

GPS RECEIVER ON-ORBIT PERFORMANCE FOR THE GOES-R SPACECRAFT

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ABSTRACT

This paper evaluates the on-orbit performance of the first civilian operational use of a Global Positioning System Receiver (GPSR) at a geostationary orbit (GEO). The GPSR is on-board the newly launched Geostationary Operational Environmental Satellite (GOES-R). GOES-R is the first of four next generation GEO weather satellites for NOAA, now in orbit GOES-R is formally identified as GOES-16. Among the pioneering technologies required to support its improved spatial, spectral and temporal resolution is a GPSR. The GOES-16 GPSR system is a new design that was mission critical and therefore received appropriate scrutiny. As ground testing of a GPSR for GEO can only be done by simulations with numerous assumptions and approximations regarding the current GPS constellation, this paper reveals what performance can be achieved in using on orbit data. Extremely accurate orbital position is achieved using GPS navigation at GEO. Performance results are shown demonstrating compliance with the 100/75/75 meter and 6 cm/s radial/in-track/cross-track orbital position and velocity accuracy requirements of GOES-16. The aforementioned compliance includes station-keeping and momentum management maneuvers, contributing to no observational outages. This performance is achieved by a completely new system design consisting of a unique L1 GEO antenna, low-noise amplifier (LNA) assembly and a 12 channel GPSR capable of tracking the edge of the main beam and the side lobes of the GPS L1 signals. This paper presents the definitive answer that the GOES-16 GPSR solution exceeds all performance requirements tracking up to 12 satellites and achieving excellent carrier-to-noise density (C/N0). Additionally, these performance results show the practicality of this approach. This paper makes it clear that all future GEO Satellites should consider the addition of a GPSR in their spacecraft design, otherwise they may be sacrificing spacecraft capabilities and accuracy along with incurring increased and continual demand on ground support.

1 INTRODUCTION

GOES-16's GPSR system consists of a single Rx antenna, bandpass filter and LNA serving to provide input to a 12 channel, single frequency (L1) coarse acquisition (C/A) GPSR. GOES-16 processes the

collected pseudo-range and Doppler data in the GPSR which provides an Earth Centered Earth Fixed (ECEF) position of the GOES-16 satellite for mission processing of collected science data. The entire GPSR system was designed and tuned in order to facilitate tracking the extremely weak GPS signals at GEO, on the order of 10^{-18} W. Use of a GNSS system on a spacecraft is desirable for three main reasons 1) Position, velocity and timing (PVT) are improved, 2) demand upon ground support is reduced, 3) having real-time PVT available to the Flight Software increases automation. For more information regarding GOES-16's guidance, navigation and control performance, see [1].

GPS navigation at low Earth Orbit (LEO) is common today, however GPS at GEO has primarily been limited to science and experiments. Traditional satellite systems that use GPS at GEO only used the main lobe and have an average in view of less than 4 GPS satellites and significant outage time. The GPSR on GOES-16 incorporates over 11 GPS satellites on average in the PVT solution with no outages. The ability to use the side lobes vastly increases the availability of GPS signals along with the accuracy achievable. The use of GPS to attain a navigation solution at a GEO orbit had never been achieved on a civilian operational satellite until GOES-16. No other satellite has a GPSR system that can consistently track side lobe GPS signals with power levels down to 17 dB-Hz. Furthermore this GPSR system meets requirements with significant margin. The scope of this paper is to describe, characterize and evaluate the performance of GPSR at GEO with respect to the GOES-16 spacecraft. For more information regarding the use of GPS at GEO, see [2].

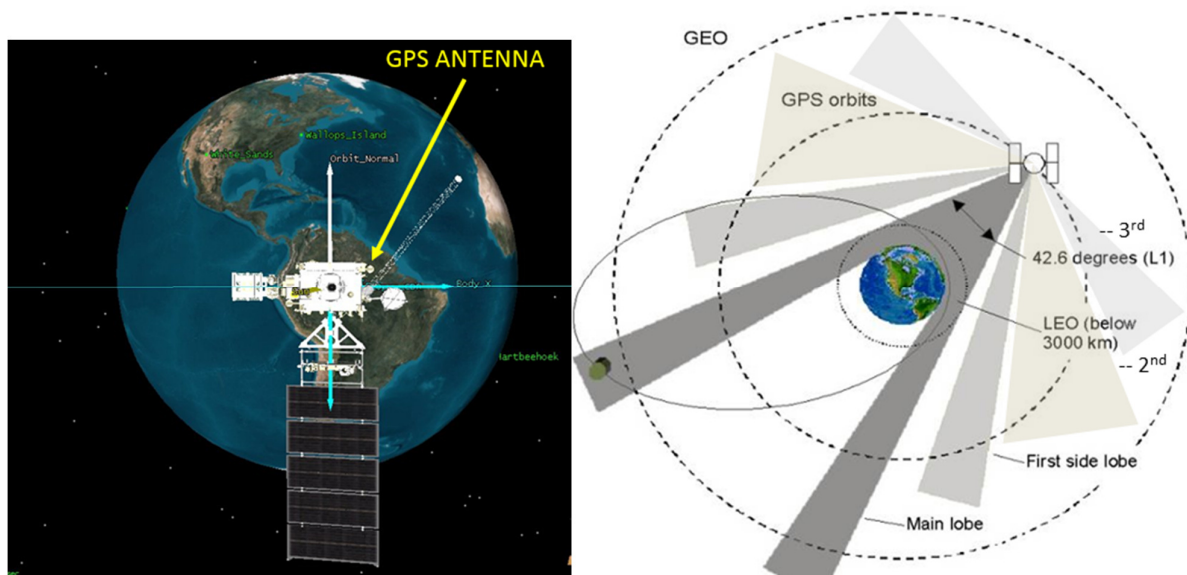


Figure 1. GOES-16 Orientation Depiction in Orbital Slot, attitude (left) and dynamics (right)

Figure 1 depicts the orientation of GOES-16 and the location of the GPS L1 Rx antenna along with the available GPS signal regimes. GOES-16 must be Nadir pointing to perform its mission, with the solar array to the South Pole. The antenna is located on the “North-East” side of the vehicle off of the center of mass by about 4 meters. Clearly illustrated, the dominate signal regime is in the side lobes. Performance expectations and characterization can only be assessed by understanding the GPS transmit (Tx) and GOES-16 receive (Rx) antennae patterns. The GOES-16 Rx antenna depicted in Figure 2 was designed for side lobe tracking. This Rx antenna has a main lobe gain of ~ 11 dB at 22 degrees off-boresight (same as off-nadir). It also limits the noise input from Earth.

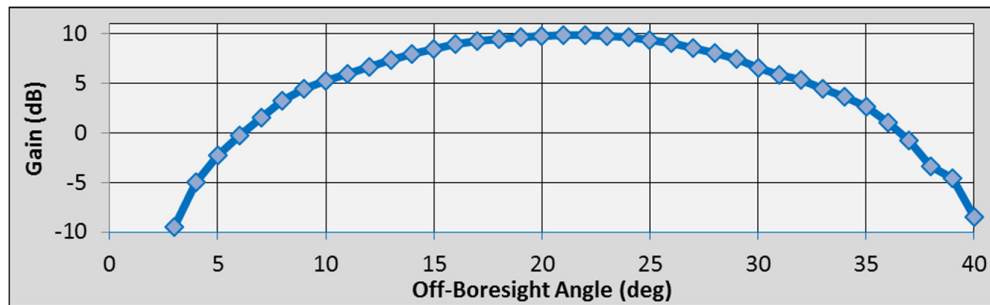


Figure 2. GOES GPS Rx Antenna Worst-Case Average Gain

There are currently three general types of GPS antenna patterns in orbit, unique to each block-type. The average gain at angles off GPS boresight (nadir) for each block-type are depicted in Figure 3. The IIR and IIR-M average gains were generated from Lockheed Martin Space Systems Company 3D antenna patterns [3], the IIF gain is a single slice in the pattern supplied by a third party and thus is a less accurate representation. Block IIR GPS satellites have the highest gain at high angles off-boresight (same as off-nadir) and moderate hills and valleys in their antenna patterns. Block IIR-M GPS satellites have a steady decrease in gain at high angles off-boresight whereas the block IIF GPS satellites have large hills and valleys in their gain patterns creating more regions where tracking IIF is unlikely. Current expectations are that block III GPS antennae will be similar to block IIR-M. Certain performance findings presented in this paper will reference the data displayed in these average antenna pattern plots.

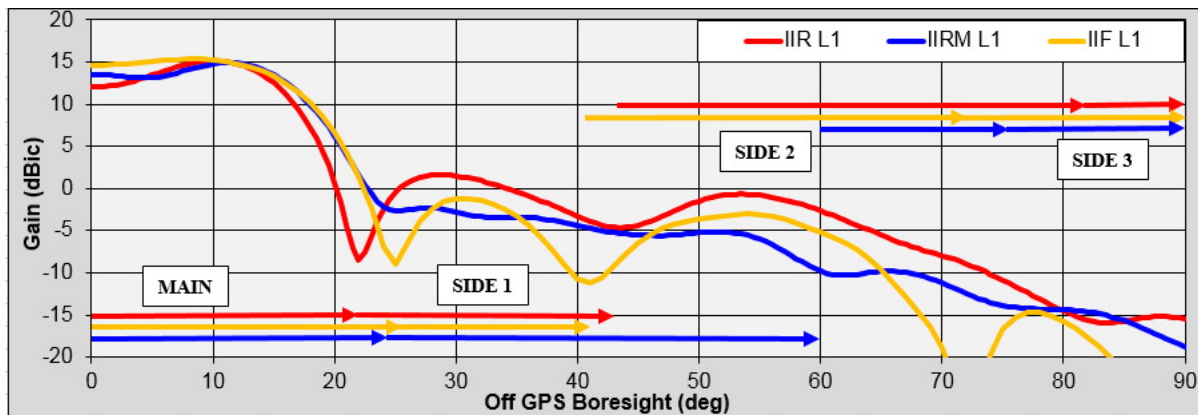


Figure 3. GPS Block-Type Average Tx Signal Patter

2 PRIMARY PERFORMANCE

The GPSR provides position, velocity and time (PVT) information to the spacecraft and its navigation software. Our GPSR provides telemetry 1Hz. Ground tracking is the standard tool to generate SV ephemeris (position information) consisting of Radio frequency (RF), Optical or Laser. GOES-16 cannot use laser ranging due to sensitive optical payloads. RF and Optical tracking are not accurate enough to determine GPSR performance, so we must rely upon other means to identify performance. In this section we will evaluate performance looking a 4 methods. 1) high-fidelity propagator comparison, 2) The GPSR solution and performance telemetry, 3) ground simulations that match the on orbit environment and 4) a high fidelity ground Kalman filter.

2.1 NASA Solution Accuracy Investigation, Maneuver Emphasis

NASA investigated GPSR navigation accuracy during free-flight and maneuvers and determined, with conservative inflation, an estimated 3σ on-orbit accuracy of 50 m. The GOES-16 ground system processes GPSR navigation solutions (NavSols) and is also capable of extracting and reconstructing GPS satellite pseudo-range and timing correction data from GPSR telemetry. A straightforward Batch Least Squares on the GPSR NavSols was sufficient to perform mission orbit determination on the ground and assess the free-flight trajectory position accuracy provided by the GPSR. In order to evaluate the GPSR performance through the largest maneuver durations, a higher accuracy sequential filter using single differenced pseudo-ranges was employed.

During normal operations, the GPSR provides GOES-16 navigation needed for on-orbit processes. The GPSR updates position estimation using GPS signal fix and runs the update through a smoothing process, providing NavSols through telemetry. The GOES-16 ground system performs orbit determination and produces maneuver planning and orbit event management and spacecraft activity planning, using the NavSols as measurements. The ground system also provides an orbit determination predictive ephemeris upload to backup the on-board solution in the event the GPSR solution degrades. Recovery of the GPSR NavSols show that non-maneuver trajectory 3σ position accuracy of 15 meters. GOES-16 maneuvers daily, either performing momentum-management maneuvers, station-keeping maneuvers, or both. The maneuvers typically are small and do not affect the Batch Least Squares process significantly. The exception is the out of plane maneuvers that control North-South motion, North-South station keeping (NSSK) maneuvers.

The largest station-keeping maneuver to date performed by GOES-16 was a NSSK maneuver delivering 0.72 meters/sec for a duration of 5343 seconds on January 29, 2017. The NSSK applies velocity predominately in the cross-track southerly direction. GOES-16 typically applies NSSK at an orbit location near the 90 degree Right Ascension. When GOES-16 executes a maneuver, the on-board flight software notifies the GPSR, via a maneuver execution flag that triggers the addition of process noise to the on-board estimation filter. This flag also relaxes covariance parameters to ensure the GPSR isn't marked degraded due to a maneuver induced jump in position/velocity solution. Therefore, the GPSR position accuracy should differ substantially from the normal operations during maneuvers. Due to the longer duration, low-thrust, North-South Station-keeping (NSSK) maneuvers, telemetered NavSols span accelerated flight during maneuvers. To assess GPSR performance, a higher accuracy maneuver modeling approach was required. A sequential filter process provided by Analytical Graphics Inc.'s Orbit Determination Tool Kit (ODTK) provided high accuracy single differenced pseudo-range navigation performed on the ground.

The single differencing method eliminates on-board clock error in the pseudo-range. The resulting orbit accuracy estimated by ODTK is initially has a standard deviation (1σ) of 8-10 meters. However, a second analysis pass checks this calculation, a Filter-Smoother Consistency Check, shows some solution accuracy is out of bounds from expected values. This result suggests the stated orbit accuracy should be inflated conservatively. Applying a conservative inflation, an accuracy of 50 meters (3σ) during the largest maneuver performed to date is achieved. The on-board GPSR solutions recover from the large maneuver noise within 2 hours. Similar results were observed for a typical East-West Station-Keeping (EWSK) maneuver performed December 18 and a smaller NSSK performed December 19. For more information regarding GOES-16's navigation solution performance, see [4].

2.2 Direct Operational Data Evaluation

The quality of the position/velocity solution is mainly effected by the relative positions of and the number of tracked GPS satellites where the more GPS tracked and the bigger the spread the better the solution. This distribution or quality of tracked satellites is calculated and output by the GPSR as dilution of precision (DOP) where lower numbers represent a better geometry. The ability to acquire and track satellites depends upon the received signal strength compared to noise, the GPSR outputs this measure as carrier-to-noise density (C/N0). Other metrics that can be used to ascertain and describe the quality of the position and velocity solution are Kalman filter metrics output by the receiver, we call these quality indicators. The GPSR also outputs clock performance information in the form of clock drift, clock offset and hardware resolution induced pulse per second (PPS) errors. The plots and data in the remainder of this paper are from one of two sources, a 50 hour span of data from February 2nd to 4th 2017 or a compilation of many datasets gathered over months representing about 230 hours of trending data.

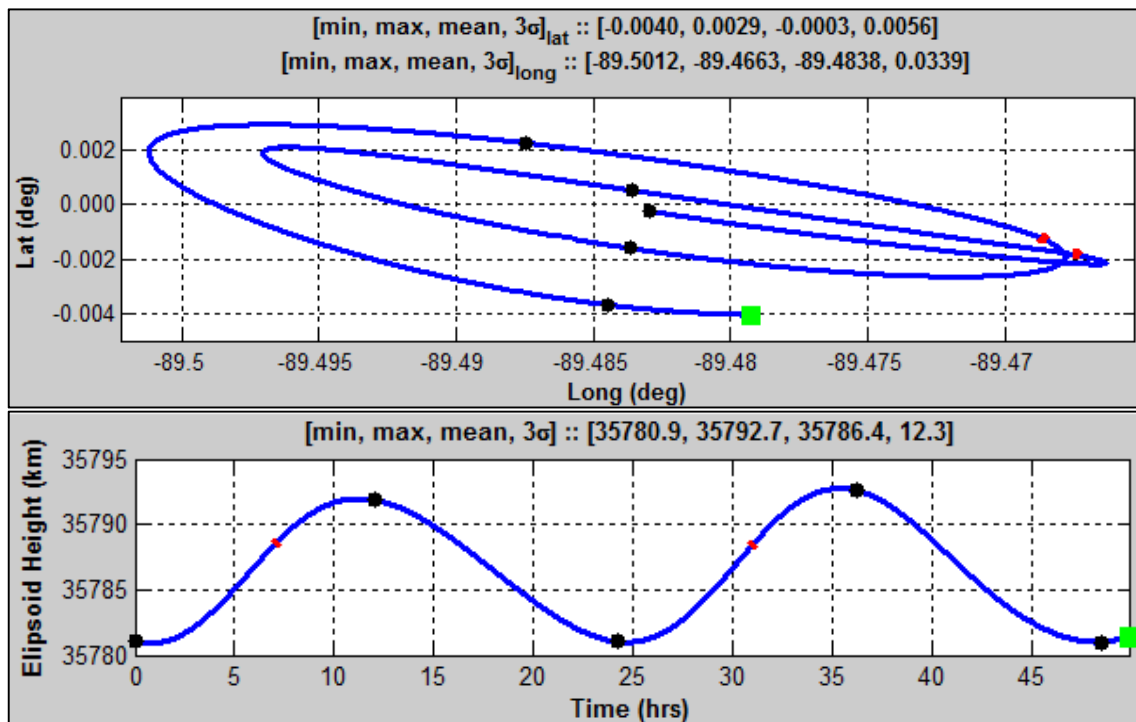


Figure 4. Latitude and Longitude (top) and Height (bottom) at PLT Station [50 hour]

GOES-16 is currently undergoing Post Launch Testing (PLT) at 89.5° W. Figure 4 shows the GPSR calculated latitude, longitude and height over a 50 hour span. The station is relatively stable with primarily East-West variance. Note, indicated on these plots are 3 types of markers: red represents the maneuver periods, black represents 12 hour increments from start and green represents final time. Two maneuvers are present over this 50 hour span, and as noted in Table 1, these maneuvers are relatively small on the magnitude of 2 cm/s in the South direction performed over an 11-12 minute duration.

Table 1. Maneuver Information for 50 Hour Dataset

Start	Start	Duration	East	North	Radial
UTC	hrs	sec	cm/s	cm/s	cm/s
Feb. 3 rd 2017 03:08:02	7.03	665.7	0	-2.010	0
Feb. 4 th 2017 03:02:51	30.95	698.5	0	-2.158	0

Figure 5 shows position and velocity variance in cm and $\mu\text{m/s}$ per 1 Hz cycle. A perfect solution would be smooth, barring maneuvers. The spikes in velocity variance show minor errors in the solution being corrected intermittently. Regularity of these spikes is not indicative of a bad solution, on the contrary it indicates regular solution convergence. Large spikes in variance would indicate a significantly diverged solution or alternatively a poor current solution. A sufficiently large pool of results in the form of position and velocity error estimates can be correlated back to these variance spikes. GOES-16 has fault management that looks for out of family position and velocity variance as a means to keep from ingesting bad measurements.

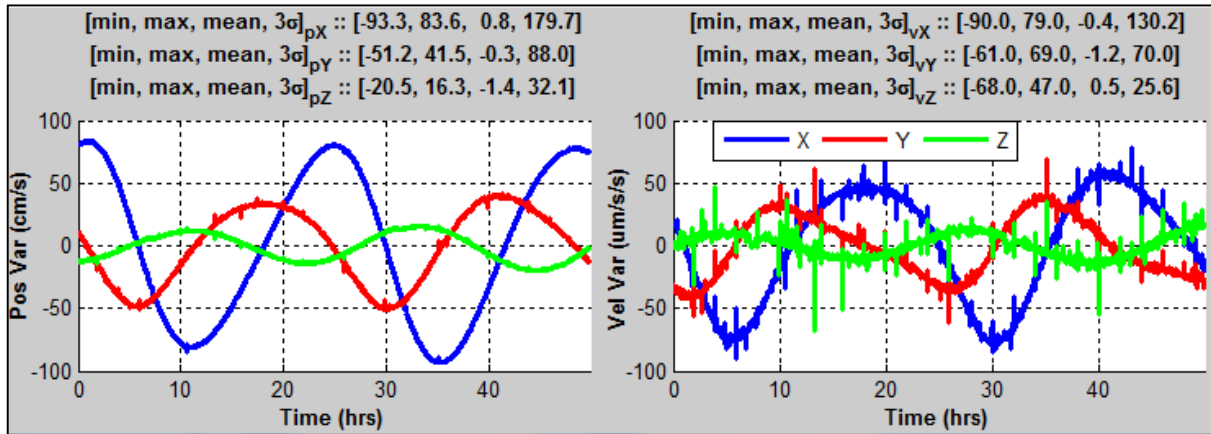


Figure 5. Position (left) and Velocity (right) Variance in ECEF Coordinates

For a GPSR two key indicators of PVT accuracy are 1) how many satellites are being tracked and 2) how spread out in space are those satellites (dilution of precision DOP). Figure 6 shows the number of tracked satellites over time where the GPSR averages over 11 (recall we only have 12 channels). With such a measurement rich environment the GPSR has redundant sources to minimize any one error or GPS satellite issue such as the GPS time glitch that occurred in early 2016 or inherent GPS biases as depicted in section 2.4.4. Our DOP values range between 5 and 15 with an average near 8 (low is better) as shown in Figure 6. These are good values considering the maximum off-nadir angle from GEO is less than 40 degrees. The best possible DOP at GEO considering realistic tracking of 12 GPS satellites is about 4, thus it is apparent that GOES-16 is finding great geometries of GPS to track. These geometries are much better than simulations had predicted and specs had allotted. Thus, based upon the quality (DOP) and quantity of tracked satellites, we can infer that our navigation solution accuracy will outperform prior expectations and margins.

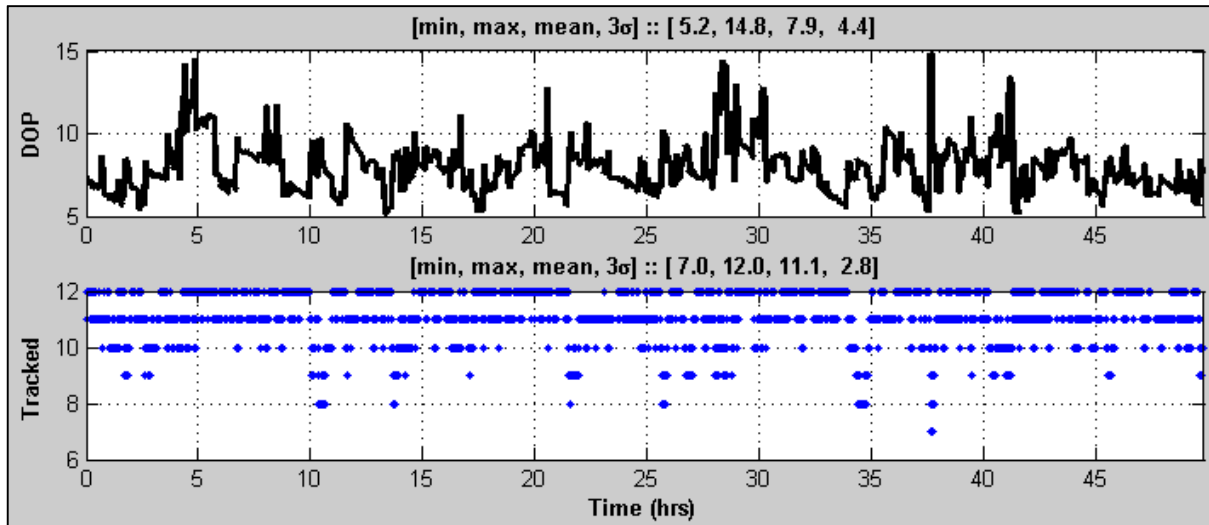


Figure 6. Dilution of Precision and Tracked Satellites

Why are DOP and tracked satellites so good? This is because the GPSR tracks GPS over the entire field of view. This is made clear in Figure 7 which shows tracking probability at angles off GOES nadir (same as boresight) in 1° increments and tracking probability at distinct 0.5° increments in azimuth/elevation. These plots contain over 230 hours of data to provide a smoothed result. Distinct ranges where tracking satellites is more likely are highlighted. These “hot” regions for tracking are near 20 degrees off-nadir which coincides with the GOES Rx GPS antenna main lobe, reference Figure 2. Also clearly visible are locations where no tracking will take place. Including the Earth, these gaps are location where no GPS satellites are visible or viable to be tracked from the GOES PLT station. More discussion on the distribution of tracking and signal quality is included later in this section, particularly regarding Figure 10. So how good is our solution? We took 2 approaches to determine this; 1) Ground Simulation and 2) Raw Measurement Analysis. See sections 2.2 and 2.4.

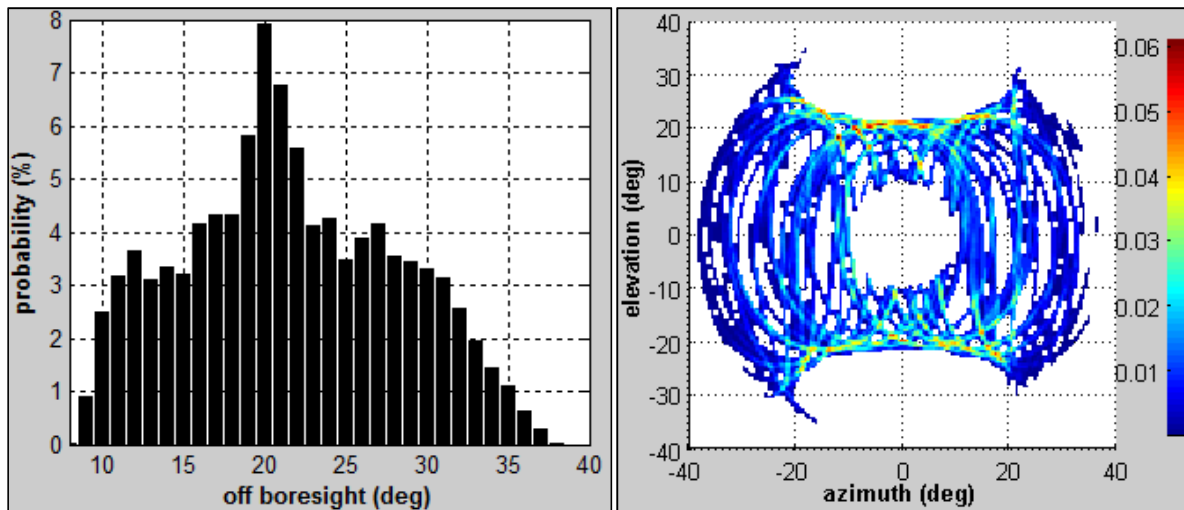


Figure 7. Tracking Density at GOES Nadir Angles (left), Azimuth and Elevation (right) [230 hrs]

Carrier-to-noise density (C/N0) is the metric output by the GPSR that describes both signal strength and noise regarding the GPS signal input into the GPSR (not at the antenna, etc.). A 50 hour span of

C/N0 and C/N0 average (black line) is depicted in Figure 8. The average C/N0 seen by the GOES-16 GPSR system is around 31.5 dB-Hz, this is about 3 dB higher than simulations (specifications). This higher C/N0 lends itself to longer, more contiguous tracking periods. Although there is a lower bound where GPS signal quality and resulting solution will start to degrade (~20 dB-Hz), higher C/N0 does not directly improve the position and velocity solution, but it does allow more tracked satellites which do.

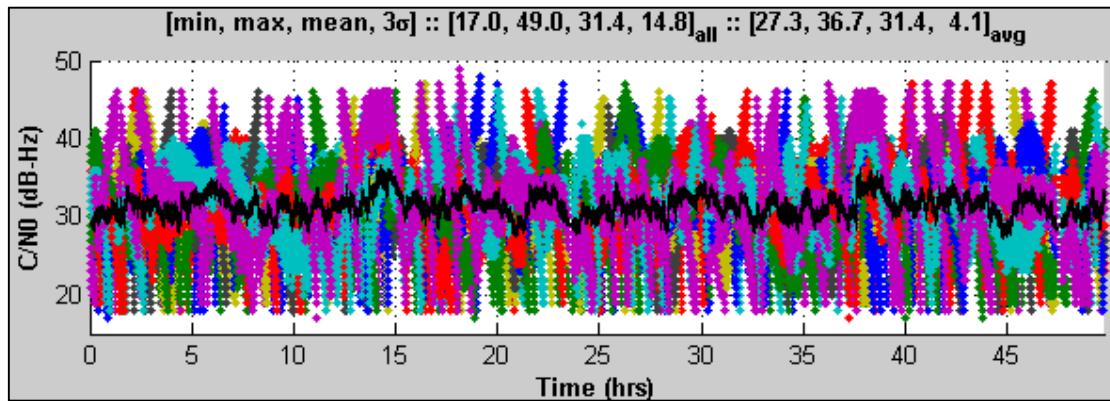


Figure 8. Carrier-to-Noise Density (C/N0) Over Time, Average in Black

This highly dynamic C/N0 is caused not only by the varying distance between Rx and Tx Antenna, but also by the interaction between the GPS antenna transmit pattern and the GOES-16 receive antenna pattern. Reference the Rx and Tx antenna patterns in Figure 2 and Figure 3 respectively. This interaction is depicted in Figure 9 as C/N0 at off-nadir angles from both GOES-16 and GPS. These plot contains over 230 hours of data, allowing for a smoother distribution. Clearly visible is the Tx main lobe below 15 degrees off GOES Nadir and the first and second side lobes. GOES-16 can track almost to 39° making for a 78° field of view. Other than accentuating the block-type lobes this figure clearly illustrates that signal quality suffers almost no deteriorating effect until after 35° off GOES nadir or alternatively 65° off GPS nadir. The distribution of C/N0, e.g. min/max at a particular range of off-boresight angles, shows the scalloping and irregular shape of the combined Tx and Rx gain patterns and in particular the high variations in the side lobe regime as compared to the average gain patterns.

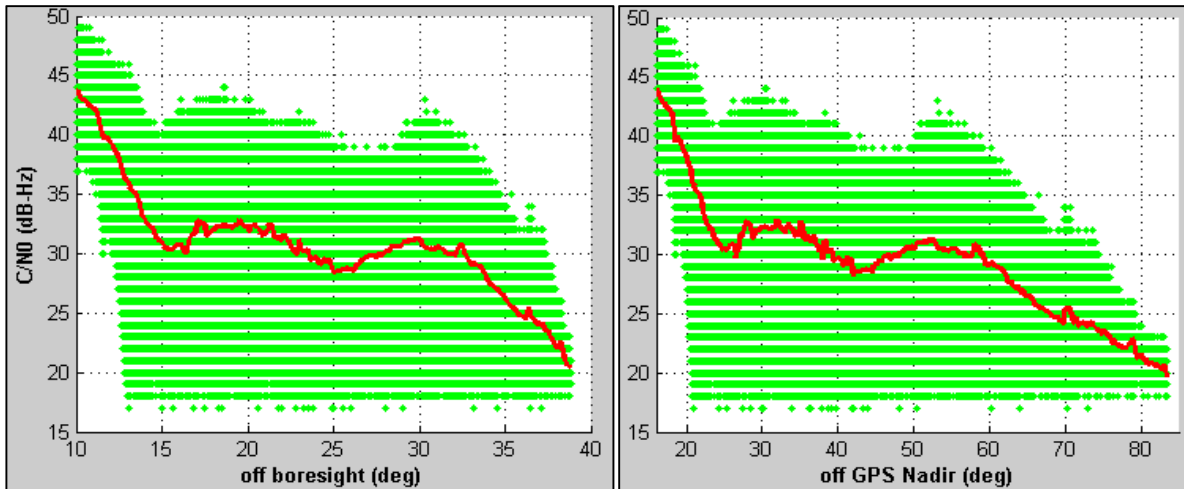


Figure 9. C/N0 at Angles Off-Nadir from GOES (left) and GPS (right), Average in Red [230 hrs]

A 3D representation of C/N0 at distinct azimuth and elevation is shown in Figure 10. The GPS Tx main lobe is clearly visible in red around Earth. Warm regions are also apparent in yellow, they appear in particular regions out to about 25° off GOES-16 nadir. Cold regions at the outer limits indicate outer side lobe thresholds and the distinct cold localities at intermediate angles highlight side lobe nulls. The sky view is leftward leaning in tracking extrema and density, the cause of which is pending future investigation. This Doppler magnitude is illustrated in Figure 10 (right) as relative velocity in km/s, where positive indicates GPS and GOES-16 are moving away from each other.

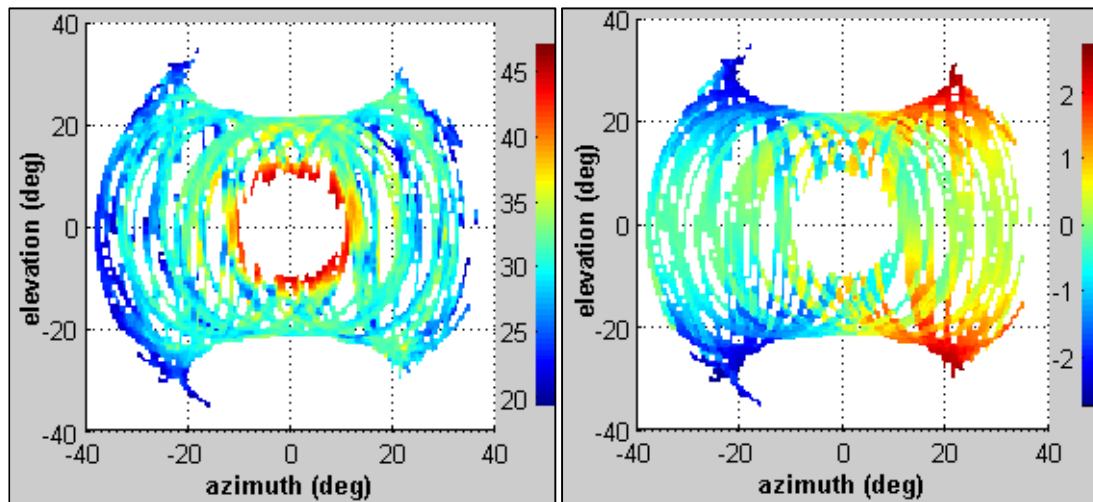


Figure 10. GOES Skyview of C/N0 (dB-Hz, left) and Relative Velocity (km/s, right) [230 hrs]

The clock performance as depicted in Figure 11 is nominal. Taking long term pre-launch and post launch samples the clock drift noise (variance) and stability of hardware induced PPS error can be confirmed. The hardware PPS error is within the normal bounds of ± 13.09 ns and follows a repetitive local pattern. Clock drift noise is minimal with an average magnitude of 3 mm/s. This indicates that the clock has no adverse effects on the navigation solution and overall GPSR performance. The total PPS time error can be assumed to match that found during oscilloscope ground

testing: about 70 ns RMS and generally between -170 and 100 ns with rare outliers between -400 and 200 ns.

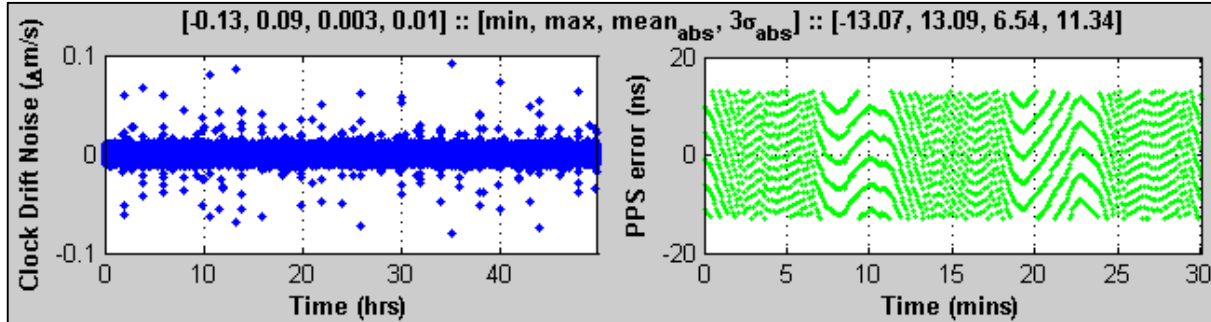


Figure 11. Long-term Clock Drift Noise (left) and Short-term PPS error (right)

2.3 Hardware-in-the-Loop Simulation Derived Solution Accuracy

This section addresses performance findings regarding the use of a 12-channel L1 Spirent GSS8000 simulator, GPSR and LNA. Scenario parameter files on the simulator were modified to attempt to match GOES-16 operational data. Simulations of GPS at GEO is limited by the current state-of-the-art of GNSS simulators. Two dominate limiting factors are the modelling of multiple transmit antenna pattern, e.g. block-type antenna patterns, and modelling GNSS constellation attitude dynamics which intrinsically effect performance because the side lobe patterns vary with attitude (radially non-symmetrical). However there are means to “trick” the simulator to generate performance similar to that observed on-orbit. Further detail is out of the scope of this paper but basically by matching DOP and tracked satellite dispersion/consistency characteristics along with orbit characteristics you can come close to matching navigation solution performance.

Over 20 iterations of sim were generated in order to drive certain metrics to parallel on-orbit data (e.g. DOP, tracking consistency and probability, etc.). Operational data at 1/4th Hz from GOES-16’s original turn-on (December 5th 2016) and 1 Hz over a 50 hour span (February 2nd 2017) was used to help generate and refine the parameters that went into this sim. The sim run depicted in the figures of this section is the final sim rendition (as of April 1st 2017) that aimed to replicate the 50 hours of operational data previously described in section 2.1 and used in the raw data analysis of section 2.4. Note that the maneuvers were filtered out of the sim and that the motion of GOES-16 was defined by an 8th order Fourier fit of the output position data.

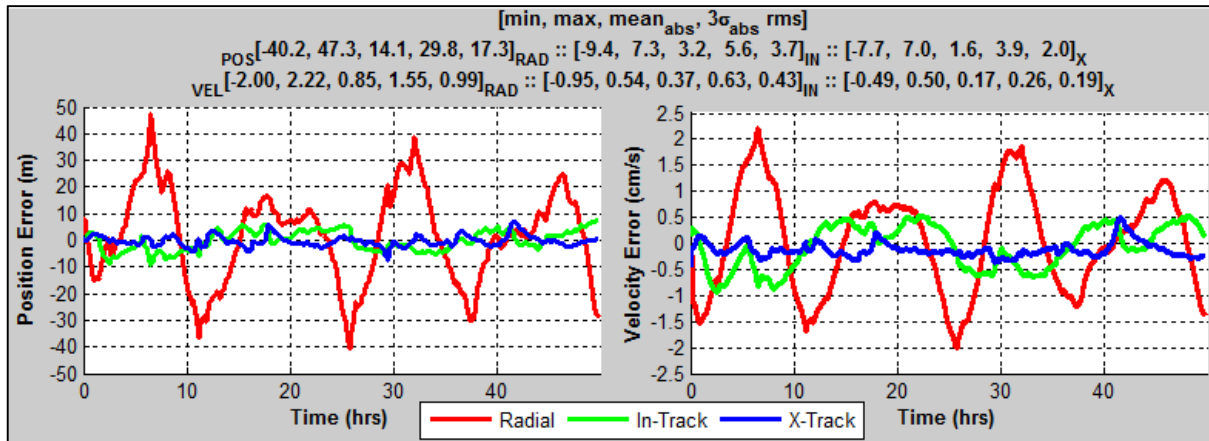


Figure 12. Sim Position (left) and Velocity (right) Error, Radial/In-Track/Cross-Track Directions

Sim position and velocity error over time, including initialization, is depicted in Figure 12. The solution error is well within requirements with a large margin. The radial/in-track/cross-track RMS position error is shown to be 17.3, 3.7 and 2 m with maximum error spikes up to 47, 9 and 8 m. The radial/in-track/cross-track RMS velocity error is shown to be 1, 0.43 and 0.19 cm/s with maximum error spikes up to 2.2, 1 and 0.5 cm/s.

Summarized below is a solution error summary of the 50 hour sim which serves as a good estimate of actual performance. Table 2 depicts the expected position and velocity errors in the Radial, In-Track and Cross-Track reference frame and total error probabilities as Spherical Error Probable (SEP) metrics. These SEP values define total error magnitude probability caps regarding 61% (R61), 90% (R90) and 99% (R99) containment.

Table 2. Simulated Position and Velocity Accuracy Ranges

	Radial				In-Track				Cross-Track				SEP		
	max	mean	3 σ	RMS	max	mean	3 σ	RMS	max	mean	3 σ	RMS	R61	R90	R99
Position (m)	47.3	1.5	51.7	17.3	9.4	-0.2	11.2	3.7	7.7	-0.2	6.1	2	17.7	19.1	25.8
Velocity (cm/s)	2.22	0.05	2.97	0.99	0.95	-0.07	1.27	0.43	0.5	0.17	0.43	0.19	1.1	1.3	1.7

These sim-derived expected solution average errors exceed the highly accurate raw data EKF results, presented in section 2.4, in radial position and all velocity directions. The in-track and cross-track position accuracy agrees extremely closely. The average radial position solution disagreed with a moderate margin on the order of 10 m. The average velocity solution disagreed with a noticeable margin on the order of 0.7, 0.3 and 0.1 cm/s in the radial, in-track and cross-track directions respectively. These correlations show the usability of this particular sim, define performance analysis fidelity and assign “good estimation” error bounds. For further details regarding prelaunch ground simulations and worst-case assumptions, see [5].

2.4 Raw Data Post-Processing Performance Analysis

Relevant raw data including pseudo-range (PR) and carrier-phase (CP) data was collected from the GOES-16 GPSR telemetry for post-processing. This data was processed with MATLAB tools to look at data noise characteristics and also with an orbit Kalman estimator tool used to process the raw data in order to output a highly accurate post/pass smoothed solution. Evaluation of the on-orbit navigation

solution by differencing it with the result of the Kalman estimator tool's smoothed solution is the most accurate (variance of 3 m) means currently available.

2.4.1 GPSR Raw Data Evaluation

The first set of analysis involved plotting the highly accurate ΔCP (Carrier Phase) measurements minus ΔPR (Pseudo-Range) measurements recorded in the GPSR raw data. These deltas, ΔCP or ΔPR , over a measurement interval is the delta range over that time, e.g. position variance or approximate velocity. Comparing these metrics indicates noise of PR since CP is a much more precise measurement. Figure 13 is a plot of the ΔCP and the ΔPR measurements where the measurements are close in value but ΔCP is visibly smoother (more accurate). The GPSR uses PR in its solution process so the noise of PR relative to CP is a clear indicator of accuracy.

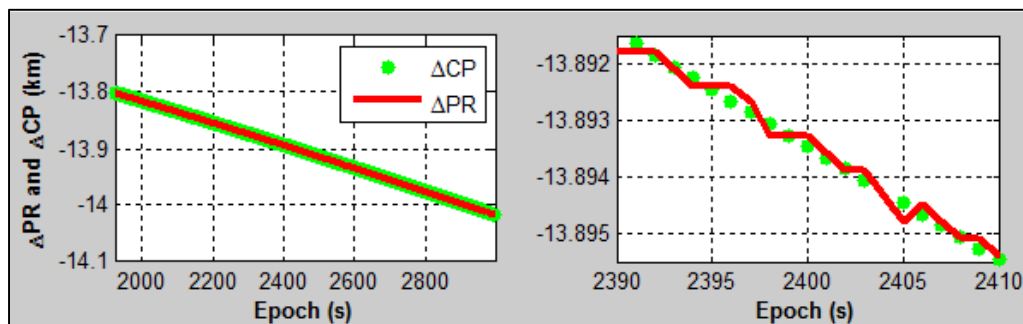


Figure 13. ΔCP and ΔPR from Raw Data, PRN 25

The difference of ΔCP and ΔPR for PRN25 is depicted in Figure 14. Note that each GPS satellite is identified by a pseudo-random noise (PRN) and labeled as PRN 1 through PRN 32. This data depicts two important metrics. First, the noise of the PR measurements (as calculated by comparing to ΔCP) is approximately 26 cm which is indicative of good C/A data, this is the expected noise level of C/A data for GPS receivers with signal power in the -180 dBW range [2]. Another characteristic is a slight signature can be seen around the 2400 1Hz epoch mark. After looking more closely at the data this appears to be at approximately 43° off nadir of a IIF antenna which is near a null (low gain region between side lobes) as shown in Figure 3. The noise of the data is consistent with the noise of surrounding data and the filter ingests the data with no issue. It shows that the data at and near the nulls of the antenna provide good data and that the GPSR can track down into some of the GPS Tx antenna side lobe nulls.

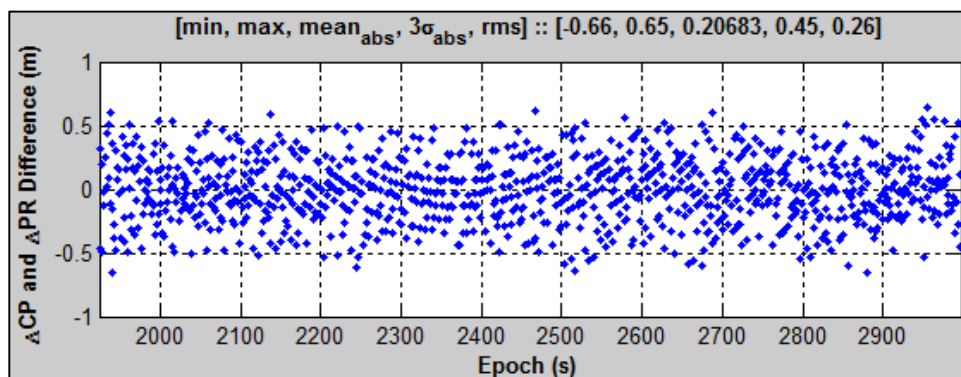


Figure 14. Difference between ΔCP and ΔPR , PRN 25

2.4.2 Ground EKF Processing, Bias Un-Modeled

The second set of analysis was processing the data in a filter/smoothing process using a Kalman estimator tool. This Kalman estimator tool has the capability to process GPS data collected from GOES-16 that is downlinked in telemetry. For this analysis, only the PR data was processed in the filter. With the high number of GPS Satellites collected and the good geometric dilution of precision of collected data, it was expected that a very accurate post/pass solution could be processed.

A 50 hour span of GOES-16 data collected on February 2nd 2017 was used for processing. The NGA precise GPS ephemeris in ECEF format was used in processing this data. NGA claims better than 10 cm accuracy on this ephemeris and clock solution and should remove any GPS errors that might be incurred by using the broadcast GPS ephemeris that GOES-16 used for its on-board solution. In the first iteration of Kalman estimator tool the filter was run solving for Position, Velocity, Solar Pressure State and GPSR clock phase and frequency. In addition, maneuvers that were done by GOES-16 were included in the estimation process. North/South maneuvers of approximately 2 cm/s were done nearly 24 hours apart. The output of the PR residuals are shown in Figure 15. The root mean square (RMS) of the smoothed residuals is 2.06 m. This is significantly higher than the expected noise per Figure 14 of 26 cm. This indicates that biases exist in the data that are not modeled by the filter. Pink data indicates measurements rejected due to earth grazing angle mask placed on the data input. Red data indicates measurements rejected due to other filter induced modeling related rejections.

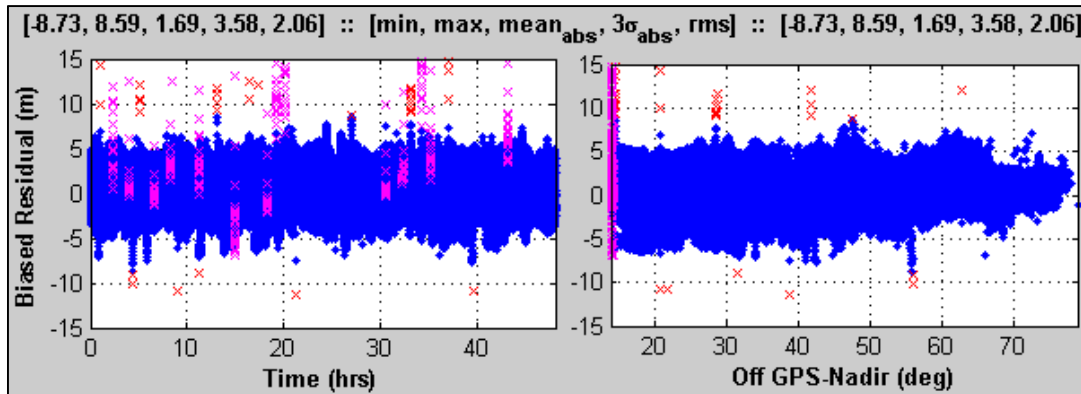


Figure 15. PR Residuals without GPS Bias vs. Time (left) and GPS Nadir Angle (right), all PRN

Figure 16 shows individual PRN residuals as a function of off GPS nadir angle, where 0° is directly nadir, the edge of earth is near 13.7° and the edge of the ionosphere is near 15.8°. This data clearly shows a bias in the data along with variation dependent on elevation angle. Furthermore it is illustrated that the bias is highly variable. Since the data was processed using NGA precise ephemeris, the bias was not caused by clock and ephemeris errors. The bias is most likely caused by inter-signal delay (ISC) and group delay (T_{GD}) biases that were not included in processing plus a group delay variation of the L1 signal in the side lobes of the signals and edge of the main signal that is not calibrated out.

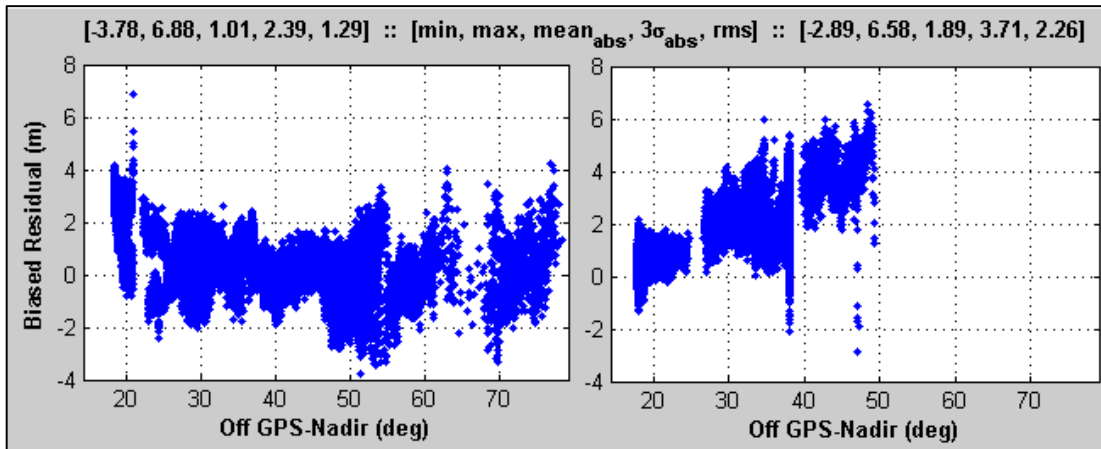


Figure 16. PR Residuals at GPS Nadir Angles, IIR PRN20 (left) and IIF PRN3 (right)

2.4.3 Ground EKF Processing, Bias Modeled

To account for this effect, a GPS bias for each SV was added to the filter estimation process. The GPS bias was modeled as an exponentially de-correlated process with a correlation time of approximately 3 hours. This allows for the estimation process to solve for a GPS bias that changes over time. This is a common estimation technique used by aircraft users of GPS to account for unresolved atmospheric effects in the measurements and also in Low Earth Orbit satellites to solve for GPS errors. In a measurement rich environment, this technique is very useful to increase ephemeris accuracy because the GPS un-modeled errors are solvable. Figure 17 shows the measurement residuals of the same run using this technique. You can see the much tighter bunching of residuals and the RMS of the residuals are 23 cm vs. the 2.06 m of the run without solving for the GPS biases. One relevant part of this depiction is that the residuals grow as a function of off-nadir angle which is indicative of the lower signal to noise ratio the further out on the GPS antenna.

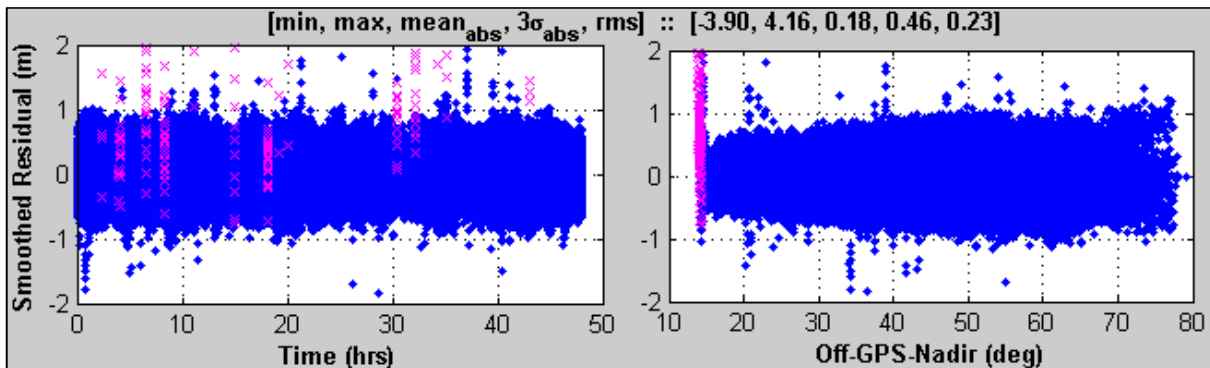


Figure 17. PR Residuals Using GPS Bias over Time (left) and GPS Nadir Angle (right), all PRN

Figure 18 shows PRN residuals as a function of off nadir angle from GPS where the biases along with the variation have disappeared, soaked up by the GPS bias state. The gaps in block-type IIF PRN3 residuals near 26° and 39° are directly attributable to nulls in that block-type antenna pattern (see the average antenna pattern in Figure 3). Block-type IIR GPS satellites track to the most extreme off-nadir angles due to their higher power side lobes. Clearly illustrated in Figure 18 is the general trend of growth in residuals as off-nadir angles increase. Also indicated in this figure are the differences

between block-types in tracking regimes and received signal characteristics, further evaluation of these performance details are out of the scope of this paper.

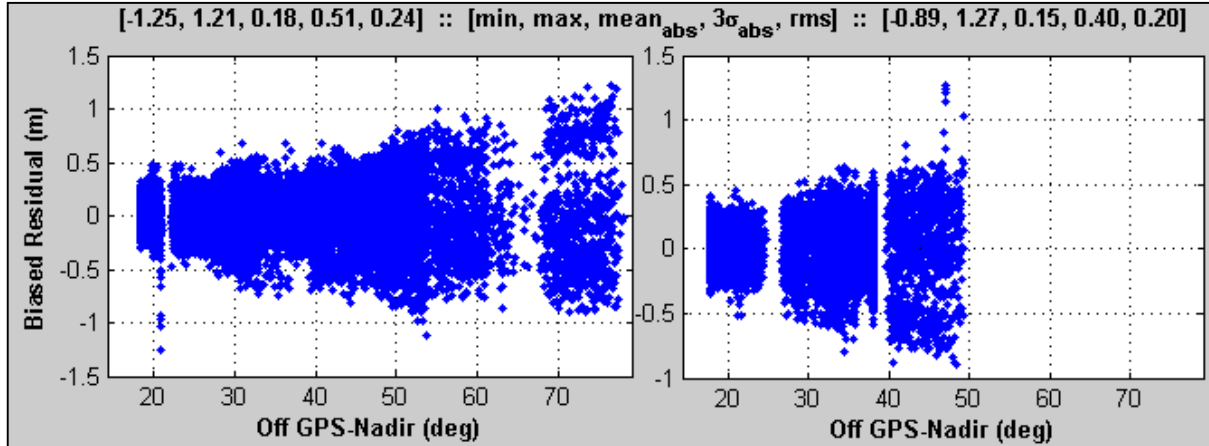


Figure 18. PR Residuals vs. GPS Nadir angles, IIR PRN20 (left) and IIF PRN3 (right)

In comparing these residuals to the C/N0 values for those PRN depicted in Figure 19 the residual magnitude can be linked to both off-nadir angle and C/N0 magnitude. As C/N0 decreases, residuals increase. Furthermore these C/N0 curves follow the average antenna pattern for each block-type so it is easy to see the nulls and how those regions of especially low C/N0 cause data to not be incorporated into the solution.

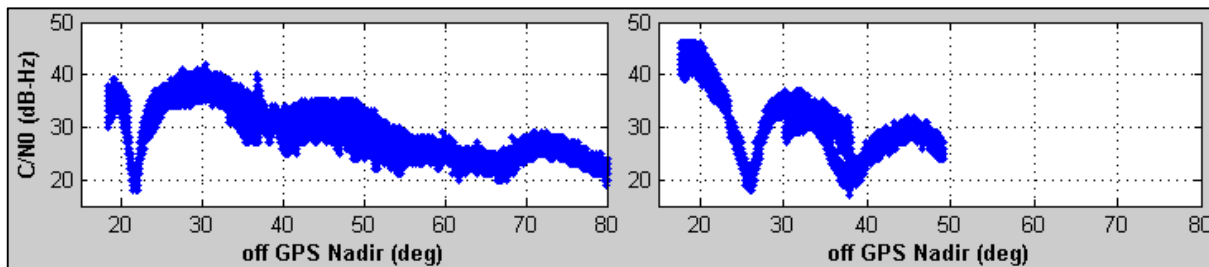


Figure 19. C/N0 at GPS Nadir angles, IIR PRN20 (left) and IIF PRN3 (right)

2.4.4 Ground EKF Processing, Thrust Data Use, Bias Un-Modeled

The effect of including and not including thrust data into the ephemeris solution was also examined. GOES-16 performed two station-keeping maneuvers of approximately 2 cm/s. In Figure 20 you can see the residuals (bias included) from the filter when the thrust was not included versus when it was included as an input for the filter to consider. When the thrust was not included in the estimation process biased residuals along with a period of rejection are seen right after the thrust. This thrust occurred at approximately 31 hours into the run. When the thrust is included in the filter, the residuals are much more stable. Currently the GOES-16 GPSR solution does not include the estimated thrusts in the filter process. The differences in the estimated solution from Kalman estimator tool were about 8 m over a period of 4 hours after the thrust. This is indicative of an un-modeled error by not including the thrust in the estimation process. Performance would improve and namely the solution convergence time after a maneuver would vastly improve if thrust data was incorporated into the GPSR's estimation process.

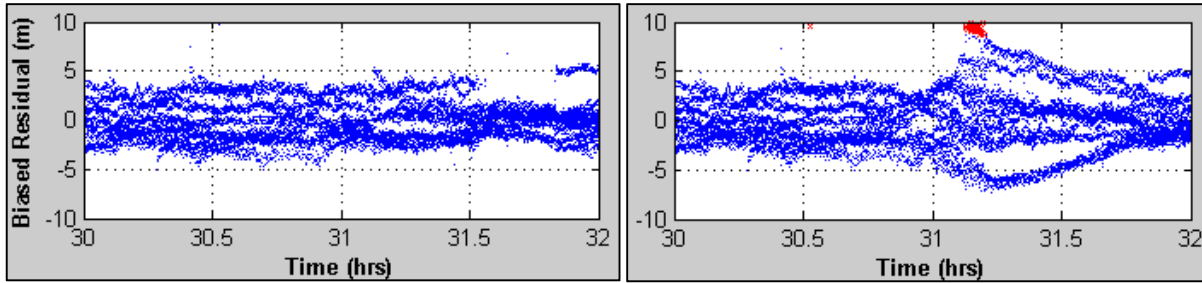


Figure 20. PR Residuals with (left) and without (right) Thrust Data Incorporation

2.4.5 Ground EKF Processing, Final Smoothed Result Compared to On-Orbit Solution

Finally, a comparison was done of the Kalman estimator tool post/pass smoothed ECEF ephemeris as compared to the GPSR calculated ECEF ephemeris as collected in telemetry. Figure 21 and Figure 22 show this comparison. When related back to the sim results, discussed in section 2.3, many similarities are apparent. One expected similarity is that radial error is the dominate error source and it has a 24 hour periodic (approximate magnitude) pattern. Further commonality discussion and sim evaluation is out of the scope of this paper. The expected accuracy of the Kalman estimator tool results indicated by the hashed lines, is the variance (square root of covariance) of the Kalman estimator tool smoothed solution which can be approximated as 3 m. Thus the GPSR performance metrics have to be adjusted, see the example in Eq. 1. Note that the variance values for velocity accuracy is too small to see in the plot, thus those performance metrics are accurate without adjustment. These plots indicate that the GPSR is providing a valid solution that can be used for mission purposes. Recall, the Kalman estimator tool solution is the best estimate of the ephemeris using a high accuracy filter that can currently be provided for comparison purposes.

$$RMS_{actual} = \sqrt{RMS^2 + variance^2} , RMS_{rad} = \sqrt{7.25^2 + 9} = 7.85 \quad (1)$$

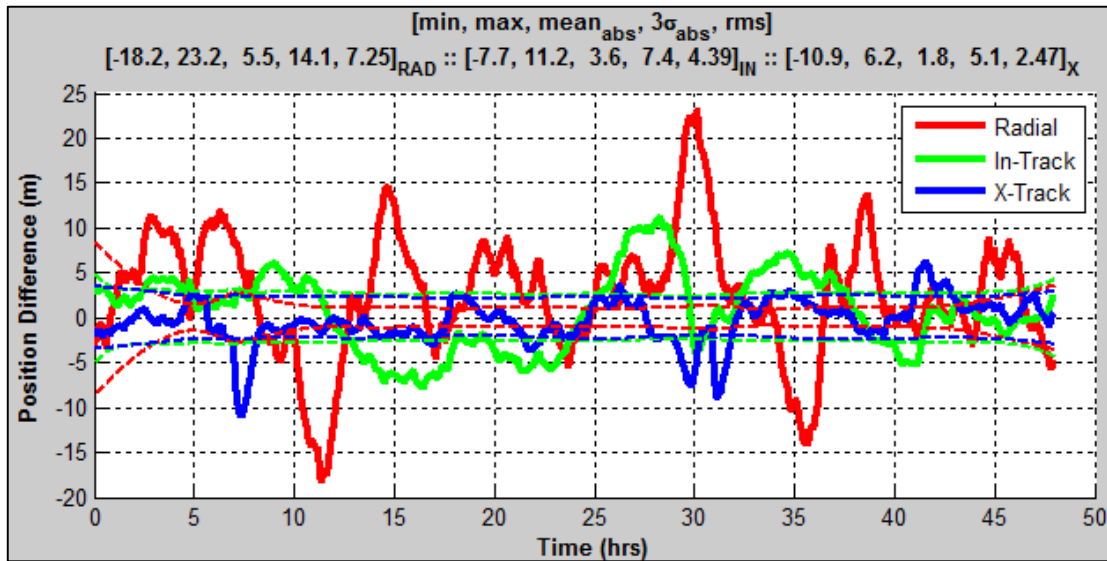


Figure 21. GPSR Position Error as Difference with Ground EKF Solution

Approximately 50 hours of steady-state position solution accuracy is depicted in Figure 21 and velocity solution accuracy is depicted in Figure 22. As depicted our radial/in-track/cross-track RMS error magnitude with variance included is approximately 7.85, 5.32 and 3.89 meters respectively. The spikes in velocity error are directly linked to North-South station keeping maneuvers performed at those times, see Table 1. Including those two maneuver induced outliers the radial/in-track/cross-track velocity RMS error magnitude is 0.14, 0.09 and 0.23 cm/s respectively. The large 3σ values for in-track and cross-track velocity accuracy is due to the two maneuvers present in this data.

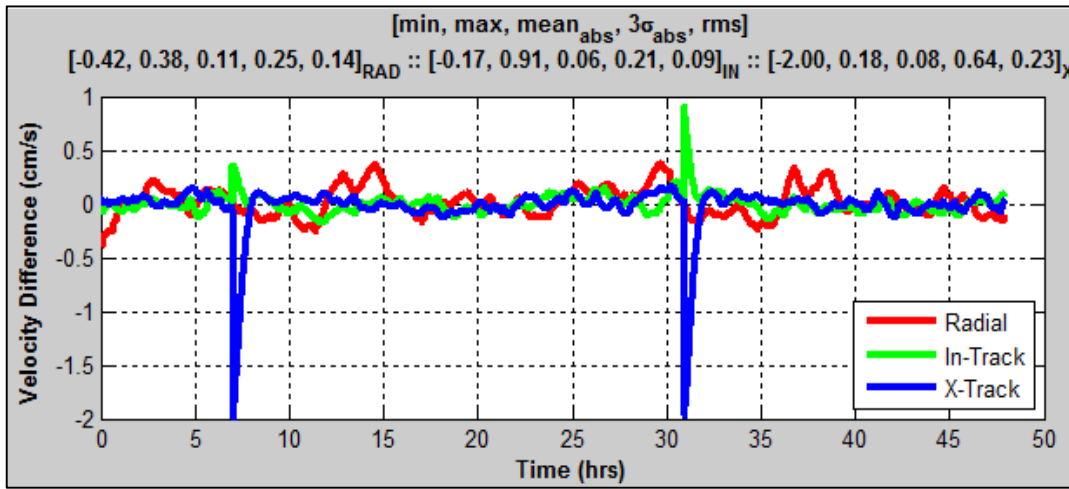


Figure 22. GPSR Velocity Error as Differenced with Ground EKF Solution

The navigation solution accuracy in steady-state far exceeds performance requirements. The position accuracy margin is approximately 65-75 m and the velocity margin is approximately 5.6-5.9 cm/s. Note that as enumerated in these figures, sigma (σ) represents standard deviation and σ_{abs} represents standard deviation of error magnitudes, thus $3\sigma_{abs}$ bounds where 99.7% of error magnitudes will fall under the upper bound is measured as mean magnitude plus the $3\sigma_{abs}$. During normal maneuvers the in-track and cross-track velocity solution is briefly effected but remains well within performance requirements. Mean and 3σ values for position and velocity errors (not error magnitude, as enumerated in the figures above) along with the associated 99.7% probability bounds are shown in Table 3. Also shown in this table are the Spherical Error Probable (SEP) values that define total error magnitude probability regarding 61% (R61), 90% (R90) and 99% (R99) containment. None of these metrics consider the data variance.

Table 3. Position and Velocity Dimensional Error Metrics (no variance) and overall SEP bounds

	Radial				In-Track				Cross-Track				SEP		
	max	mean	3σ	RMS	max	mean	3σ	RMS	max	mean	3σ	RMS	R61	R90	R99
Position (m)	23.2	2.6	20	7.3	11.2	0.7	13	4.4	10.9	-0.4	7.3	2.5	8.4	11.3	15.2
Velocity (cm/s)	0.42	0.02	0.4	0.14	0.91	0.001	0.28	0.09	2	-0.02	0.69	0.23	0.28	0.38	0.51

3 CONCLUSION

From the moment the GOES-16 GPSR was initialized on December 2016 (in less than 5 minutes) it has exceeded expectations. This paper demonstrated GOES-16 3D position accuracies is less than

15.2 meters 99% of the time this includes normal NSSK maneuvers. The total velocity accuracy for 99% probability is found to be 0.52 cm/s, including normal NSSK maneuvers. Additionally the clock accuracy can be assumed to be consistent with ground testing, near 70 ns PPS accuracy RMS. This exceeds all position, velocity and timing requirements by orders of magnitude. The average tracking of 11 GPS and an excellent average DOP of 7.9 shows we have significant margin to maintain this excellent performance. Furthermore we can improve performance in the near future. Data biases in the side lobes caused by Group Delay variation is present and could be removed to improve precision and maneuver generated errors could be greatly reduced by filter tuning. These GOES-16 performance results show that the final frontier of GPS at GEO, is now a proven operational capability. This paper makes it clear that all future GEO Satellites must consider the addition of a GPSR in their spacecraft design, otherwise they are sacrificing spacecraft capabilities and accuracy along with incurring increased and continual demand on ground support.

4 FUTURE WORK

Work to further refine the performance regarding the use of GPS at GEO include investigations into: 1) inclusion of a solar pressure state in the GPSR solution to help model Keplerian motion between measurement points, 2) inclusion of estimated ΔV 's in the propagation of the GOES-16 position states, 3) inclusion of GPS biases to account for biases caused by ISC and T_{GD} and group delay variation in the side lobes, 4) investigation of the use of full carrier methods in the estimation process.

Considerations in the near future will focus on preparing for eventual scenarios. One obvious consideration is determining the impact of GPS III via simulations. The distribution of tracking along with PRN and block-type characteristic focused observation from GEO are the subject of future work. Another slightly more obscure consideration is simulation based determination of performance if a super-synchronous orbit contingency was deemed necessary during orbit raising. Also, high magnitude maneuver performance will be examined by simulation. Loss of a full GPS constellation effects on performance is also a simulate-able issue. Performance investigation regarding transformation from antenna phase center (location of solution) to vehicle center of gravity for ephemeris generation and orbit propagation.

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