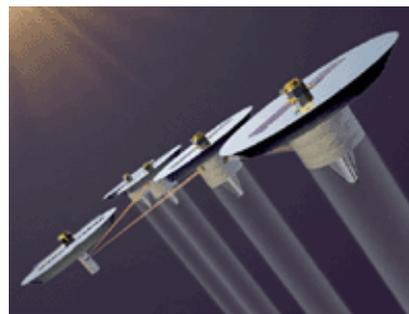
Space Weather Observations



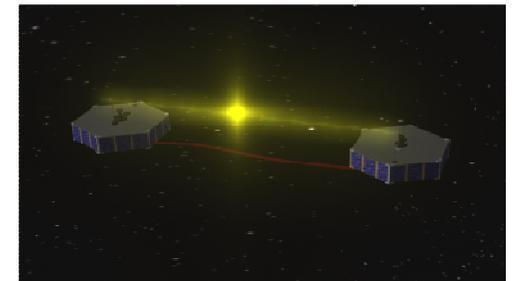
Astrophysics Observations



En-route Lunar Navigation Support



Formation Flying & Constellation Missions



Closer Spacing of Satellites in Geostationary Arc

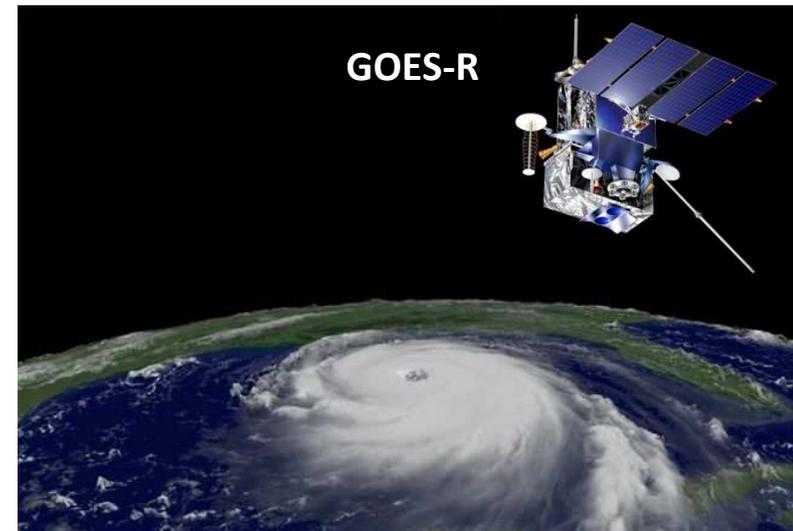


Current U.S. Missions using GPS above the GPS Constellation



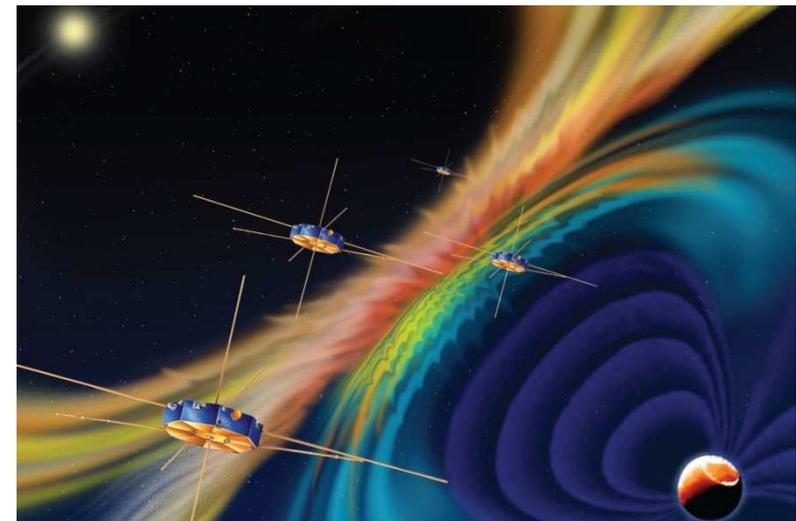
GOES-R Weather Satellite Series

- 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		Geometry
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	



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



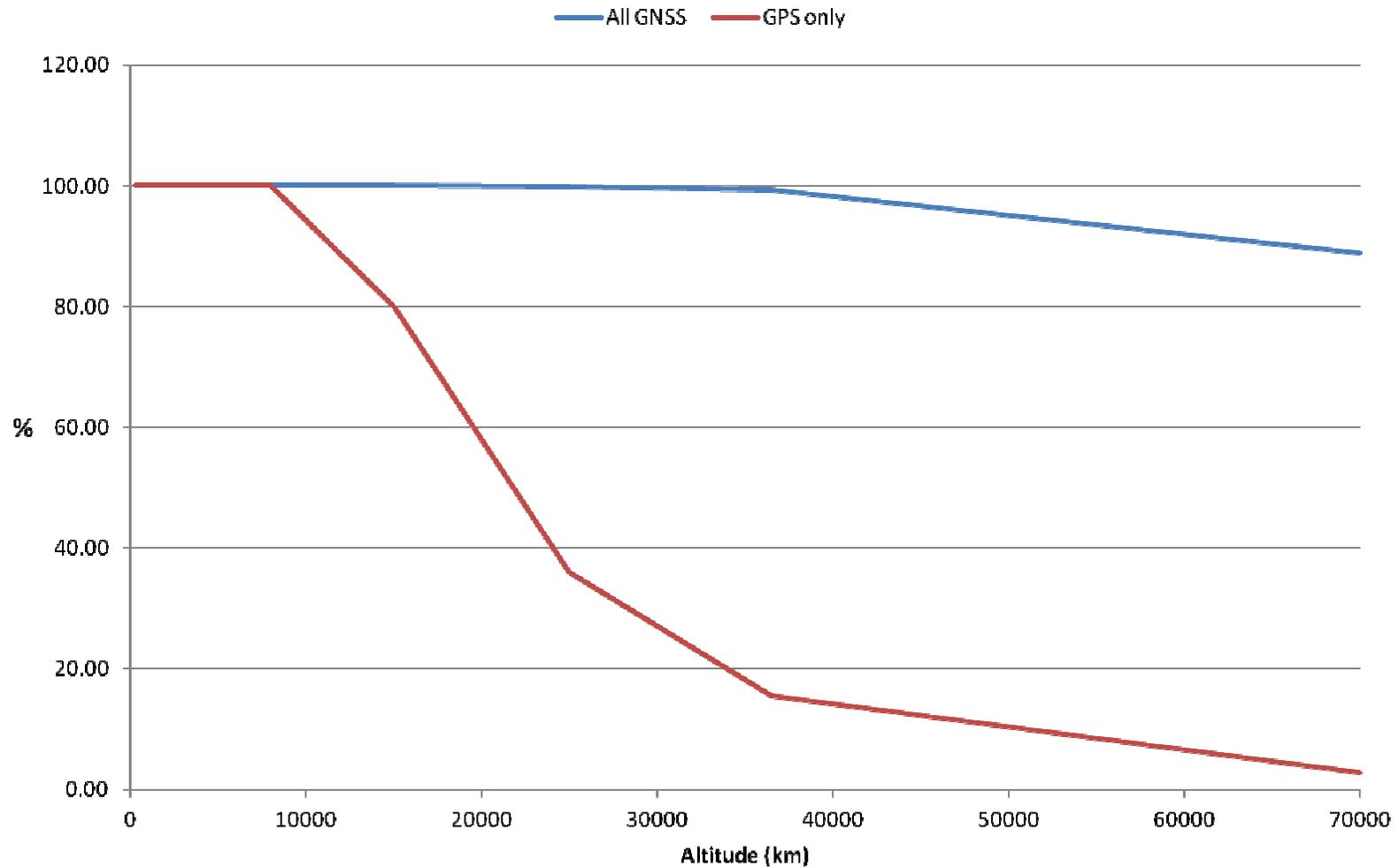
Navigation Improvements Resulting from an Interoperable SSV



- 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**

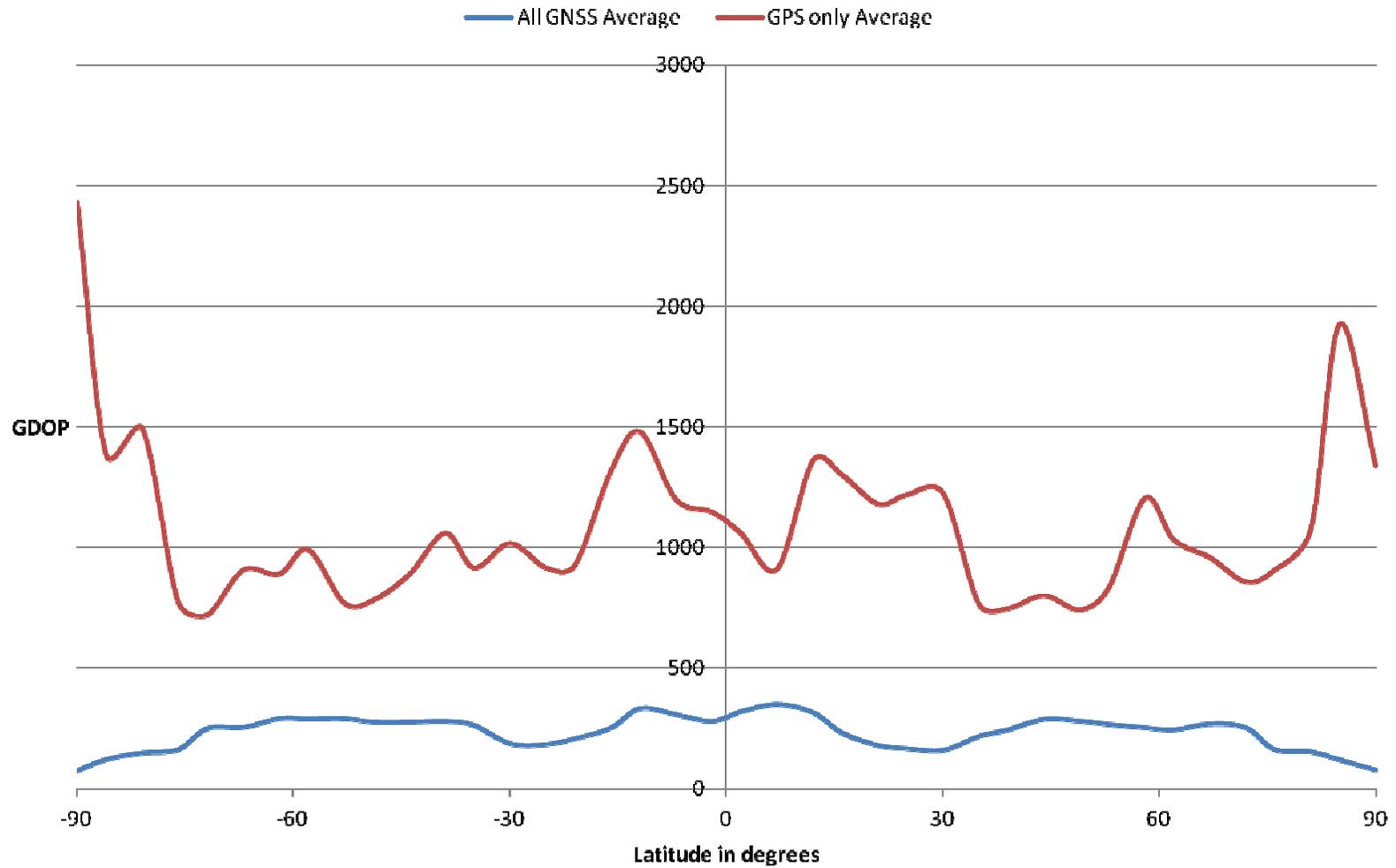


Navigation Coverage, 4+ Satellites in View GNSS Constellations + SBAS





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
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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



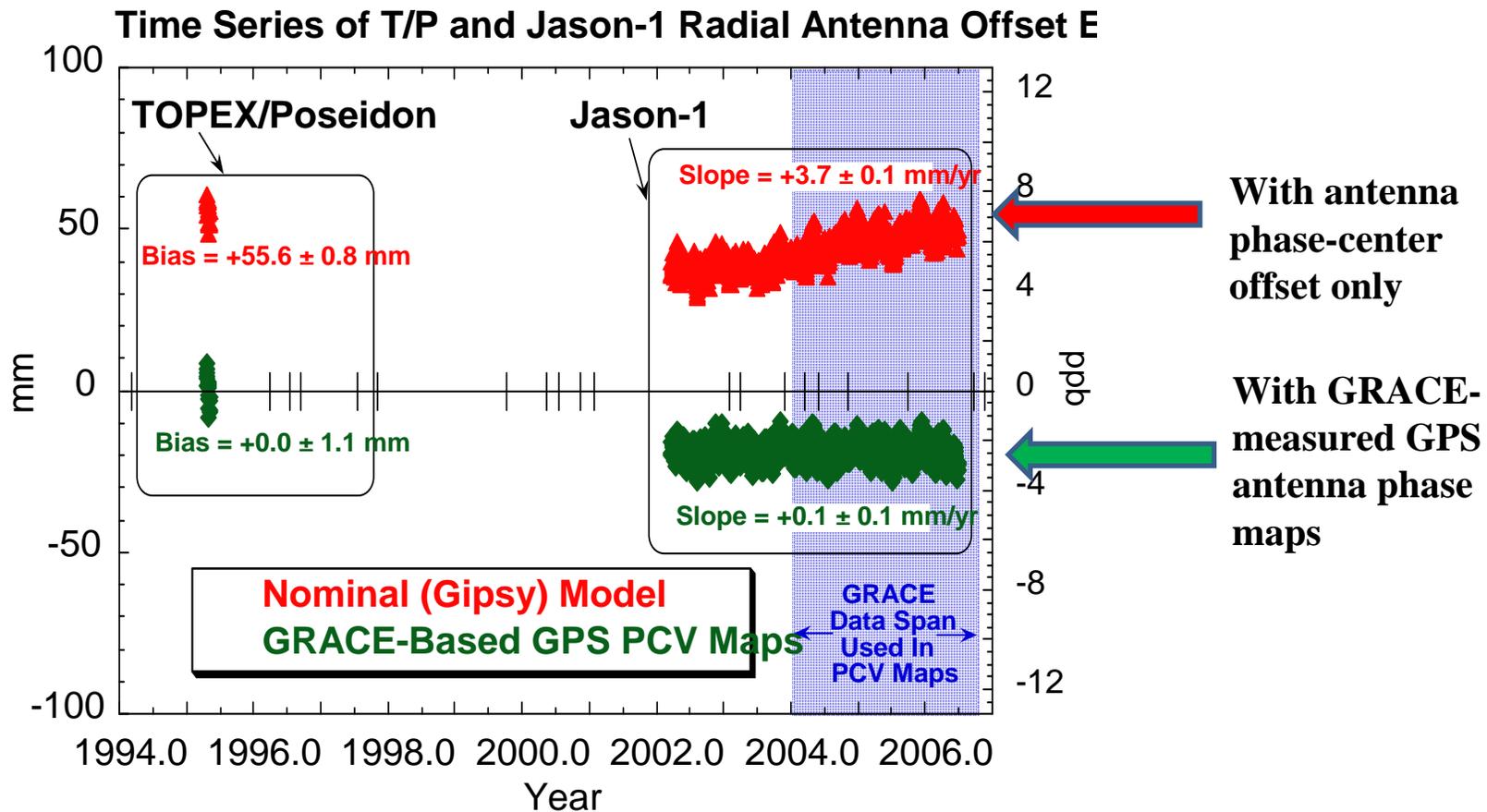
Application: Ocean Altimetry



(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

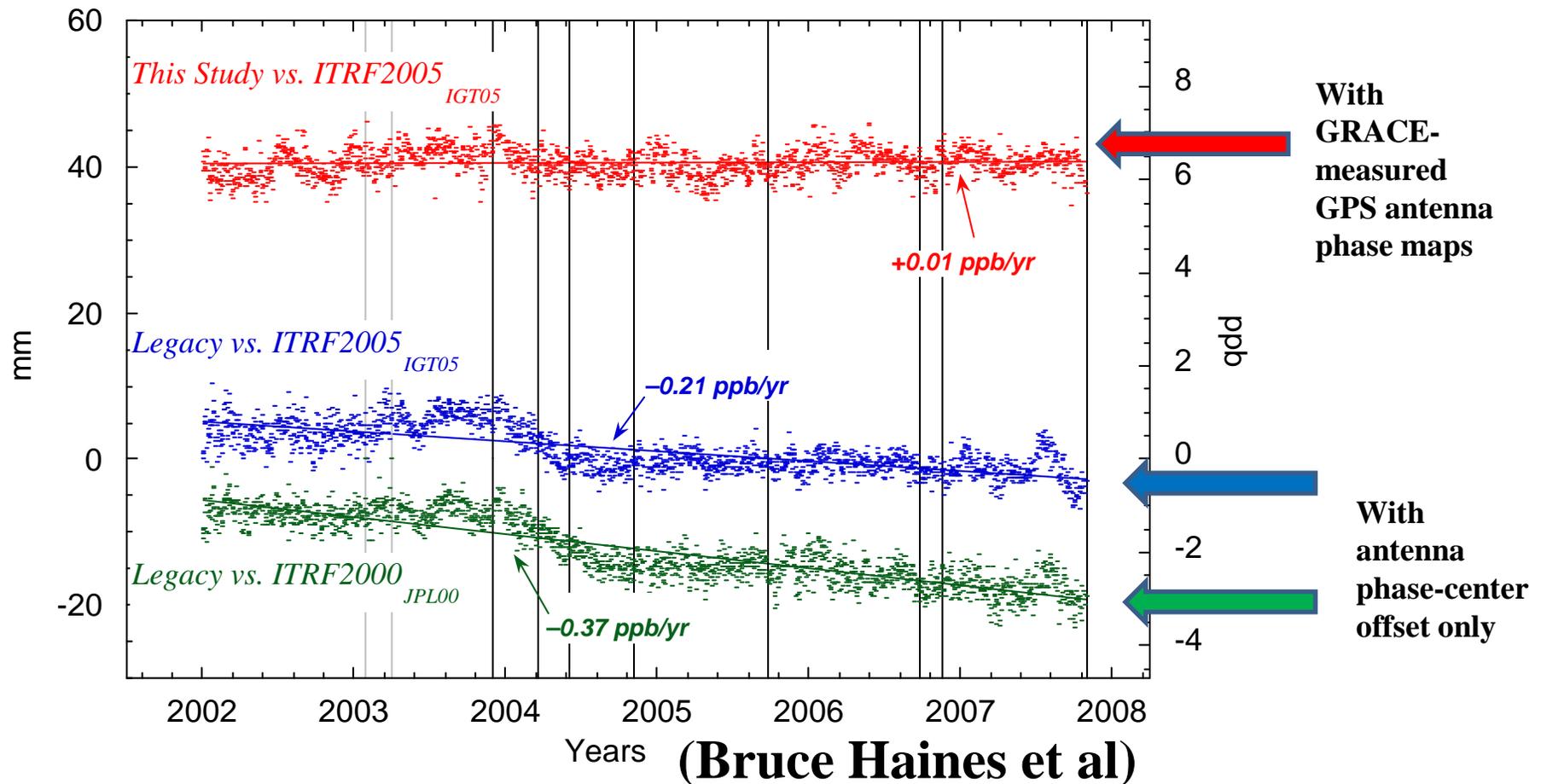




Application: Reference Frame



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



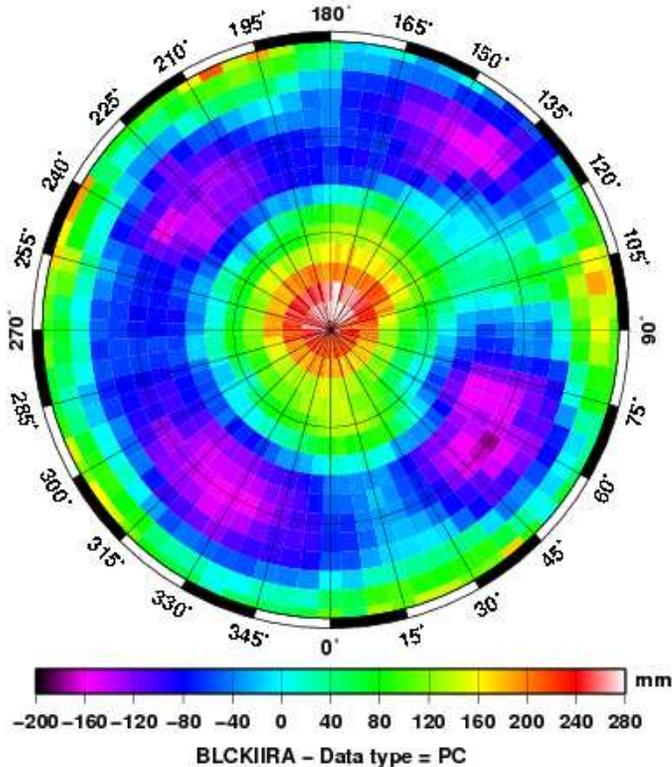


GPS Transmit Antenna Maps

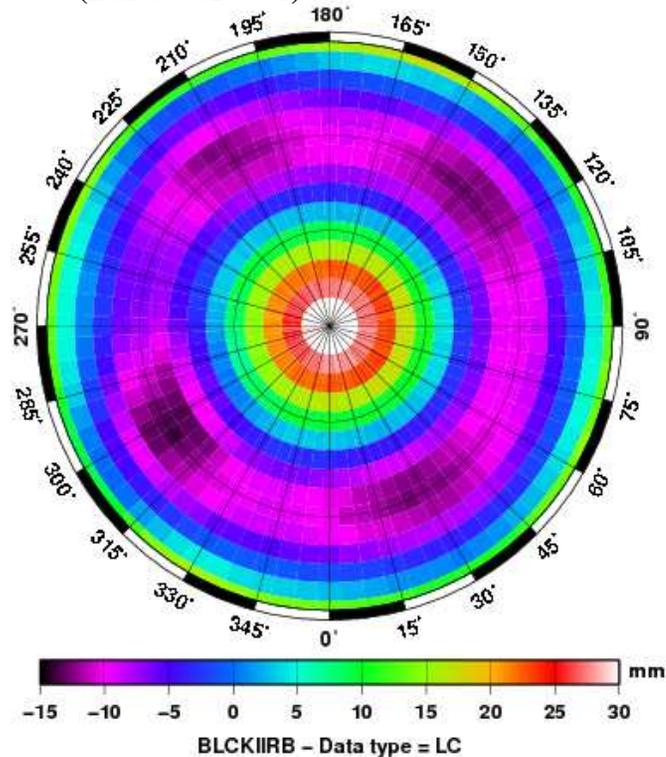


- Maps are made from 0° to 15° off nadir
- Ionosphere-free GPS L1/L2 measurements

BK IIR-A Group Delay vs Angle
(Shailen Desai et al)



BK IIR-M Phase Variations
(Bar-Sever et al)



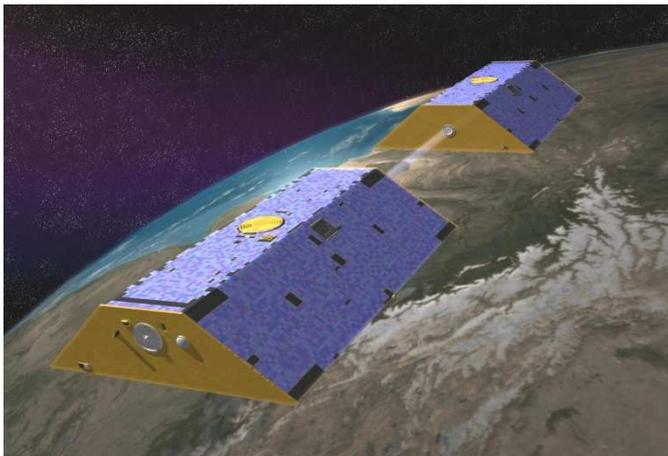


GPS Antenna Maps Created from Orbit

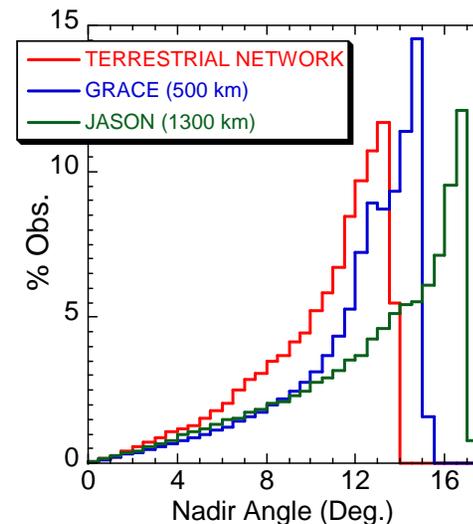
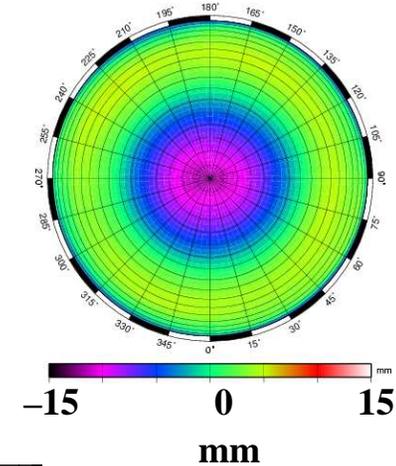


Maps created from stacked post-fit POD residuals:

- Iterative approach
- A priori GRACE antenna model from pre-launch anechoic chamber 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

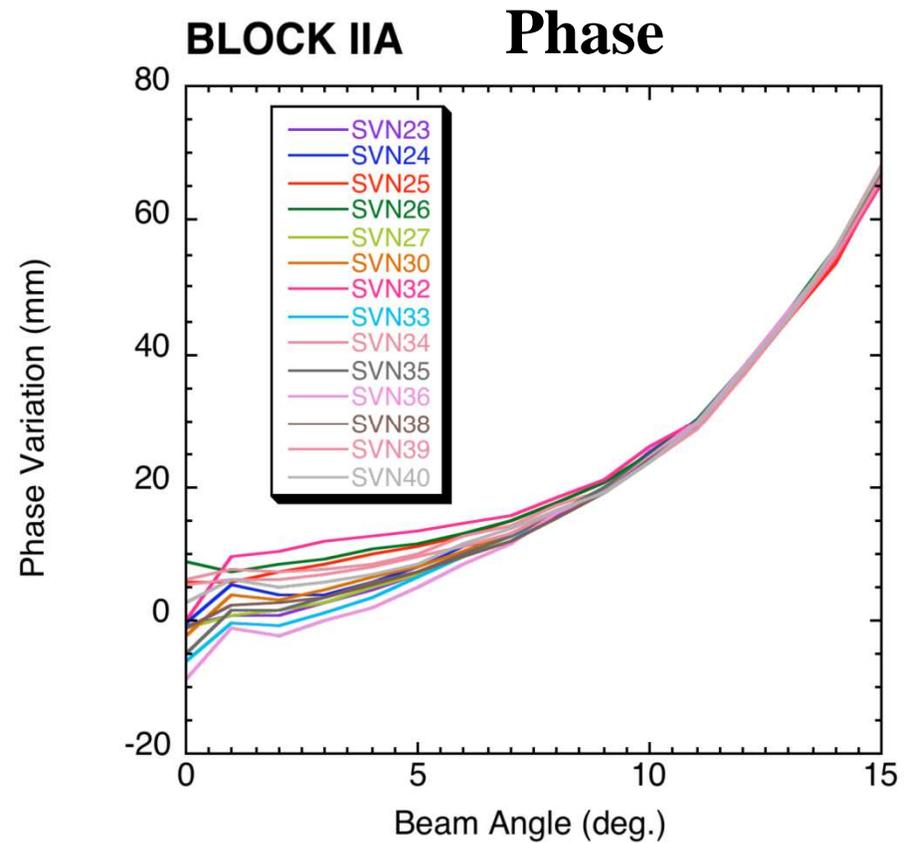
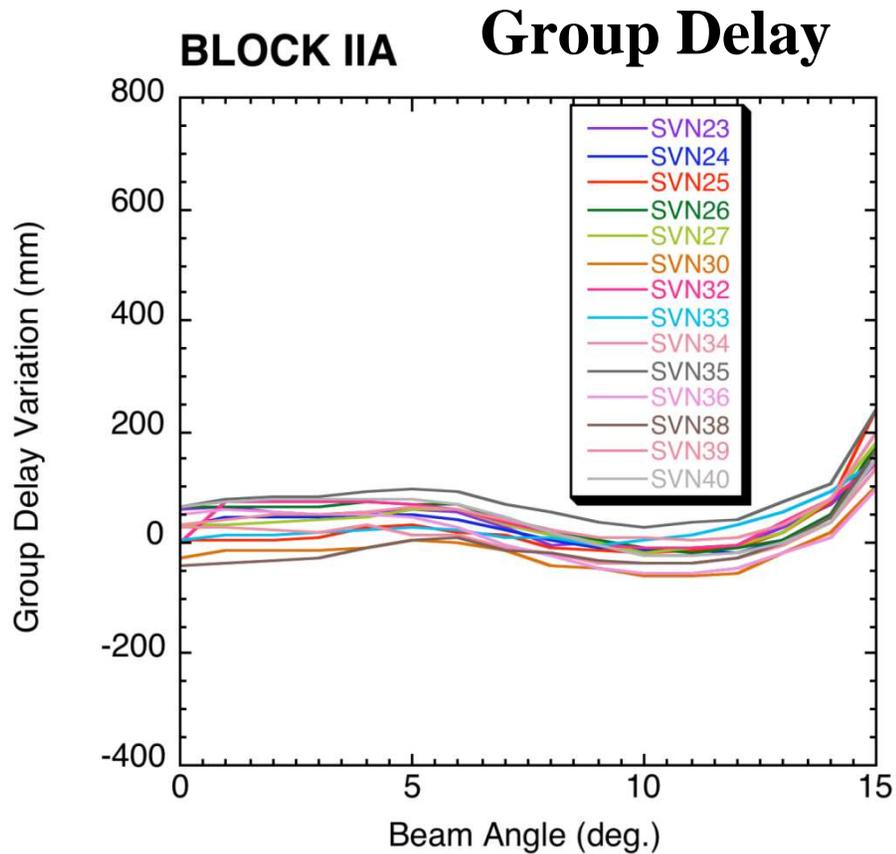


(Bruce Haines et al)

Off-nadir angle vs. percentage of observations



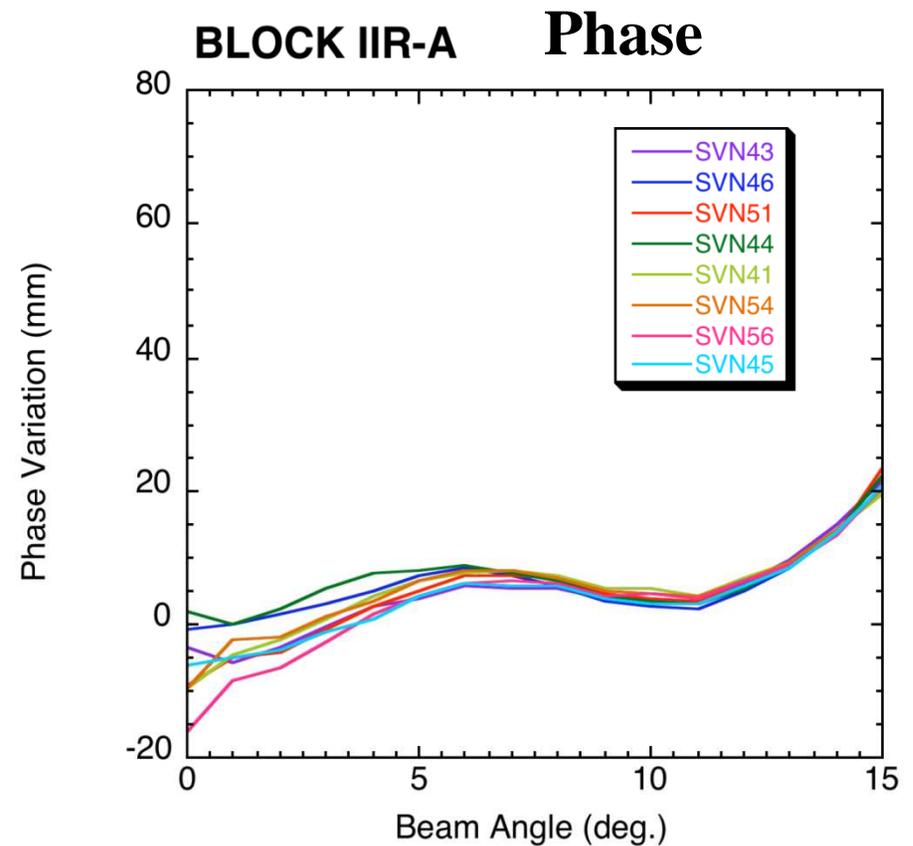
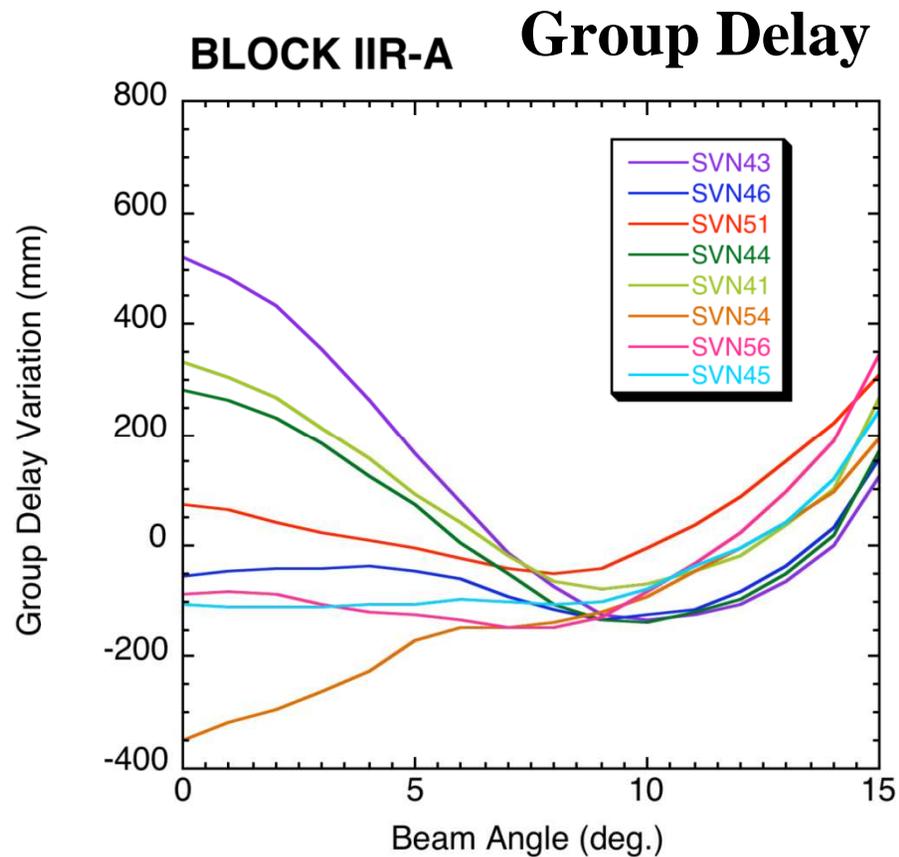
GPS Block IIA Transmit Antenna



(Bruce Haines et al)



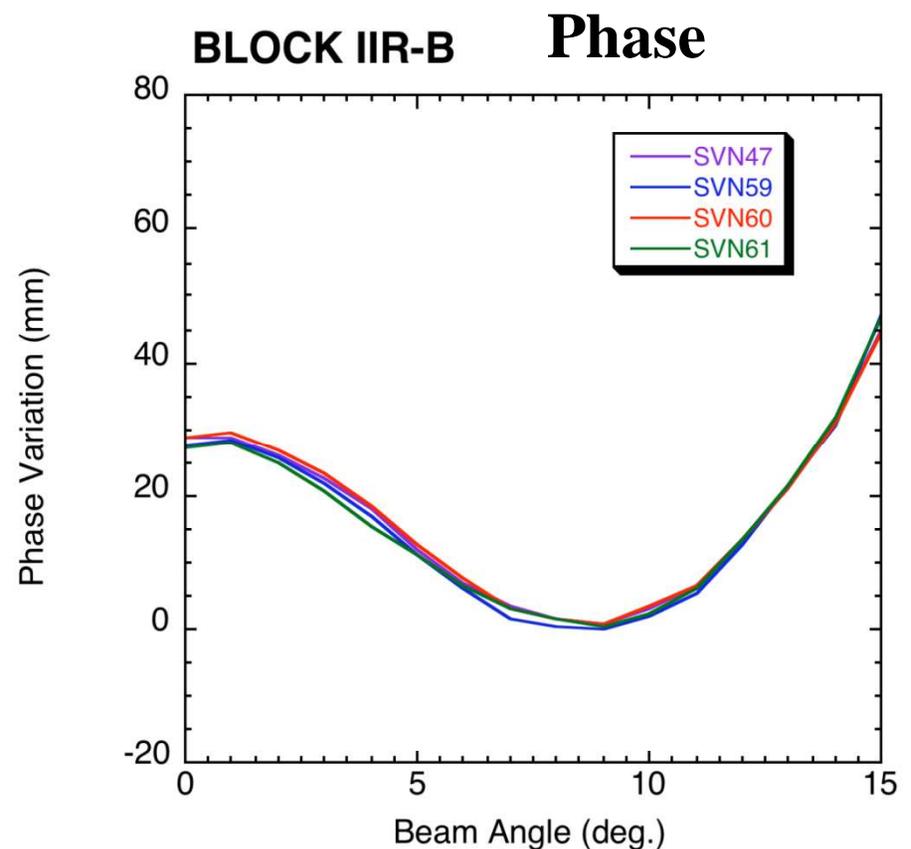
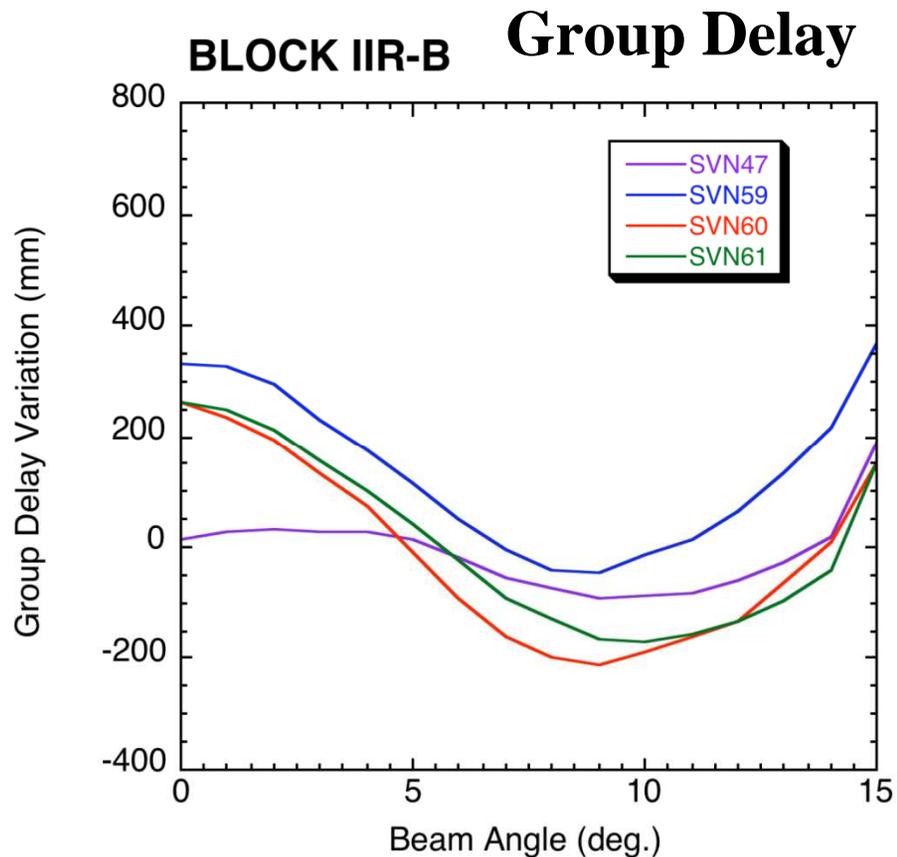
GPS Block IIR-A Transmit Antenna



(Bruce Haines et al)



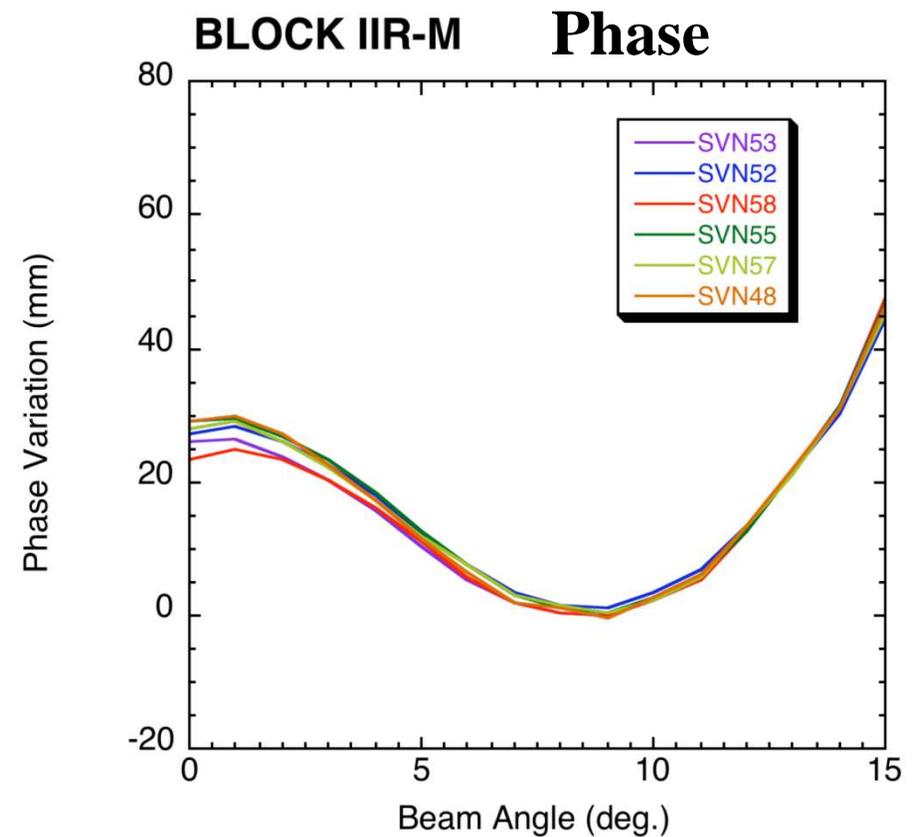
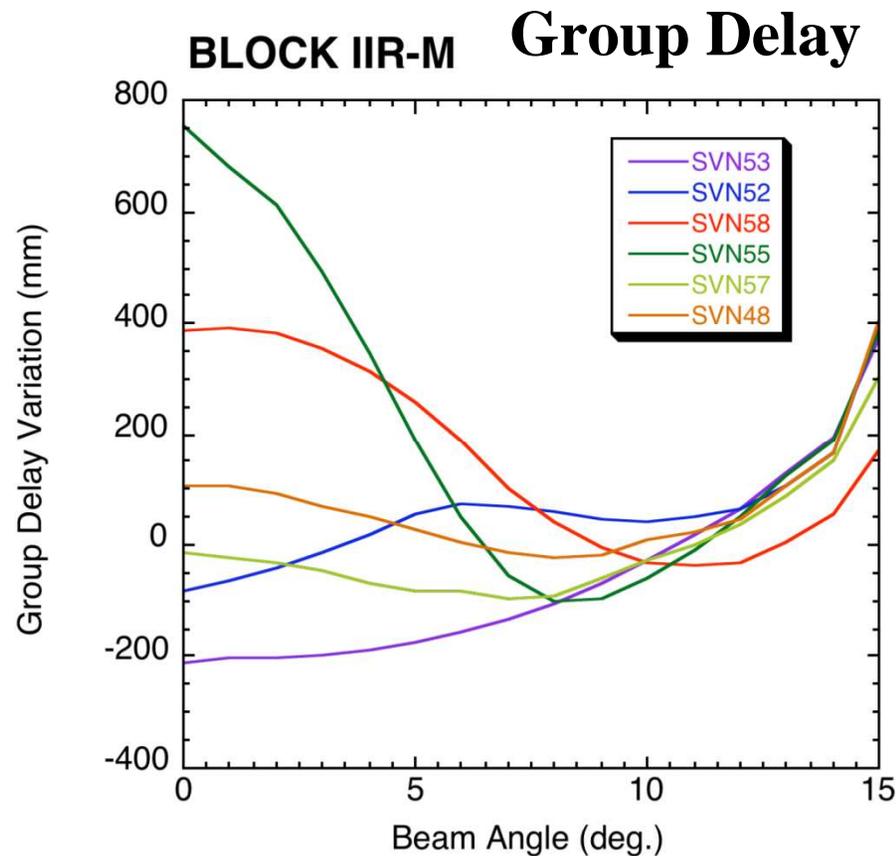
GPS Block IIR-B Transmit Antenna



(Bruce Haines et al)



GPS Block IIR-M Transmit Antenna



(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%	$\geq 97\%$	$\geq 80\%$ ₁	$\geq 1\%$
L2, L5	100%	100%	$\geq 92\%$ ₂	$\geq 6.5\%$
1. With less than 108 minutes of continuous outage time.				
2. With less than 84 minutes of continuous outage time.				

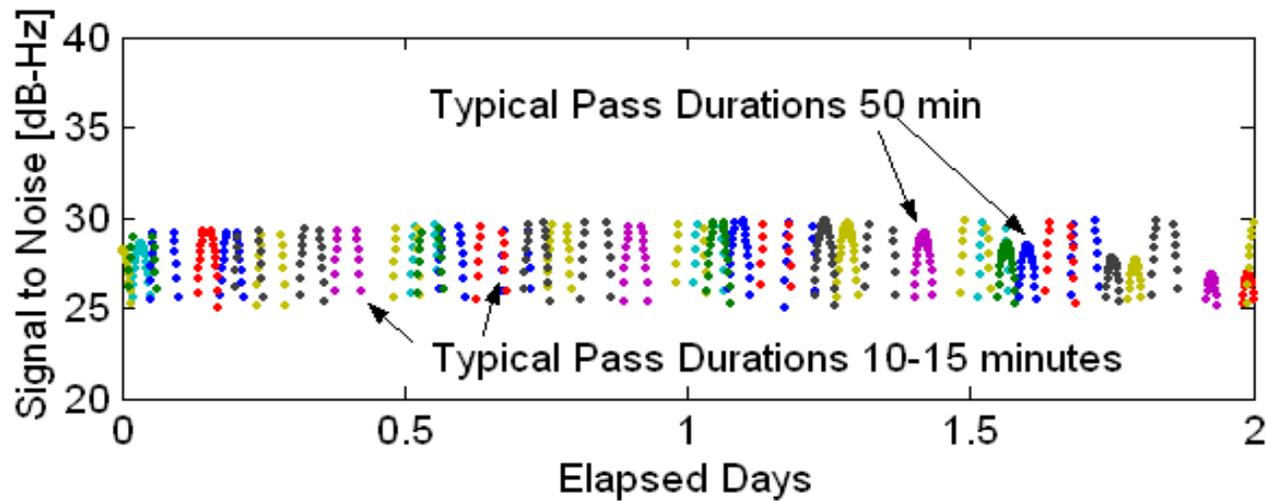
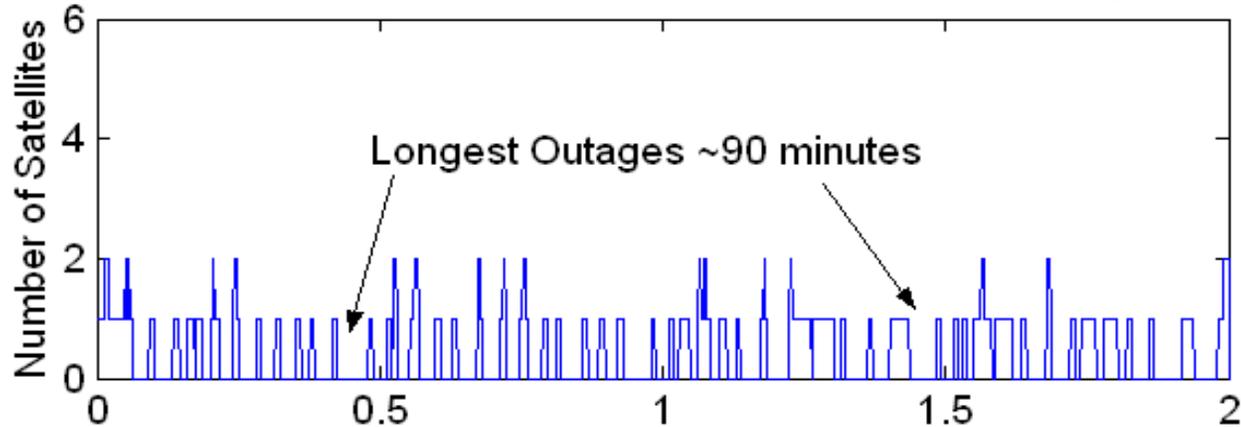
- Objective:
 - MEO SSV: 4 GPS satellites always in view
 - HEO/GEO SSV: at least 1 GPS satellite always in view



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



Receiver at Moon: 25 dB-Hz Sensitivity and 10 dB Receiving Antenna





GPS Use in Cislunar Space



- Weak GPS signal tracking technology enables tracking signals up to approximately $\frac{1}{2}$ 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

