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GOES-R SERIES GEO SIDE-LOBE CAPABLE GPSR POST-LAUNCH REFINEMENTS AND OPERATIONAL CAPABILITIES

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This paper addresses three topics: 1) EOPP file modification, 2) Kalman filter parameter tuning regarding maneuvers and 3) off-pointing GPS tracking capability. GOES-R (Geostationary Operational Environmental Satellite-R Series) is the first in a 4-part series of new weather satellites set to replace and upgrade the older GOES constellation. Two GOES-R have been launched to date, GOES-S and GOES-R. GOES-R is operational over the Eastern United States and GOES-S over the West. The Global Positioning System Receiver (GPSR) on board this geostationary weather satellite is a mission critical enabling technology which has been both tested on the ground and evaluated on-orbit to verify its effectivity. Since becoming operational in November 2016, the GPSR onboard has performed extremely well under nominal circumstances. Further refinements regarding a variety of facets have taken place since the launch of GOES-R. One such refinement was the implementation of a modified EOP parameter set to improve ECEF to ECI transformation by restoring zonal tides removed from the EOP parameter fit per tech note 36. Another relevant refinement combined thermal consideration with Kalman filter tuning to improve orbit determination performance during maneuvers. Now with two years of data and two vehicles in orbit many capabilities of the GPSR have been identified and defined to a higher degree. For example, metrics on side-lobe tracking and off-Nadir tracking capabilities have been quantified to a high degree. This paper will seek to supplement the ESA GNC 2017 GOES-R GPSR performance paper as a deeper dive on specific tracking capabilities and performance improvements now implemented on the GOES-R and GOES-S vehicles.

INTRODUCTION

The GOES-R series 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 a Kalman filter output Earth Centered Earth Fixed (ECEF) position of the GOES-R series satellites for mission processing of collected science data. The GPSR system was designed and tuned in order to facilitate tracking the extremely weak GPS signals, including sidelobes, at GEO, on the order of 10e-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 automaton.[1]

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This paper presents a deeper dive into the GOES-R class vehicles Viceroy 4 GEO GPSR performance and relevant operational improvements implemented since the launch of GOES-R in November of 2016. It serves as a supplement to the paper presented at ESA GNC 2017.[1] Topics of discussion are a) improved and minimal impact ECEF-to-ECI conversion via EOPP modification, b) Improved GPSR navigation performance during maneuvers, c) insight into the GOES-R GPSR use of GPS sidelobes at GEO and an analysis regarding GPSR (and antenna) tracking capabilities regarding operations that take the antenna off-Nadir. More information regarding GOES-16's guidance, navigation and control performance can be referenced.[2] Note, that at this point in time (November 2018) GOES-R is also called GOES-16 and GOES-East whereas GOES-S is also called GOES-17 and GOES-West.

EOPP FILE MODIFICATION – INNOVATIVE APPROACH

This section presents the innovative approach used by the GOES-R program regarding the operationally implemented Earth Orientation Prediction (EOP) parameters via a modification scheme. EOP parameters (EOPP) are used to calculate the transformation between the Earth Centered Earth Fixed (ECEF) and Earth Centered Inertial (ECI) reference coordinate systems. To be precise, EOPP provides 1) Earth pole wander used to transform between the International Terrestrial Reference System (ITRS) and the Terrestrial Intermediate Reference System (TIRS), and 2) UT1-UTC (dUT) used in the transformation from TIRS to the Celestial Intermediate Reference System (CIRS). Both are necessary steps towards transforming to ECI. Note, GPS Receiver provided data is referenced to the ECEF coordinate system.

National Geospatial Intelligence Agency (NGA) EOPP fits parameters I, J, K1, K2, L1 and L2 for "Delta UT1" (equivalent to dUT) bias, rate, and approximate zonal tide contributions respectively.[3] Parameters K3, K4, L3, L4 represent seasonal tides. Equation 1 is used to evaluate the EOP parameters to solve for dUT.

$$UT1 - UTC(t) = I + J(t - tb) + \sum_{m=1}^{4}\left(K_m \sin\left(\frac{2\pi(t - tb)}{R_m}\right)\right) + \sum_{m=1}^{4}\left(L_m \cos\left(\frac{2\pi(t - tb)}{R_m}\right)\right) \tag{1}$$

The approximate zonal tide contribution was removed from the NGA EOPP on June 14th, 2016 when NGA implemented Tech Note 36 (TN36).[4] Subsequent this implementation date the user must calculate the zonal tide contribution to dUT independent of EOP parameters, e.g. via the Gross 62-term zonal tide model.[5,6] The result of removing the zonal tide contribution to the dUT calculation in terms of the EOPP themselves is an altered fit value for the I and J terms, and zeroed out K1, K2, L1 and L2 terms.

Effect - Apparent Bias in Image Navigation

GOES-16's on-orbit Earth imaging observations were analyzed via landmarking and an image bias was evident. On 9/26/2017 this image bias was determined to be an in-track (Eastward) image shift with a magnitude of approximately 7.4 urad which converts to nearly 310 m of in-track orbit error or 0.1 second of timing error. The GPSR solution (ECEF) was shown to be accurate to within 20 meters nominally and the image time tagging was determined to be accurate. However, the bias was shown to be consistent over long term durations with zonal tide contributions to the rotation from ECEF to ECI. See Figure 1.

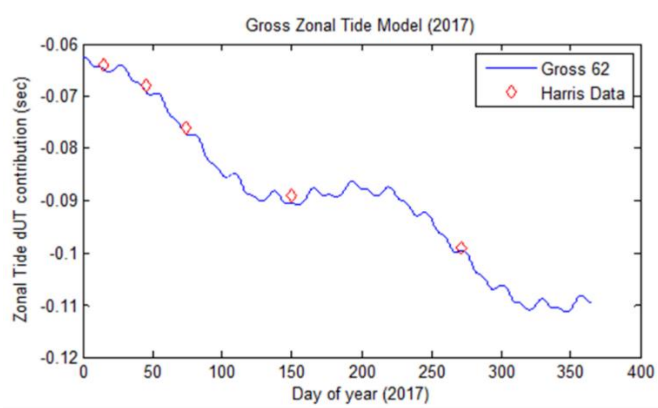

Figure 1: Image bias data points plotted against the Gross 62 model

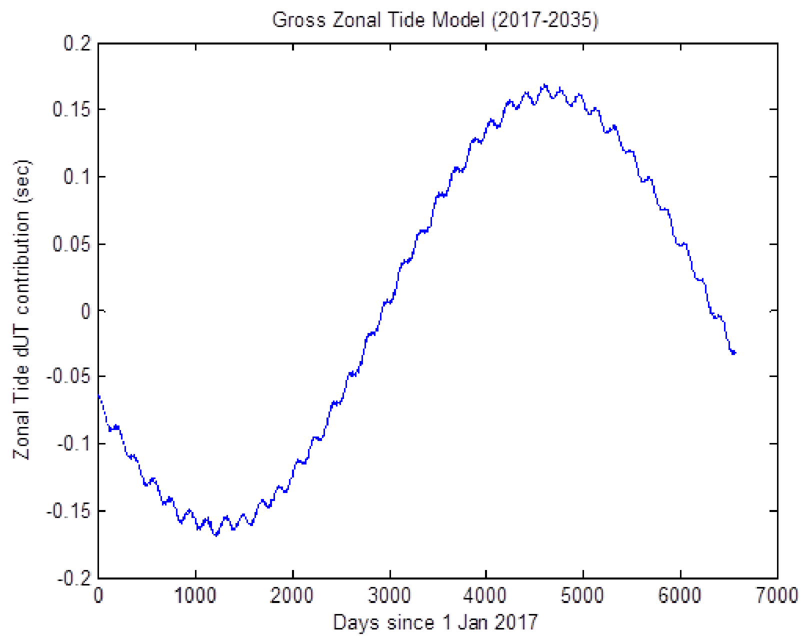

Figure 2: Long term Trends of Zonal tide contribution to dUT

The zonal tide contribution to the dUT calculation is periodic in nature and varies between approximately +/-0.165 seconds. See Figure 2 for a visual depiction of the Gross model calculated zonal tide contribution in seconds over an 18-year span. Note, a 0.1 second error in the dUT calculation converts to approximately 310 meters of East-West error at GEO or about 7.4 urad of Nadir pointing error.

Cause – EOPP Tech Note 36

After investigation regarding the instrument image bias it was determined that the ephemeris transformation from GPSR provided ECEF to ECI was the cause of error. More precisely, the rotation defined by EOPP was identified as the source of the coordinate frame transformation issue. GOES-R flight software (FSW) usage of NGA EOPP was developed prior to NGA's adoption of TN36. NGA's change occurred after the GOES-R verification work and prior to launch. The EOPP algorithm documentation during development for transforming ECEF to ECI did not take into account the removal of approximate zonal tides from the EOPP. The NGA change has no effect on ECEF information produced by the GPSR: GPS/UTC time and ECEF P/V solution remain the same.

Remediation - Modified EOP Parameters

With the NGA transition from Tech Note 21 (TN21)[7] to TN36, the theory and procedure for accounting for predicted zonal tide contribution to 'UT1-UTC' (dUT) changed. Use of the 41 term truncated Yoder zonal tide model[8] was discontinued in favor of full 62-term Gross model as the preferred zonal tide model. Under TN36, the dUT parameter fit has the Gross model zonal tide model removed and the EOPP zonal tide approximation parameters (K1, K2, L1, and L2) are set to zero. The user must restore the zonal tide contribution to the dUT calculation independently. The suggested remediation of the TN36 change was FSW calculation of the zonal tides contribution and addition of that result into the dUT calculation computed by the TN36 EOP parameters in Equation 1.

In lieu of altering FSW to include the Gross zonal tides contribution to the dUT calculation, the GOES-R program opted to restore the zonal tides to the EOP parameters I, J, K1, K2, L1 and L2 by modifying six relevant parameters as broadcast by NGA using a 6-parameter fit to the Gross model over a relevant temporal span. This modification to the NGA provided EOPP is designed to restore the contribution of zonal tide effect on the dUT correction term contained in the EOPP message such that the given calculation of dUT is coherent with the Gross model within 5 cm over a span of 2 weeks.

Fit terms dI and dJ terms are calculated zonal tide contributions of Gross to the EOPP dUT I (bias) and J (rate) terms. The newly fit K1, K2, L1 and L2 terms are the remaining harmonics of the approximation. Additionally, the R1 and R2 terms are restored to the TN21 values (unchanging constants). The modified

EOPP data are uploaded weekly while the fit algorithm is performed over two-week spans for contingency purposes. Figure 3 illustrates several consecutive fits differenced against the Gross zonal tide model.

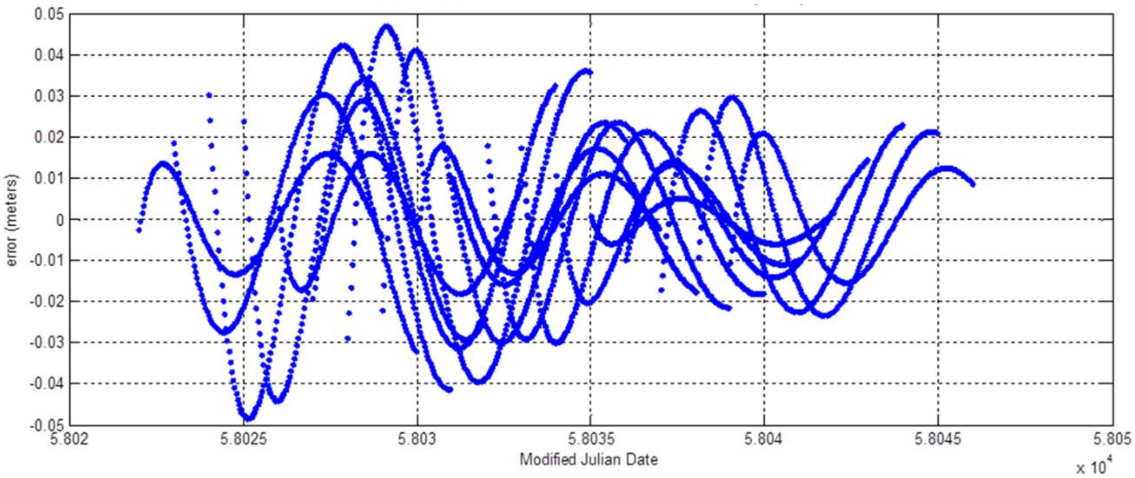

Figure 3: Modified EOPP Performance Compared to Gross 62, 26 Daily Iterations over the 15 Day Fit Spans

Summarizing, the approach chosen by the GOES-R program to account for the zonal tides is to perform a 15-day fit to the Gross zonal tide model to adjust EOPP I, J, K1, K2, L1 and L2. The fit start time should coincide with the effectivity date of the EOPP file that is to be uploaded to the vehicle. The EOPP files will be referred to as unmodified when identifying original TN36 style EOPP data retrieved from NGA and modified when referring to zonal restored EOPP data as described above. The magnitude of difference when accounting for versus not accounting for zonal tide contribution means the user must be cautious when switching between modified and unmodified EOPP files, as large residuals in X and/or Y ECI position can result.

Automated Creation and Uplink of Routine GPSR Configuration Files

In order for GOES-R to meet its orbit knowledge requirements, the EOPP configuration file (as mentioned in the previous section) and the Celestial Intermediate Pole (CIP) configuration file must be created and uplinked to the spacecraft on a weekly basis.

The initial operations concept was formulated with the premise that GOES-R spacecraft configuration files, of which there are over 200, would be relatively static and require update on an infrequent basis. As a result, the tools provided within the Ground Segment (GS) to manage these files require significant operator intervention. The steps include the use of the web-based tool called the GOES Parameter Database (PDB), which resides on the GS Integration and Test Environment (ITE). The operator would identify the desired file to change and would use the tool to create a new version of the file. Next the operator would ingest (or manually) update the necessary parameter values. Then the tool would be used to export the data into a binary format suitable for use by the GOES-R series Flight Software. This file then goes through a validation and test phase, a peer review process, and upon approval of a Configuration Change Record, would be transferred by authorized Configuration Management personnel onto the Operational Environment (OE), whereby the file could be uploaded by flight controllers. This process was determined to be too operationally burdensome to execute for the weekly EOPP and CIP GPSR maintenance configuration files.

To reduce the operational burden in preparing the routine EOPP and CIP GPSR maintenance files, a new tool was created. The input to the tool is the ascii EOPP file, which is downloaded by administrators from the NGA website and placed onto the Ground System. Using this input, the tool modifies the I, J, K1, K2, L1 and L2 EOPP to restore the zonal tide contribution as described in the previous section, then generates the binary configuration file, which is suitable for upload to the spacecraft. This greatly simplifies the file generation process, reducing cost and minimizing risk of an operator error.

To further reduce operator intervention, this tool is scheduled to execute in an automated manner by the GOES-R GS OS/Comet OA/Tool application. The Mission Planner will then schedule a task for upload and assertion of these GPSR configuration files to all operational GOES-R series spacecraft. Quality assurance is provided by the tool in the form of validation on the calculated parameters, which will report alarms to the operator if parameters are out of the expected range. Upon success, the tool will reschedule itself for execution again the following week, which is the coordinated date that new EOPP will be available on the GS.

Result Summary

The use of modified EOPP (restored zonal tides) as described in this section has been verified as a valid and accurate means to perform coordinate transformation from GPS Receiver provided ECEF (ITRS) to ECI (EME2000). This methodology only required changes to ground processes and was minimal impact to operations. By effectively returning these EOP parameters to their pre-TN36 values, no changes on the vehicle were necessary. There are no foreseen issues regarding use of modified EOPP as directed for long-term operations. This approach to determining a 6-parameter fit uses a span of 14 days (past the effectivity date), thus these modified EOPP files tend to diverge after 14 days and should not be used past that point.

KALMAN FILTER PARAMETER TUNING REGARDING MANEUVERS

After extensive on-orbit navigation performance analysis it was determined that navigation performance did not quite meet expectations. The source of this navigation performance degradation was determined to be thermal fluctuation induced variance in clock drift combined with a GPSR EKF maneuver parameter allocation that induced clock coasting. This receiver, the General Dynamics Viceroy 4, has an EMXO oscillator (clock) that is sensitive to temperature. The chosen solution was to tune relevant EKF maneuver parameters such that clock coasting was disabled, the velocity solution was allowed to vary as intended and the position solution, in particular, maintained a high level of accuracy (with margin to requirements). Note, the relevant GPSR navigation accuracy requirements (3σ) are as follows: a) position solution 100m radial and 75m in-track/cross-track, and b) velocity solution 6 cm/s radial/in-track/cross-track.

Thermal Considerations

The GPSR's EMXO is thermally sensitive so any improvement to the thermal stability of the oscillator pays dividends to performance in general and particularly during a maneuver if clock coasting is enabled. The original spacecraft panel Heater Control Record (HCR) was designed such that all heaters would toggle on at once when a common low limit (set point) was violated by any of the relevant sensors. This exacerbated the navigation performance issues cause by clock coasting. An updated HCR was developed shortly after the GOES-17 Launch and Orbit Raising (LOR) campaign which staggered the set points for pairs of heaters such that only a pair of heaters should toggle at once resulting in smoother thermal profiles over the entire panel and the GPSR baseplate/EMXO. Two HCR iterations were implemented on-orbit each both better than the last for GPSR thermal stability, more detail can be referenced.[9]

Kalman Filter Parameters

There are three ways to improve GPSR navigation performance considering the issue described above: 1) improve the thermal stability of the GPSR EMXO, 2) change the approach to maneuver consideration regarding the GPSR EKF maneuver parameter and FSW side where you calculate/input an approximate acceleration ECEF vector for each maneuver as opposed to using relaxed covariances, or 3) tune the GPSR EKF maneuver parameter covariance set. The GPSRs do not have dedicated heaters so tight thermal control is not possible for the already launched vehicles. We did improve the thermal profile on the MY panel as described below but that did not guarantee our desired level of performance. Simulated performance using approximate acceleration vectors produced great performance but the implication on operational burden and/or FSW changes made this option less desirable. The only reasonable mitigation approach was to tune the GPSR EKF maneuver parameter set.

A specialized hi-fidelity test configuration was used in the EKF iterative tuning effort where clear navigation performance metrics were visible without thermal control implemented. These metrics of note include clock drift variance, clock bias to drift agreement, position/velocity variance, position/velocity accuracy and Kalman filter covariance metrics when the maneuver parameters were applied. During this iterative tuning, only a large NSSK was applied to the dynamics. The GPSR manufacturer was consulted twice during the tuning process to ensure proper methodology was used in parameter manipulation.

Dozens of iterations were run, initial tests determined a suitable range of clock bias and clock drift variance and covariance metrics (3 parameters) and the primary tests determined suitable position and velocity variance (6 parameters) values and further refined the clock parameters. Position-to-velocity covariance manipulation was tested but the default parameters were determined to be proficient.

Runs for record were performed once a set of tuned EKF parameters were settled upon with thermal control (worst-case on-orbit conditions replicated) and monitoring in place. The runs for record were a) a simulation containing both a North-South Station Keeping maneuver (NSSK) with pre and post Momentum Adjust (MA) along with b) a simulation containing an East-West Station Keeping maneuver (EWSK). These runs for record define the best approximation of expected on-orbit performance using the tuned parameters.

Resulting On-Orbit Performance

The tuned GPSR EKF parameters were uplinked to GOES-17 and asserted to the GPSR on October 9th, 2018 (prior to GOES-16) when in its Post-Launch Test (PLT) phase. Shortly thereafter a pre-MA was performed followed by a NSSK with a duration of 3374 seconds and post-MA. The GPSR NSSK navigation performance is outlined in Figure 4 where the pre-MA starts near the 20.8 hour mark, the NSSK starts near the 21.65 hour mark and the post-MA starts near the 23.15 hour mark. Regarding the performance shown when not using the tuned parameters, the presence of a maneuver is evident when the velocity error starts oscillating. This oscillation is due to clock coasting and thermal fluctuation induced clock drift error.

The on-orbit performance using these tuned EKF parameters has been shown to meet requirements with significant margin considering all station keeping maneuvers (some can last nearly two hours in duration), this is illustrated in Figure 4 along with a before/after comparison showing the direct navigation improvement. Additionally, this approach resulted in no operational burden. During even the longest duration station keeping maneuver we expect position solution accuracy on the order of 30 meters or better depending upon the axis. It is worth noting that our primary instrument, the Advanced Baseline Imager (ABI), is most sensitive to position error in the in-track and cross-track axes, where position error translates to pointing error. Whereas radial position error would translate to pixel size error. Thus, the intent of improving performance was foremost to improve in-track and cross-track position solutions then radial position solutions followed by velocity.

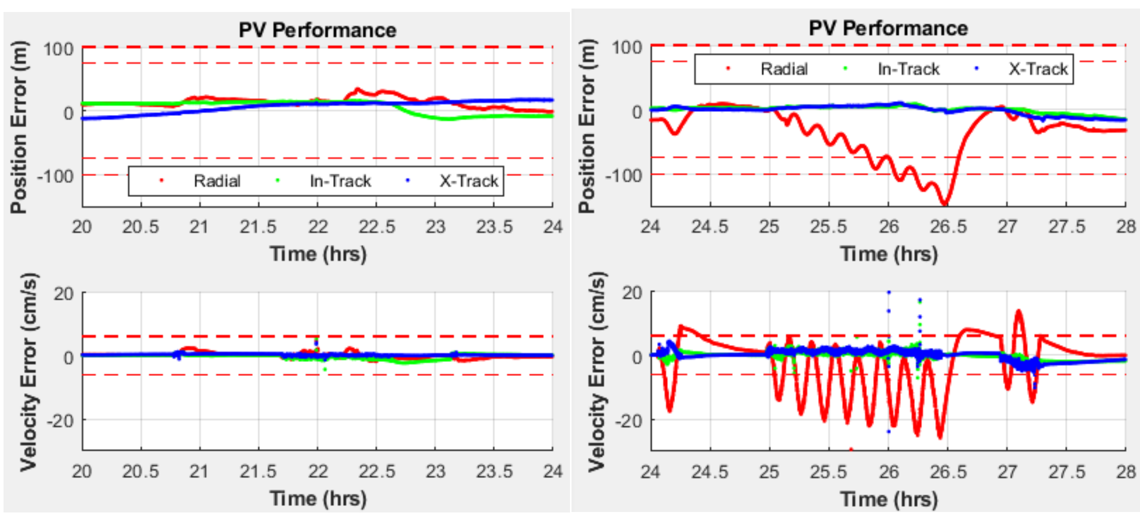

Figure 4: GOES-17 GPSR Performance with (left) and without (right) Tuned Parameters, MA-NSSK-MA shown against Requirements

GPSR OFF-POINTING TRACKING CAPABILITIES

The GOES-R series satellite GPSR system is designed for GEO application, including GPS sidelobe tracking capability. The GPSR system consists of a receive (Rx) antenna, a Low-Noise Amplifier (LNA) and the GPS Receiver (GPSR) itself. The receiver is the Viceroy 4 GPSR (12-channel, L1 C/A) and LNA built by General Dynamics (GD) and a Lockheed Martin specially designed/built directional GEO GPS L1 Rx antenna. This GPSR system has proven itself to have great coverage capabilities under nominal Nadir pointing circumstances, tracking over 11 satellites on average. This section will describe the robustness of the overall GPSR system design as defined by tracking capabilities when the vehicle is and is not nominally pointed Nadir. The Nominal data source for this section is a 48-hour span of data acquired on GOES-16 at its PLT slot of 89.5 West. The off-Nadir data source for this section is the GOES-17 Magnetometer calibrations which performed slews about the Nadir vector up to over 62 degrees off-Nadir, these are two 2-hour data sets also at the PLT slot of 89.5 West.

Nominal Tracking

More details on GPS Tx antennae patterns and GPSR system Rx antenna pattern necessary in the nominal tracking discussion have been covered in a previous paper.[1] Detail on simulation and testing were also covered in previous work.[10] There are currently three general types of GPS antenna patterns in orbit, unique to each block-type. An example of a 3D antenna pattern is shown in Figure 5. Clearly visible are the highly dynamic sidelobe regions with all the hills and valleys. Note that 90 degrees off the GPS boresight translates to about 40 degrees off a GEO satellites boresight (considered Nadir).

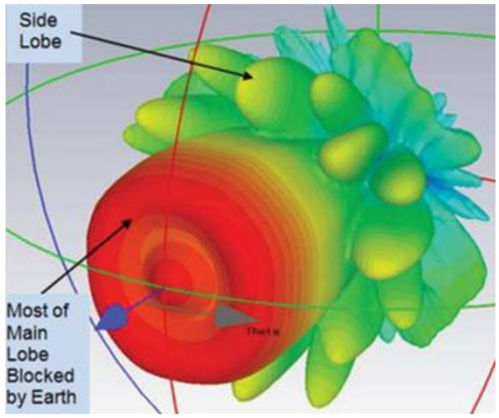

Figure 5: 3D rendering of (Real) Ground Measured GPS Antenna Pattern

GOES-16 must be Nadir pointing to perform its mission, with the solar array to the South Pole (or North Pole if inverted). The dominate tracked 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 was designed for side lobe tracking. This Rx antenna has a main lobe gain of ~11 dB near 20 degrees off-boresight (nominally same as off-nadir).

An understanding of nominal tracking capabilities is important to the comprehension of off-nominal (off-Nadir) tracking capabilities. In conjunction with the above generalized discussion this section should fully frame the tracking capabilities with respect to off-Boresight angle when Nadir pointed. Note, elevation is N-S angle and azimuth is E-W angle. This section is not a compressive analysis or detailed discussion on tracking metrics rather its intent is to set the stage for the off-nominal (off-Nadir) tracking capabilities analysis.

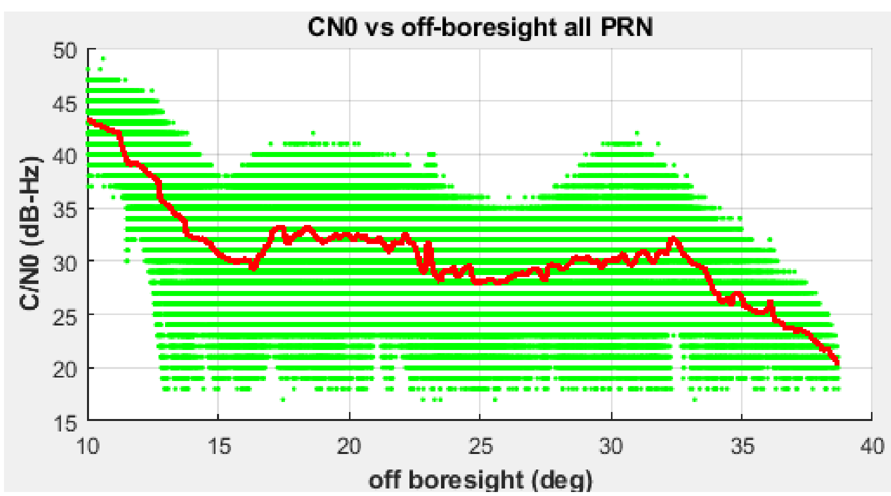

Figure 6: C/N0 Spread and Average (red) based on Off-Boresight Angle

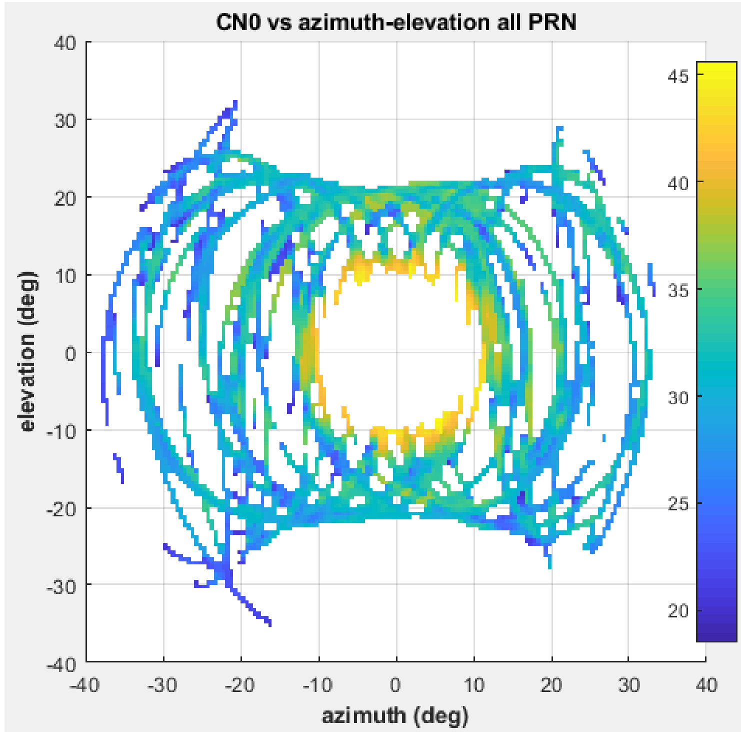

Figure 7: C/N0 Sky Plot based on Elevation (N-S) and Azimuth (E-W)

Shown in Figure 6 and Figure 7 are carrier-to-noise spectral density metrics quantified against off-boresight and North-South East-West angles respectively. Clearly visible is the high-power GPS main lobe. The primary receive gain (near 20 deg off-boresight) which corresponds with the first sidelobe regime is also accentuated. Another bump in received power can be seen in the second sidelobe regime. Also noteworthy is how the receive antenna gain pattern levels out the transmit pattern to near 35 degrees off-boresight but it rapidly tapers after that.

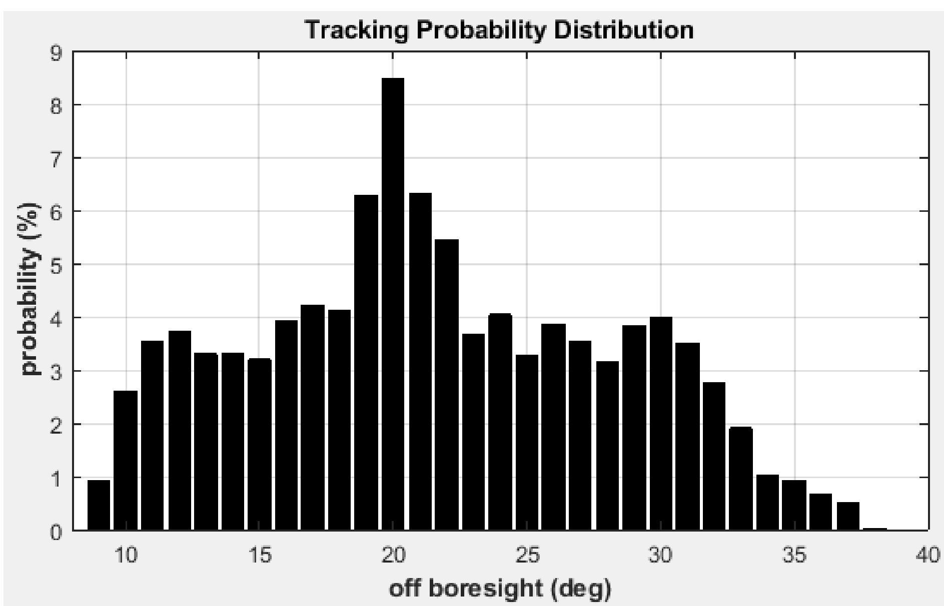

Figure 8: Tracking Density based on Off-Boresight Angle

Shown in Figure 8 is tracking density metrics quantified against off-boresight angle. The dominate takeaway is the high density of trackability near 20 degrees off-boresight. Visible in the C/N0 skyplot is the gap in the GPS constellation near the North/South poles…the GPS orbits are inclined by 55 degrees. Note these tracking metrics will shift slightly based on GEO longitude slot, this data is at the GOES PLT location of 89.5 West.

Off-Nadir Pointed Tracking

Two calibration maneuvers were performed, one on 7/12/2018 and one on 8/20/2018. The maneuver consists of two sets of three revolutions where the first set of three revolutions rotates the spacecraft about the boom axis (i.e. Mag axes X and Y go through full +/- oscillations), and the second set of three revolutions rotates the spacecraft about an axis perpendicular to the boom (i.e. the Mag Z axis goes through full +/- oscillations). Note, the above word "maneuver" translates to "slew event". This results in the GPSR antenna being off pointed from Nadir (~35 deg) and then rotated about the Nadir vector three revolutions then pointing to another off-Nadir angle (~55 deg) and again rotating thrice about the Nadir vector.

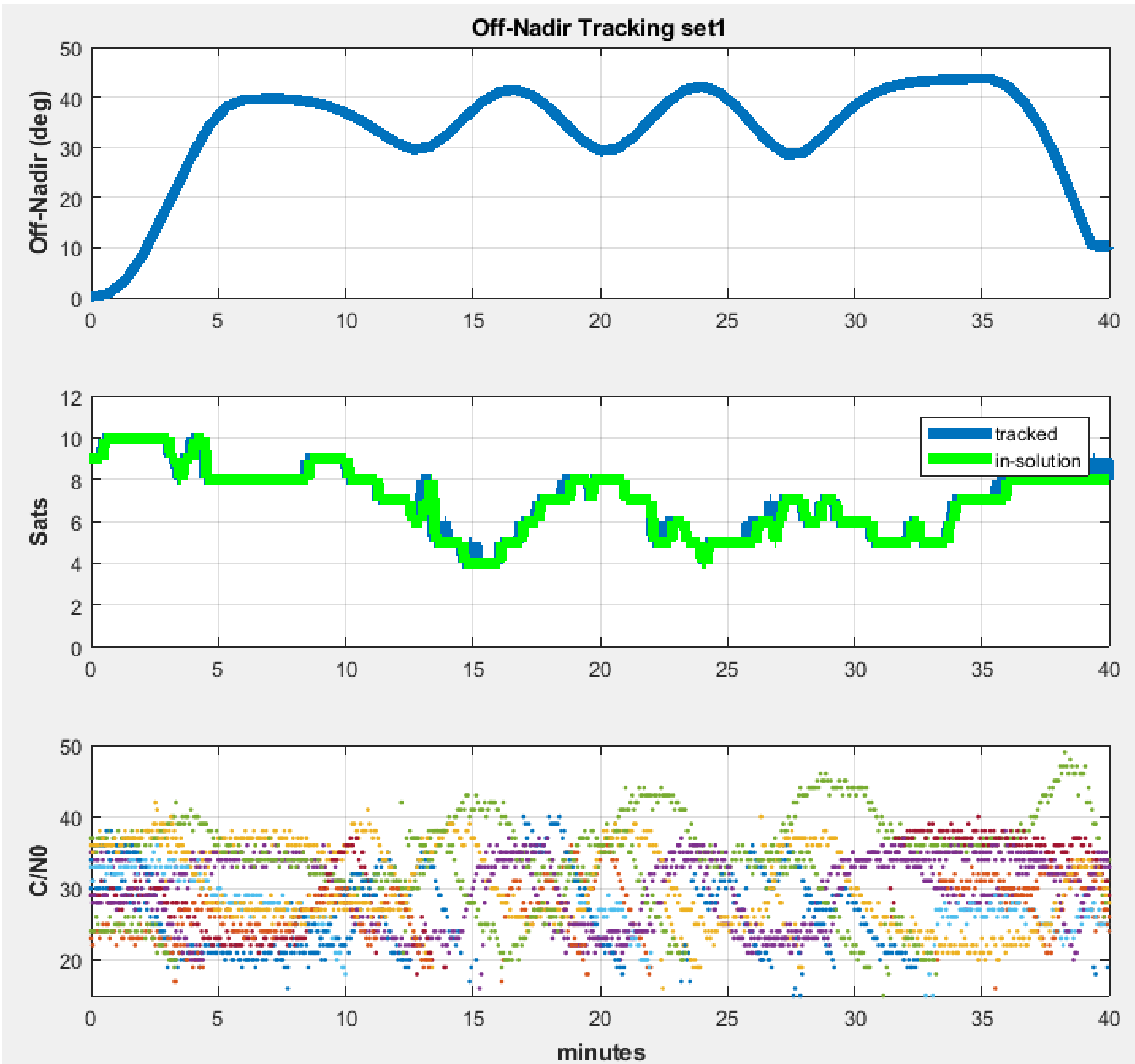

Figure 9: 30-45 Deg. Off-Nadir GPSR Tracking, Mag Cal Slew 7/12/2018

The first slew event for the July calibration (30-45 degrees off-Nadir) is depicted in Figure 9. The calibration from July shows the results of having relatively good geometry during the first slew event, a continuous navigation solution was maintained throughout the slews. The carrier-to-noise spectral density (C/N0) becomes more variable as the receive antenna gain pattern moves around in space, although the signal quality stays in family with nominal conditions for the most part.

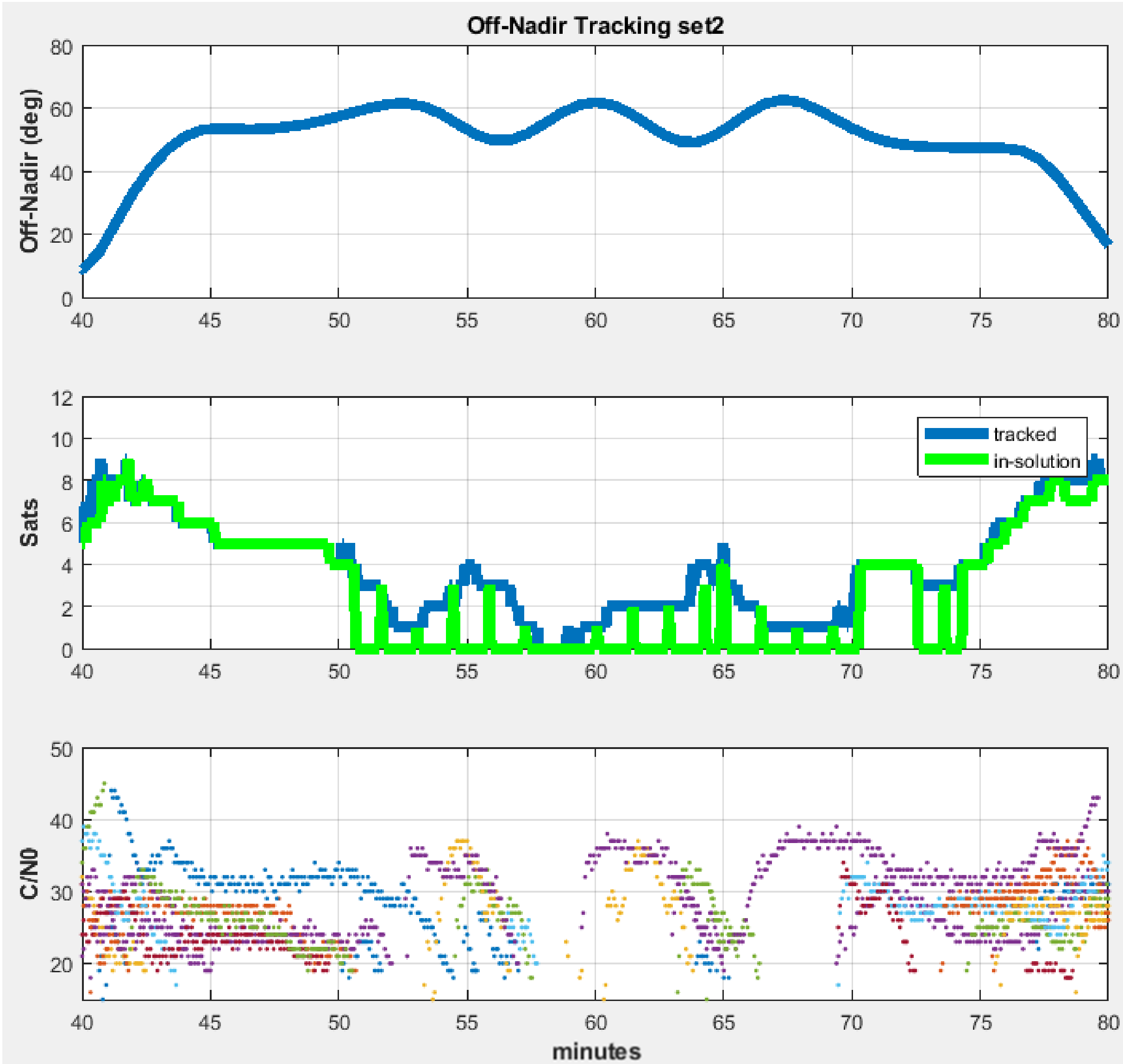

Figure 10: 50-65 Deg. Off-Nadir GPSR Tracking, Mag Cal Slew 8/20/2018

The second slew event for the August calibration (50-65 degrees off-Nadir) is depicted in Figure 10. The calibration from August shows the results of having relatively good geometry during the second slew event, the navigation solution was lost at about 56 degrees off-Nadir and was recovered at the end of the slew event. The clock solution was only lost for two very brief spans when the vehicle was off-pointed by less than 63 degrees (one satellite tracked required).

GPSR tracking performance is tied to relative geometry and the difference between each calibration can be associated with changes (good and bad) in relative geometry. With these two data sets general off-Nadir tracking and navigation can be approximated in off-Nadir angle bins. Future magnetometer calibrations can be added to these results to produce more comprehensive binning results. Recall the attitude can be described as a pair of slew activities which results in the GPSR antenna being off pointed from Nadir (~35 deg) and then rotated about the Nadir vector three revolutions then pointing to another off-Nadir angle (~55 deg) and again rotating thrice about the Nadir vector. This gives a good distribution of geometry for general analysis…e.g. the GPS constellation is not evenly distributed around the Earth so if you simply off pointed in one direction you wouldn't get a globally representative relative geometry distribution.

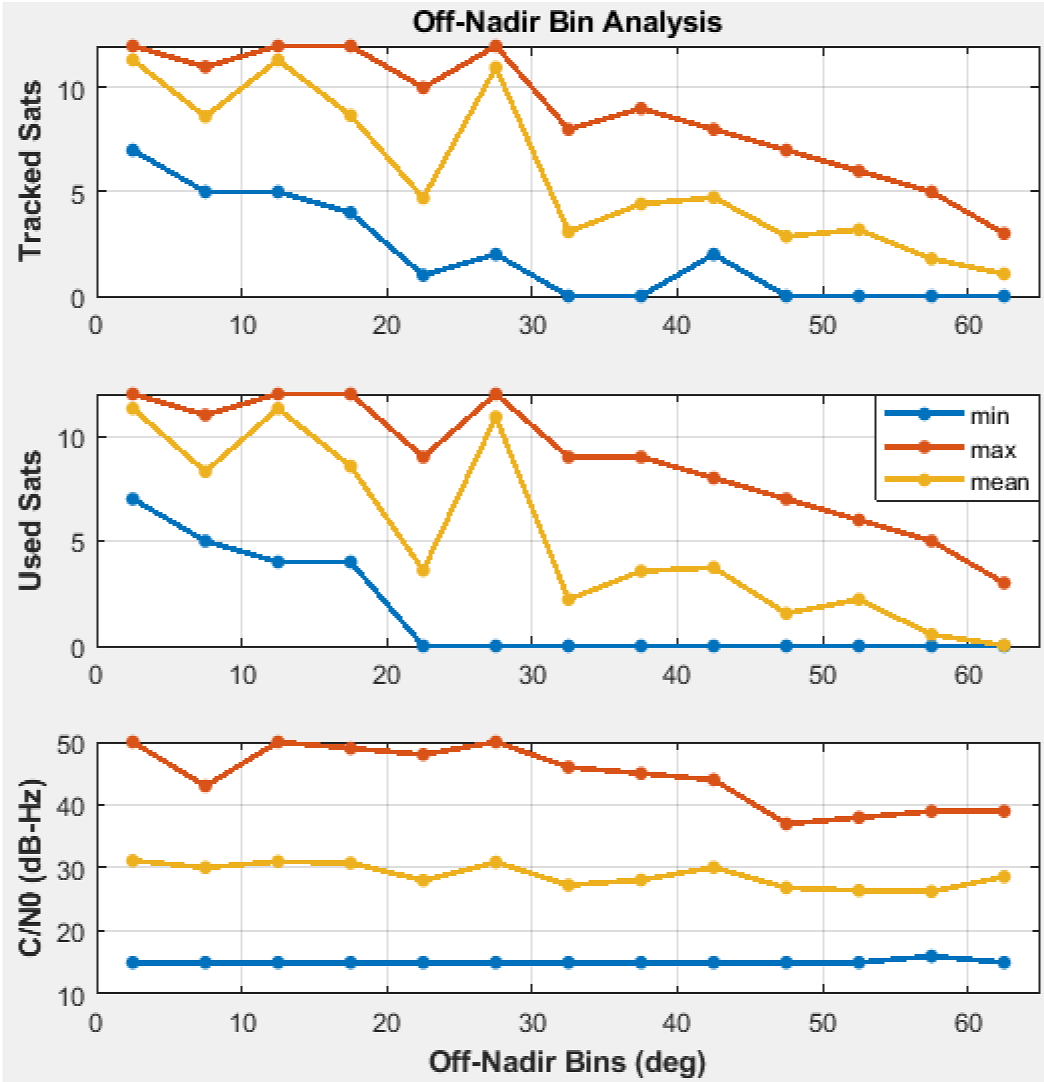

Figure 11: Off-Nadir 5 deg Binning Results

Generalized results were determined in a "binning" analysis where data was analyzed in particular off-Nadir angle bins. These bins were picked at 5 degree increments as 0-5 degrees up to 60-65 degrees resulting in 13 total bins. The metrics analyzed here are tracked satellites, satellite used in the navigation solution and signal to noise spectral density (C/N0). The results are shown visually (min/max/mean) and tabularly (mean only) in Figure 11 and Table 1.

A continuous navigation solution (minimum of 4 used in the solution) is maintained up to 20 degrees off-Nadir. In the 20-25 degree off-Nadir bin the tracking performance takes a clear hit, this is due to the receive antenna gain pattern null around its boresight…the boresight null is pointed where many satellites are usually tracked. Once above 20 degrees off-Nadir it is possible that the GPSR system could have intermittent navigation outages. Once above 45 degrees off-Nadir it is likely that the GPSR system will have intermittent navigation outages. Above 55 degrees off-Nadir it is unlikely for the GPSR to get a navigation solution. The clock solution (assuming you had a solution going into off-Nadir activity) is unlikely to go significantly stale (intermittent updates applied at worst) up to the limit of this data at about 63 degrees off-Nadir. There is no major degradation to the acquired carrier-to-noise spectral density (C/N0) when operating in these off-Nadir regimes although the individual signal C/N0 profiles follow the relative transmit to receive gain pattern total, reference the nominal tracking section.

Table 1: Off-Nadir Binning Results, Average Metrics

	Angle	Mean Metrics Tracked	Used	C/N0
	deg	sats	sats	dB-Hz
Bin 1	0-5	11.33	11.31	31.15
Bin 2	5-10	8.61	8.31	30.07
Bin 3	10-15	11.33	11.31	31.01
Bin 4	15-20	8.75	8.43	30.59
Bin 5	20-25	4.73	3.92	29.39
Bin 6	25-30	8.63	8.23	30.46
Bin 7	30-35	3.09	2.22	27.28
Bin 8	35-40	4.42	3.56	28.10
Bin 9	40-45	4.73	3.74	30.10
Bin 10	45-50	2.86	1.55	26.86
Bin 11	50-55	3.18	2.22	26.42
Bin 12	55-60	1.79	0.55	26.26
Bin 13	60-65	1.06	0.03	28.61

CONCLUSION

The use of modified EOPP, via incorporating a 6-parameter fit using a span of 14 days to restore zonal tides has been verified as a valid and accurate means to perform coordinate transformation from GPS Receiver provided ECEF (ITRS) to ECI (EME2000). This methodology only required changes to ground processes and was minimal impact to operations. By effectively returning these EOP parameters to their pre-TN36 values, no changes on the vehicle were necessary. There are no foreseen issues regarding use of modified EOPP as directed for long-term operations.

After implementing the GPSR tuned EKF maneuver parameter set the GPSR navigation performance meets requirements with margin for all station keeping maneuvers. Additionally, this approach resulted in no operational burden. During even the longest duration station keeping maneuver we expect position solution accuracy on the order of 30 meters of better depending upon the axis. It is worth noting that our primary instrument, the Advanced Baseline Imager, is sensitive to position error in the in-track and cross-track axes, where position error translates to pointing error. Whereas radial position error would translate to pixel size error. Thus, the intent of improving performance was first to improve in-track and cross-track position solutions then radial position solutions followed by velocity.

The off-Nadir navigation, clock maintenance and overall tracking capabilities regarding the GOES-R series GEO GPSR sidelobe capable system exceed expectations and provide significant operational leeway, off-nominal robustness and dynamic capabilities.

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