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USE AND PROTECTION OF GPS SIDELOBE SIGNALS FOR ENHANCED NAVIGATION PERFORMANCE IN HIGH EARTH ORBIT

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The application of the Global Positioning System (GPS) for navigation of spacecraft in High and Geosynchronous Earth Orbit (HEO/GEO) has crossed a threshold and is now being employed in operational missions. Utilizing advanced GPS receivers optimized for these missions, space users have made extensive use of the sidelobe transmissions from the GPS satellites to realize navigation performance that far exceeds that predicted by pre-launch simulations. Unfortunately, the official specification for the GPS Space Service Volume (SSV), developed in 2006, assumes that only signals emanating from the main beam of the GPS transmit antenna are useful for navigation, which greatly under-estimates the number of signals available for navigation purposes. As a result, future high-altitude space users may be vulnerable to any GPS design changes that suppress the sidelobe transmissions, beginning with Block III space vehicles (SVs) 11–32. This paper presents proposed changes to the GPS system SSV requirements, as informed by data from recent experiments in the SSV and new mission applications that are enabled by GPS navigation in HEO/GEO regimes. The NASA/NOAA GOES-R series satellites are highlighted as an example of a mission that relies on this currently-unspecified GPS system performance to meet mission requirements.

BACKGROUND

In the late 1980's, as the Global Positioning System (GPS) development matured and constellation deployment accelerated, NASA, the U.S. Air Force, and the international space community began to investigate how best to exploit these Positioning, Navigation, and Timing (PNT) signals for space missions. Missions in Low Earth Orbit (LEO), below 3000 km altitude, remain exclusively within the main broadcast beam (or mainlobe) of the GPS signals, and enjoy GPS availability and performance similar to terrestrial users (Figure 1). At the time, it was uncertain if space missions in Medium Earth Orbit (MEO), High Earth Orbit (HEO), and Geostationary Earth Orbit (GEO) could employ GPS, or whether the power levels, availability, or accuracy of GPS signals in these orbits would adequately facilitate navigation solutions to enhance mission objectives.

By the mid-1990's, several flight experiments[1–4] were proposed and conducted to determine the viability of using GPS in these orbits, and the first efforts were started to define a Space Service Volume (SSV) that would augment the region where Earth or near-Earth use of GPS is conducted. The first space user requirements on GPS were adopted as part of the 2000 GPS Operational Requirements Document; however, the requirement only specified a constraint on beamwidth of the GPS L1 mainlobe signals, and only applied to a subset of space users in the Geostationary belt.

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Data from the AMSAT OSCAR-40 (AO-40) experiment [4,5] provided some of the first insights into the characteristics of the GPS antenna patterns and the significant variability in the antenna characteristics between blocks of GPS satellites (II/IIA, IIR & IIR-M). Observed variability in the beamwidth of the mainlobe signals highlighted the critical importance of establishing a more comprehensive baseline for GPS performance in the SSV if future space missions were to exploit these capabilities.

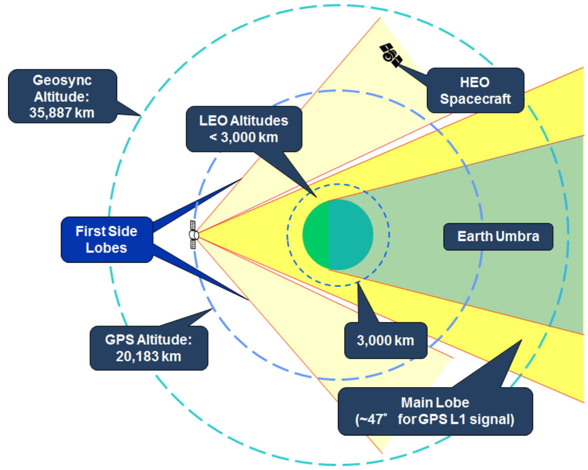


Figure 1: Reception Geometry for GPS Signals in Space.

Backed by additional data and subsequent analyses from the aforementioned HEO/GEO flight experiments, a more comprehensive SSV requirements set was accepted in 2006[6] for the GPS-III satellites now in production. The new SSV definition expanded the use of GPS to the entire volume from 3,000 km to 36,000 km above the Earth. It defined minimum received signal power requirements that stabilized the signal strength of the mainlobe signals at a given off-nadir angle (Table 1), ensuring that future mainlobe signals in the SSV would be no worse than those from the Block II series of satellites. These requirements also specified signal availability across the SSV (Table 2) and defined a 0.8 meter pseudorange accuracy for these signals. This accuracy specification was demonstrated by analysis to be met by the Block II GPS satellites within the reference off-nadir angles specified in Table 1. The updated SSV mainlobe requirements were developed for the GPS Block III satellites, but are also met by all previous blocks. The AO-40 data also showed that sidelobe signals from some of the GPS satellites were much stronger than expected, suggesting these could contribute significantly to signal availability. While specification of the sidelobe signals was considered to enhance availability and solution geometry, at the time, there insufficient flight data to fully characterize these signals. Therefore, contributions from sidelobes were not included when developing the 2006 SSV specification.

Table 1: Current SSV Minimum Received Signal Power[6]

Signal	RX Power (dBW)	Ref. Angle (deg)
L1 C/A	-184.0	23.5
L1C	-182.5	23.5
L1 P(Y)	-187.0	23.5
L1 M	-183.5	23.5
L2C	-183.0	26
L2 P(Y)	-186.0	26
L2 M	-182.5	26
L5 (I/Q)	-182.0	26

Since the 2006 SSV requirements were implemented, additional knowledge about the sidelobes has been gained from HEO/GEO missions that are utilizing these signals for science applications. These missions have demonstrated both the value of using these signals and the limitations of the current SSV specifications. Using the sidelobe signals, the Magnetospheric Multiscale (MMS) mission is demonstrating 1–10 meter real-time navigation performance with an average of 6–8 satellites in view and 4+ GPS satellites in view 100% of the time, even at an apogee of 12 Earth radii (RE)—nearly twice GEO altitude.[7] This performance is made possible by technology innovations in weak-signal tracking spaceborne receivers (e.g. NASA Goddard's Navigator[8]) and on-board orbit estimation and propagation software (e.g. the NASA Goddard Enhanced On-board Navigation System (GEONS)[9]).

Table 2: Current SSV Minimum Availability[6]

	Medium Altitude SSV		**High/GEO Altitude SSV**	
	at least 1 signal	at least 4 signals	at least 1 signal	at least 4 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.			

Space users employing the aggregate signal availability of mainlobes and sidelobes are enjoying significant performance improvements, but as sidelobe signals are unspecified, users are still vulnerable to GPS constellation design changes that would impact the sidelobe signal strength and antenna patterns. Thus, the potential exists for a significant loss of current and future capability of GPS in HEO orbits for civil and military SSV users when the next generation of GPS-III satellites (space vehicle (SV) 11+) are launched in the 2025–2040 time frame.

HIGH EARTH ORBIT APPLICATIONS ENABLED BY NAVIGATION WITH GPS

While GPS use is ubiquitous across LEO space applications, only more recently have operational missions begun to demonstrate autonomous GPS navigation in the more challenging HEO and GEO orbital regimes. Based on the demonstrated performance of the current GPS constellation, a myriad of future HEO missions are poised to benefit from improved navigation, timing, and on-board autonomy enabled by the use of GPS sidelobes. Figure 2 summarizes examples of mission applications enabled by precision GPS navigation in high Earth orbits, such as remote sensing in GEO requiring precise geolocation, highly-maneuverable spacecraft that must maintain orbit knowledge in the vicity of maneuvers, formation flying missions, and others.

The Geostationary Operational Environmental Satellite (GOES) program provides a textbook example of a GEO remote-sensing spacecraft using GPS for precise geolocation. GOES is a joint NASA/NOAA weather satellite program that provides continuous imagery and atmospheric measurements of Earth's western hemisphere that are used in weather prediction and modeling. The GOES-R (GOES-R, S, T & U) series of spacecraft, planned to be operational in 2016–2035, provide an example in which improved science products result directly from improved navigation performance enabled by GPS. The Image Navigation and Registration (INR) system on GOES provides accurate Earth location knowledge and control for each imager and sounder picture element (pixel). By utilizing GPS navigation, GOES-R provides significantly improved image registration performance relative to ground-based ranging techniques employed on the earlier series of GOES satellites, directly benefiting weather prediction, warnings of severe storms, hurricane monitoring, etc.

GOES-R further illustrates the class of applications in which navigation performance must be maintained during and subsequent to propulsive maneuvers. On the legacy GOES N–Q satellites, station-keeping maneuvers required relaxing INR requirements for up to six hours post-maneuver, directly impacting the geolocation accuracy for time-critical weather events such as tornadoes, flash floods, and forest fires. By tracking both mainlobe and sidelobe signals to increase signal availability, the GOES-R Viceroy-4 GPS receiver allows for a more rapid recovery from station-keeping maneuvers, resulting in zero impact to science operations. Similarly, another class of missions that

Figure 2: Current and Potential Future Missions Employing GPS in SSV HEO/GEO Segment

will benefit from higher GPS availability include platforms that require precision maneuverability to perform rendezvous and proximity operations, such as satellite servicing missions under study by NASA and DARPA. By taking advantage of the aggregate signal, these missions may see improved absolute positioning performance during the far-field rendezvous portion of their mission.

There are numerous examples of scientific missions requiring constellations of satellites or precision formation flying in HEO regimes. NASA's MMS[7] is an example of a mission that is truly enabled by GPS. MMS is a formation flying mission made up of four spacecraft in a 1,300 by 70,000 km (altitude) orbit, expanding in Phase 2 to 154,000 km. As discussed previously, MMS uses GPS to autonomously estimate vehicle position and velocity, which enables the rapid design of the series of maneuvers required to achieve the desired formation between the four satellites. This precise formation is required for the science observations that are used to better predict fluctuations in the Earth's magnetosphere, which is critical for advanced warnings of space weather events that can impact ground infrastructure such as the national power grid. High altitude solar occultation missions, such as the Project for On-Board Autonomy-3 (PROBA-3), use precise formation flying in a 600 by 60,000 km orbit to perform detailed observations of the Sun's corona. On PROBA-3, this will be accomplished using GPS and other sensors to fly two spacecraft in a precise, choreographed formation, with one spacecraft, a coronagraph, taking measurements and a second, a spherical shield, which serves to occult the Sun.

Other HEO missions that will benefit from high altitude GPS include: commercial satellites desiring closer spacing in the GEO arc and lunar and deep space missions navigating out-bound from and in-bound to Earth. NASA is also considering the use of GPS in several future astrophysics missions, such as HEO exoplanet finder missions and the Wide-Field Infrared Survey Telescope (WFIRST). With such a diverse range of missions under development and on the horizon which will benefit from high altitude GPS navigation, NASA is motivated to protect a robust GPS signal capability in the HEO and GEO segment of the SSV.

PROTECTION OF AGGREGATE SIGNAL CAPABILITY

Additional knowledge about the GPS sidelobes, combined with newly-developed receivers specially designed for the SSV, have enabled many users to utilize signals from the sidelobes to greatly increase navigation performance. For some users, such GOES-R, this level of performance is mission-critical. Because the sidelobe signals are not protected by any GPS specification, they are vulnerable to changes in future GPS blocks due to changes in antenna design.

This risk is illustrated by the average received power at GEO for L1, shown in Figure 3 as computed from the GPS Antenna Characterization Experiment (ACE),[10] which illustrates the variability in the GPS transmitter antenna patterns across the different blocks of GPS satellites. The data collected by GPS ACE has demonstrated that Block IIA, IIR-M, and IIF all have very similar mainlobe patterns, but all of the designs have variability in the sidelobes, both in azimuth and off-boresite angle. The block IIR satellites have a narrower mainlobe, and consequently larger sidelobe signal peaks. In particular, the Block IIR-M design was the product of a conscious effort modify the antenna pattern for enhanced terrestrial performance, which had the effect of depressing the sidelobes signals as compared to Block IIR. The Block IIA and IIF antenna patterns are similar, hinting at their common design heritage. Future GPS satellite designs will likely have their own distinct antenna characteristics, and because the capability provided by the sidelobes is unspecified, further changes are likely.

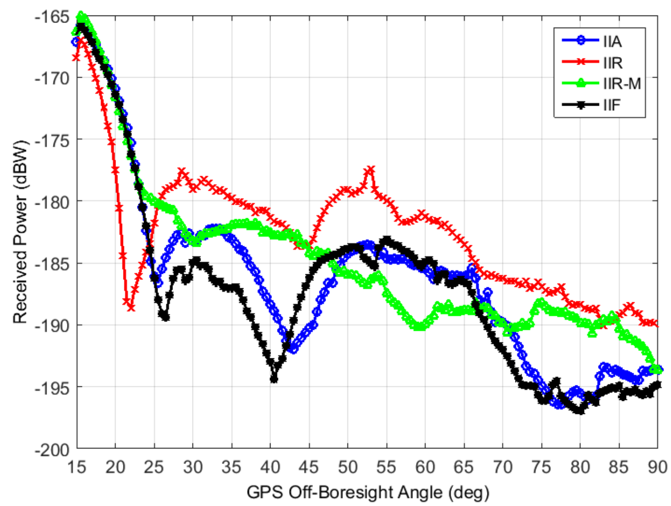


Figure 3: Averaged Received Signal Power at GEO

While the impact of reduced capabilities on future GPS satellites would not begin to occur until the 2030–2040 time frame, the lack of a specification has immediate consequences. Missions of national importance are at risk if they take full advantage of available GPS performance that may disappear in future constellations. Instituting requirements-level protections will enable greater utilization of GPS in the SSV by these users starting today.

NASA is proposing a modification to the existing SSV requirement that would effectively increase the specified signal availability in the SSV to be more consistent with documented user needs and the performance that is delivered by the current constellation, while keeping within the framework of the current SSV requirements "triad" of availability, received power, and pseudorange accuracy. This proposal is intended to not drive any enhancement to the current system and will extend this capability to all users, both civilian and military. To meet these goals, the current requirements specifying a triad of availability, received power, and accuracy for GPS mainlobe signals are left intact and unchanged. A new specification is proposed to document the higher availability

Table 3: Minimum Availability Performance Simulation Parameters

Parameter	Nominal Value	Comment
Grid Points	1652	5° equatorial grid spacing; equal-area method
Duration	24 hours	Length of time GPS constellation is propagated
Step Size	60 sec	Availability step size
GPS Half-Beamwidth	90°	Full aggregate pattern
GPS Constellation	27/6	27-satellite, 6-plane constellation of Block IIR-M
Signals	L1, L2, L5*	All codes within each band are equivalent for availability; *L5 assumes L2 antenna pattern
Availability Constraint	Minimum isotropic power at receiver	Minimum power consistent with current requirement
Earth Atmosphere Mask	50 km	Satellite considered visible if line of sight does not cross below atmosphere mask altitude

values considering the full aggregate transmissions above the specified received power threshold. The specified signal availability may be met by any GPS signals meeting the power and accuracy requirements, even if these signals originate outside of the mainlobe. A less stringent pseudorange accuracy value is specified for the aggregate signal availability.

SPACE SERVICE VOLUME CURRENT MINIMUM PERFORMANCE

The performance margin of the current GPS constellation relative to existing SSV requirements was characterized by analysis, with the goal of documenting the worst-case performance margin over the current requirement when the full aggregate signal is employed. This expanded the analysis performed by Bauer et al. in Reference 6, and established the limits for the proposed requirement that could be met within the existing performance of the GPS. This analysis focused primarily on signal availability, using minimum received power as a threshold, independent of pseudorange accuracy. A small followup study of pseudorange accuracy was performed as well.

In order to fully define the performance capacity of the existing Block II GPS constellation, an availability analysis was performed that includes ground-based and on-orbit antenna pattern measurements that have become available since the current requirements were written in 2006. This analysis compares the actual performance when the full aggregate signal is considered, versus the required performance, which only defines mainlobe characteristics. This comparison shows a that wide margin between actual and specified performance exists, easily supporting the navigation requirements of missions such as GOES-R. The observed wide margins also demonstrates that future GPS III satellites should be able to accommodate the NASA proposed requirement modification with no SSV-specific design modifications or enhancements required and still support HEO/GEO space user needs.

Analysis of Current Minimum Signal Availability Performance

Table 3 summarizes the parameters of the availability analysis. It specifically focused on performance of the Block IIR and IIR-M satellites, due to the public availability of full transmit antenna gain patterns to an off-nadir angle of 90°and high resolution in azimuth.[11] The GPS constellation was modeled as a 27-satellite, 6-plane constellation of like designs (e.g. all Block IIR-M), consistent with the analysis used to derive the current SSV specification.[6] The specific satellites were chosen from the 1 January 2014 GPS Operational Advisory, such as to model a realistic constellation geometry in keeping with previous work.[12] The exact ephemerides were taken from the week 749 YUMA almanac with time of applicability (TOA) of 503808 s. The GYM-95 GPS yaw model was used as described by Bar-Sever.[13]

At each simulation time, a GPS SV was considered "available" at a given coverage point if the link budget calculation resulted in a received power greater than the threshold power for the given signal. The link budget was calculated as $P_r = P_t + A_t + A_d$, where P_r is the received power, P_t is the transmit power of each GPS satellite, A_t is the transmit antenna gain of the GPS satellite at the applicable azimuth and off-nadir angle, and A_d is the path loss from the GPS satellite to the coverage point. The P_t values were conservatively derived as the levels necessary to meet the terrestrial received minimum signal power specified in the GPS user interface description, IS-GPS-200. In accordance with the specification definition, the minimum signal power is as measured on the Earth's surface at the worst-case orientation through a linearly-polarized antenna with a gain of 3 dB, with a 3.4 dB loss associated with an RCHP signal received by a linear antenna, a minimum elevation angle of 5°, and assuming an atmospheric loss of 0.5 dB. This link budget is described in more detail in Reference 14.

At each coverage point, availability was calculated for both 1+ and 4+ SVs visible for the entire simulation period. Then, in accordance with the definition of the current SSV requirement, the 95th percentile was reported across the set of points. The maximum continuous outage time (when no SV is visible) was calculated for each point over the simulation interval, then reported at the 95th percentile as well.

Table 4: Block IIR-M Minimum Availability Performance and Margin at GEO

	Signal	1+ Availability	4+ Availability	Max Outage (min)
Performance	L1	100%	92.6%	-
	L2	99.2%	77.4%	9
	L5	99.2%	78.6%	8
Current Requirement	L1	80%	1%	108
	L2	92%	6.5%	84
	L5	92%	6.5%	84
Performance Margin	L1	20%	91.6%	108
	L2	7.2%	70.9%	75
	L5	7.2%	72.1%	76

Table 4 shows the results of the availability analysis for the Block IIR-M satellites, for the HEO/GEO SSV region (36,000 km altitude). Since it is well documented that the IIR-M pattern shows depressed sidelobe characteristics when compared to the Block IIR pattern (see Figure 3), only results for the more conservative IIR-M example are shown here. Analysis on the Block IIR patterns confirms that performance is consistently better than that for Block IIR-M. The current specification requires only 80% availability of 1 GPS signal, with a maximum outage time of 108 minutes, but by utilizing the entire aggregate transmit signal, 100% availability is achieved. The 4+ availability metric shows the greatest margin—here, for the L1 signal, a required value of 1% increases to over 92%. The MEO SSV region (8,000 km altitude) shows consistent performance improvement, increasing to 100% availability of 4+ signals across all bands. In the current mixed constellation, capability is expected to be better than shown in Table 4, due to the availability of better-performing Block IIR and IIF satellites. The first block of GPS III SVs currently being built to the existing requirements can be expected to perform similarly to the IIR/IIR-M results because they are built by the same contractor, but it cannot be assumed that this will be true for the follow-on procurement unless the requirements are updated.

Analysis of Current Minimum Pseudorange Accuracy Performance

The availability shown in Table 4 is independent of pseudorange accuracy, for which limited data is available. Therefore, the actual availability that could be utilized by a specific user may be lower, depending on that user's required accuracy level. The only contributions to pseudorange deviations in the sidelobes that are not in common with the mainlobe signal as received on the Earth are due to the variations in the antenna response. An analysis to characterize the group delay in the sidelobes was performed utilizing internally available data for GPS Block III. The results of this analysis show that for the transmitted signals that are above the minimum required signal strength in the SSV (i.e., excluding signals from nulls in the antenna pattern), the group delay variation is minimal and therefore should result in sufficient pseudorange accuracy for HEO/GEO users even beyond the mainlobe. These results are consistent with pseudorange accuracy performance measured on-orbit by recent operational missions including MMS and GPS ACE.

GOES-R SPACE SERVICE VOLUME USER NEEDS ANALYSIS

It is desirable to define the updated SSV requirements based not on the current GPS constellation performance, but rather on what users in the SSV need in order to meet their mission objectives. The GOES program was chosen as a representative user that relies on performance of the GPS constellation not captured by the current requirements, and is therefore at risk that future capabilities may be reduced. This section presents results from a sensitivity analysis to examine the minimum signal availability and pseudorange accuracy necessary to meet GOES-R mission requirements, to inform the proposed updates to the SSV specification.

NOAA/NASA GOES Program Requirements

GOES-R requires orbit knowledge accuracies of 25 meters in-track and cross-track and 33 meters in the radial direction, 1-sigma. A timing accuracy of < 85 nanoseconds 1-sigma is also specified. All of the guidance, navigation, and control requirements, including orbit knowledge and timing, also apply during and immediately after station-keeping and momentum management maneuvers. These requirements must also be met for the follow-on GOES-S, T, & U series satellites. Analyses performed prior to launch[15,16] show that requirements can only be met when the GPS receiver utilizes both mainlobe and sidelobe signals.

Measurement Simulation

Simulated GPS L1 C/A pseudorange measurements were generated using the NASA Goddard Orbit Determination Toolbox (ODTBX).[17] ODTBX provides the ability to model physical parameters of the GPS transmitters and receiver including orbit dynamics, relative geometry, transmitter power levels, receiver noise figures, and high fidelity antenna patterns; compute a link budget; and produce simulated GPS measurements. A 27-satellite constellation (as described previously) populated with GPS Block IIR-M series satellites was modeled. The ODTBX simulation used the full GPS Block IIR-M transmit antenna pattern,[11] an implementation of the GPS yaw model as described in Reference 13, and a transmit power of 12.8 dBW derived from the minimum terrestrial received power as described in the previous section. An additional pseudorange error of 2 meters 1-sigma was applied to account for errors in the broadcast ephemeris and clock predictions, as well as any deviations due to the antenna. This value was adjusted afterwards to determine sensitivity to pseudorange accuracy. No losses or additional errors due to atmospheric effects were added because it was assumed that the receiver will apply an ionospheric mask and will not track those signals.

The GPS receiver was simulated in a representative GEO orbit with a 2.5° inclination. A model of the unique Lockheed Martin GOES-R antenna, which directs the maximum gain to 20° off boresight in order to take advantage of the signals that spill over the edge of the Earth, was used for the receiver gain. A conservative assumed receiver measurement error of 6 meters 1-sigma was modeled and added to the total pseudorange error. Maneuver dynamics were included in the simulation with 1 day spacing: North-South and East-West station keeping maneuvers, which are used to keep the spacecraft within the specified latitude and longitude tolerances, and a momentum management maneuver, which is typically performed frequently to dump accumulated angular momentum. Table 5 lists the details of the maneuvers used in the simulation. These maneuvers were derived from the requirements levied on the receiver and were placed at worst-case locations for GPS signal availability. Table 6 provides a full list of the measurement simulation parameters.

Table 5: Maneuvers Included in the Simulation

Simulation Time	Maneuver Type	Direction	Duration (mins)	Thrust (N)
Day 1: 06:45:00	N/S Station Keeping	Cross-Track	45	0.5
Day 2: 07:30:00	Momentum Management	In-Track	5	0.24
Day 3: 07:00:00	E/W Station Keeping	In-Track	15	0.22

Table 6: Measurement Simulation Parameters

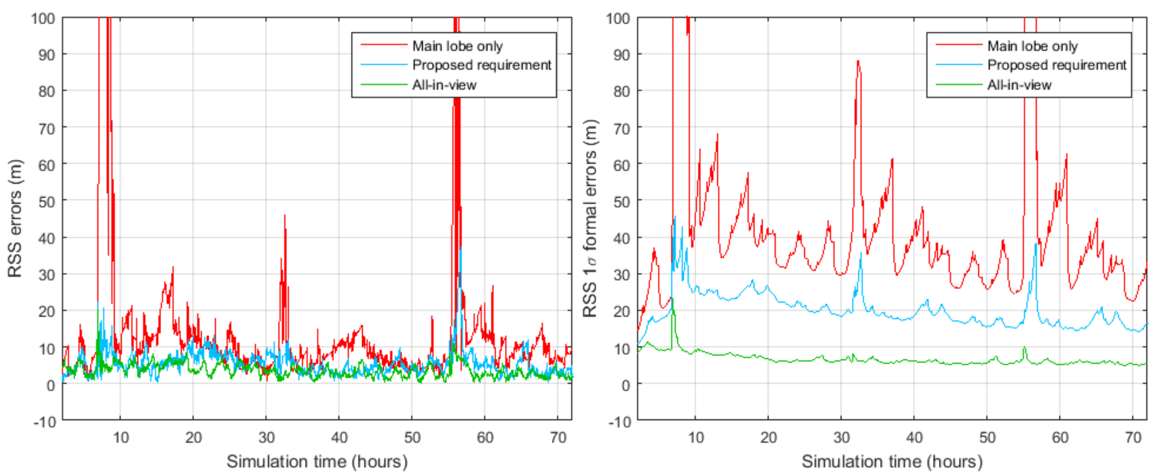
Parameter	Value
GPS signal tracked	L1 C/A
Simulation time span	3 days
GPS ephemerides	Broadcast ephemerides for January 1-4, 2014
Constellation size	Same 24+3 SV constellation described previously
GPS SV type	Block IIR-M, 12.8 dBW transmit power
Pseudorange noise	2 meters 1-sigma
User antenna model	Lockheed Martin design
Receiver sensitivity	Acquisition down to 30 dBHz, tracking down to 26 dBHz
Received power thresholds	SV available if received power *before* the user antenna is above -184 dBW and within receiver dynamic range and acquisition and tracking thresholds *after* the user antenna
Receiver dynamic range	15 dB
Number of channels	12
Visibility restrictions	Earth blockage, 1000 km Height of Ray Path (HORP) mask, varying transmitter cone angles $> 23.5°$
Measurement data rate	Every 30 seconds
Receiver measurement error	6 meters 1-sigma

Analysis Approach

After simulation, all pseudorange measurements, including those derived from sidelobes, were processed by the ground-testing version of the GEONS extended Kalman filter flight software.[9] It was assumed that the GOES-R filter is not given acceleration information about each maneuver event, but rather is sent a command at the maneuver time to adjust the process noise based on the direction and magnitude of the accelerations during the event. Several runs of the filter were performed with varying levels of signal availability above the -184 dBW minimum power threshold. Navigation performance results were then compared to the GOES-R requirements to determine if the availability modeled was sufficient for mission success. The first trial run assumed mainlobe-only signals (corresponding to a 23.5° transmit off-nadir angle). Subsequent analyses increased the off-nadir angle mask to include an increasing quantity of measurements derived from the transmit antenna sidelobes.

Navigation Performance Results

In the mainlobe-only case, the navigation performance results, particularly the positioning accuracy shown in Figure 4, are poor during times of limited availability, especially during maneuvers. The North/South station keeping maneuver, which is the largest in magnitude and duration, violates requirements by a factor of 3 or more in the worst direction. The minimum number of SVs needed to recover is 1–2, however, since there can be up to 108 minutes of loss of coverage per the current SSV requirements, the maneuver recovery requirement cannot be met with the current specified capability. These results show that it can take approximately 3 hours to recover the navigation solution performance to required levels. Figure 4 also illustrates navigation performance when the proposed SSV requirement is employed ("Proposed requirement") and when the full aggregate signal (mainlobe and sidelobes) are included ("All-in-view"). Figure 5 shows the total number of satellites visible throughout the simulation for each case.



(a) Errors with respect to simulation truth

(b) Filter formal errors

Figure 4: Filter Performance for Varying GPS Signal Availability

Subsequent analysis with increasing SV availability levels shows the availability needed to meet the GOES-R position accuracy requirements. Table 7 summarizes the results of this analysis. The minimum availability needed was found to be 1 or more SV 99% of the time and 4 or more SVs 33% of the time. The positioning performance and visibility for these values are shown as the "Proposed requirement" series in Figures 4 and 5, respectively.

Assuming the 99% 1+ and 33% 4+ availability levels, an additional pseudorange accuracy sensitivity analysis was performed. Increasingly large random pseudorange errors were added to the

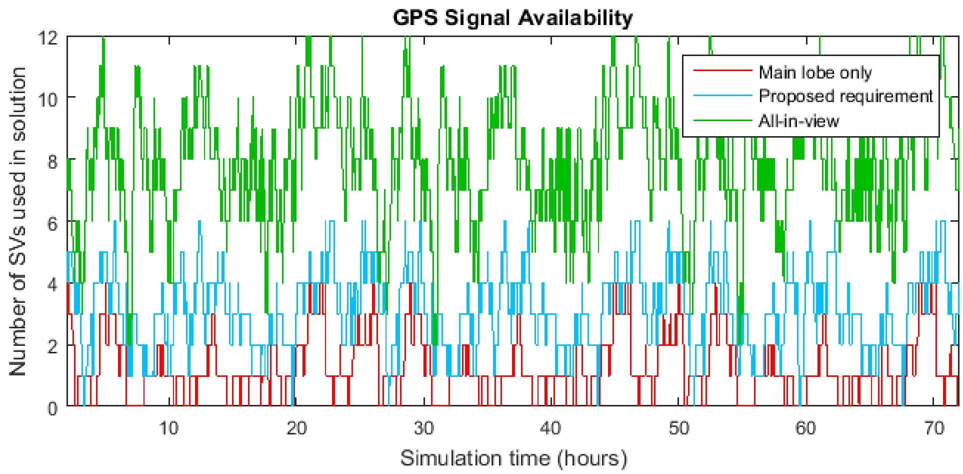


Figure 5: GPS SVs Available Above -184 dBW and Used in the Filter Solution

simulated measurements until the positioning requirements were violated. This conservative analysis assumed a decreased pseudorange accuracy in both the mainlobe and sidelobes. When the errors were increased to 4 meters, both the E/W station keeping and momentum management maneuvers caused the filter errors to grow large enough to violate GOES positioning requirements for more than 5 minutes. At 5 meters, the violation increased to 15 minutes. The 4 meter pseudorange accuracy value was chosen as an acceptable 1-sigma requirement for the aggregate signal availability for GOES-R because of the conservatism in the analysis.

Table 7: Summary of Navigation Performance Results

TX mask (deg)	Avail. [1+, 4+]	Pass/Fail	Details
23.5	80%, 2.5%	Fail	Mainlobe only, fails positioning and stability requirements for all maneuvers, outages of up to 80 minutes near the time of the maneuver
30	96.75%, 20.5%	Fail	Partial 1st sidelobe, fails positioning and stability requirements for all maneuvers
33	98.75%,32.3%	Pass	Passes with minimum required performance for N/S maneuver
35	99.5%, 45%	Pass	1st full sidelobe, passes but with less than ideal performance for N/S maneuver
45	100%, 84.5%	Pass	1st full sidelobe, partial 2nd, passes with very stable positioning during maneuvers

Based on the documented GOES-R mission needs and NASA's stated goal of proposing a requirement based on user needs, this analysis leads to an updated signal availability requirement for SSV users in HEO/GEO, as shown in Table 8. This increased availability is specified at the level of the GOES-R needs analysis, with no margin, and is specified at a less stringent pseudorange accuracy value of 4 meters root mean square (rms). The availability requirement for L2 and L5 is set to the same value as L1, capturing the needs of GOES-R as if it carried a receiver on those frequencies instead. All values fall within current margins for availability and accuracy, and the existing mainlobe availability at 0.8 meters pseudorange accuracy remains unchanged. The MEO component is unchanged as well. While the analysis approach presented here assumes that sidelobes similar to those transmitted by the Block IIR-M satellites provide the increased availability, it is not necessarily assumed that sidelobes are the required solution to meet the desired performance.

Table 8: Proposed availability in the HEO/GEO SSV (4m rms accuracy). Availability at 0.8m accuracy is unchanged.

	High/GEO Altitude SSV	
	at least 1 signal	at least 4 or more signals
L1	$\geq 99\%^1$	$\geq 33\%$
L2, L5	$\geq 99\%^1$	$\geq 33\%$
	1. With less than 10 minutes of continuous outage time.	

CONCLUSION

A wide variety of future space applications stand to benefit from precision GPS navigation in high Earth orbits. Recent operational missions have demonstrated that actual performance of the current GPS constellation greatly exceeds the levels required by existing GPS specifications. This is largely due to GPS sidelobe transmissions, which contribute a large number of GPS signals above the signal acquisition threshold of modern GPS receivers. This additional performance is being utilized, and in some cases relied upon, by numerous missions spanning a range of flight regimes and mission types, including MMS and GOES-R.

An analysis of the minimum signal availability performance of the GPS Block IIR and IIR-M satellites, utilizing the full aggregate signal (mainlobe plus sidelobes) was presented. This simulation conservatively assumed the GPS satellites transmit only the power necessary to meet the minimum specified power levels in the IS-GPS-200, and demonstrated that the aggregate signal availability in the SSV when mainlobe and sidelobe signals are included greatly exceeds the current SSV signal availability specification. A specification to protect these signals is critical to prevent degradation in capability with future blocks of GPS satellites, for space users operating into the 2030s. GOES-R mission requirements were examined in an attempt to establish threshold GPS signal availability requirements that would encompass at least a subset of future precision navigation applications. This analysis has led to a proposed modification of the current SSV requirement that can be reasonably achieved by future designs of GPS satellites. NASA is working with the U.S. Air Force through the GPS Interagency Forum for Operational Requirements (IFOR) process to document and approve the proposed GPS requirements modifications, which would apply to GPS III SVs 11 and later. If adopted, the updated GPS SSV requirements will protect critical capabilities required by users today, and will enable enhanced utilization of GPS at high altitude for all users for decades to come.

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