Test Results of the PiVoT Receiver in High Earth Orbits using a GSS GPS Simulator

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BIOGRAPHY

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ABSTRACT

There is widespread interest in expanding the use of GPS for real-time on-orbit navigation of satellites or satellite constellations in highly eccentric or geostationary orbits. Recent studies have indicated that GPS is a viable option for these missions when used with an orbit determination filter to sequentially process sparsely available pseudorange measurements. Several organizations have undertaken efforts to develop new space GPS receivers that will satisfy this need.

This paper presents results of tests conducted on the PiVoT GPS receiver under development at NASA Goddard Space Flight Center. A variety of design enhancements are being incorporated in the PiVoT receiver to enable its operation in a wide variety of high Earth orbits (HEO). Some of these features include integration of the GPS Enhanced Orbit Navigation System (GEONS), a good quality local oscillator, a robust clock model, and enhancements to basic receiver acquisition and tracking algorithms to enhance the ability of the receiver to track weaker GPS signals present in HEO.

A realistic HEO test capability has been developed using a Global Satellite Systems (GSS) GPS simulator at NASA GSFC. The hardware in-the-loop test setup is detailed, including specific

measures that have been implemented to allow a realistic simulation of HEO signals. Initial results from tests of the PiVoT receiver tracking in a geostationary orbit are presented. With only minimal modifications to satellite acquisition algorithms, the existing PiVoT receiver was able to track main lobe and side lobe signals in the geostationary orbit.

INTRODUCTION

There is widespread interest in expanding the use of GPS for real-time on-orbit navigation of satellites or satellite constellations in highly eccentric and geostationary orbits. GPS is a key technology to enable autonomous navigation, relative navigation, and formation flying in these as well as low Earth orbits (LEOs), but the high altitudes reached by HEO spacecraft present a highly unfavorable environment for the reception of GPS signals. To date, the operational use of GPS in space has been limited primarily to regions where point positioning is possible, typically below altitudes of 3000 km; however, recent studies have indicated that GPS is a viable option for HEO missions when used with an orbit determination filter to sequentially process sparsely available pseudorange measurements.

Figure 1 illustrates the geometry for receiving GPS main and side-lobe signals in a HEO, when the spacecraft is above the altitude of the GPS constellation. For the spacecraft shown near the geostationary altitude, the only GPS signals that can be tracked originate from satellites on the opposite side of the Earth. For a GPS satellite to be available, or *visible* to the receiver, the line-of-sight (LOS) to the satellite must be unobstructed *and* the power level at the receiver must be sufficient for signal acquisition and tracking. LEO spacecraft that are always within the main transmitted beamwidth of the GPS satellites (below 3000 km) generally have many visible GPS satellites with a good geometric distribution in the sky and uniform power levels. The most significant difference for a user at high altitudes is the sparse GPS visibility. There are rarely four or more satellites present simultaneously, the condition required for a GPS receiver to produce an instantaneous point solution for position and time, and there can be significant outages during which no satellites are visible. Furthermore, the available signals are sometimes very weak and originate from only a small region of the sky.

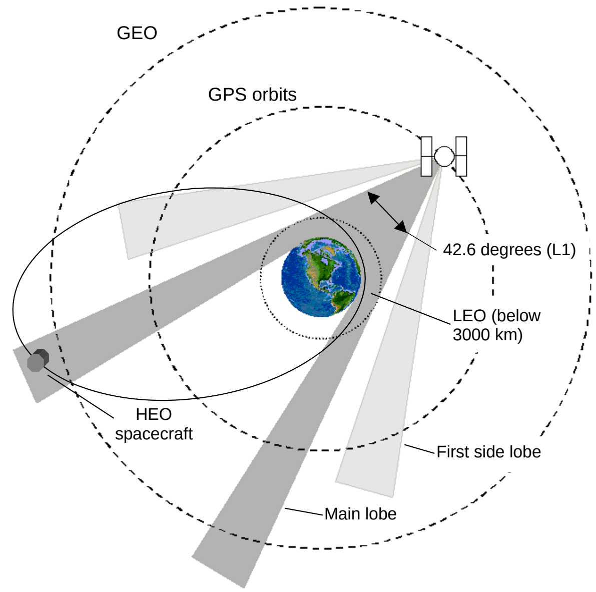

Figure 1: Geometry for reception of GPS signals by a HEO spacecraft. Side-lobe signals are weaker, but can still contribute to GPS observability for HEO users.

In recent years, several organizations have undertaken efforts to develop new space GPS receivers capable of operating on HEO spacecraft. Developed by CNES and Alcatel, the TOPSTAR 3000 includes a real-time extended Kalman filter and is slated to fly on the geostationary STENTOR spacecraft in 2001 [2]. MosaicGNSS is a project of Astrium GmbH funded in part by the German Aerospace Center (DRL) to design a receiver for geostationary applications. They have proposed replacing the digital ASIC with a software correlator [3]. NASA Goddard Space Flight Center (GSFC) is developing a new GPS receiver called PiVoT (for Position, Velocity and Time) based on the open-source GPS development system marketed by Mitel (formerly GEC Plessey) Semiconductors [1]. GSFC has supported an ongoing program of research to develop the architecture and algorithms for a HEO receiver based on PiVoT [6, 8]. This paper discusses some of the software and algorithm modifications being implemented in the PiVoT receiver to enable its operation in HEOs. The capability to test GPS receiver performance in HEO scenarios has been developed using a hardware in-the-loop GPS simulator, and this test setup is being used to evaluate the HEO design modifications to the PiVoT receiver.

HEO DESIGN ENHANCEMENTS TO PIVOT RECEIVER

The GSFC PiVoT receiver was developed to provide a low-cost GPS navigation instrument for NASA's Small Explorer (SMEX) and Spartan series of spacecraft, as well as other LEO navigation applications [1]. PiVoT is based in part on commercial, open-architecture hardware and software, and it incorporates high fidelity orbit dynamic models and an extended Kalman filter implemented in the GPS Enhanced Orbit Navigation System (GEONS) software to allow for filtering of the solutions. The oscillator provides good stability performance relative to other Temperature Compensated Crystal Oscillators (TCXOs), and the receiver components have been selected to provide a moderate level of radiation tolerance. These existing capabilities make PiVoT an excellent candidate for a HEO GPS receiver. The availability of the source code allows customization of algorithms guiding satellite selection, acquisition, and tracking functions to optimize the performance for HEO, or space in general. Furthermore, the GEONS software running in real time satisfies the need for a high fidelity navigation filter and clock model to enable operation through data outages and incorporates fault detection capabilities important for a space receiver.

Even so, significant software modifications are required to add the necessary functionality for the receiver to be applied to HEO missions. Improvements or enhancements to PiVoT algorithms are being developed in the following key areas: 1. add the basic capabilities to allow the receiver to acquire and track signals in HEO geometries, 2. allow the receiver to function and produce a solution even in the presence of sparse observations or temporary data outages common at high altitudes, and 3. enhance the ability of the receiver to track weaker GPS signals, at or just below the nominal tracking threshold, to improve GPS observability.

The most basic requirement for the HEO receiver is a signal acquisition design that allows for tracking of GPS satellites through a down-looking antenna, including satellite selection logic that can predict the GPS satellite passes for any altitude or antenna orientations. Furthermore, the ionospheric corrections transmitted in the broadcast ephemeris and used in a single frequency receiver are no longer valid for the limb-crossing signals received at high altitudes.

The fact that the receiver is often required to operate for long periods with fewer than four GPS satellites visible simultaneously affects many of the internal functions in the receiver related to timing and formation of measurements. The existing point-solution-based clock model in PiVoT was not intended to be used for long periods in the absence of an update from a point solution. A navigation filter is required not only to provide filtered solutions and propagate the state of the receiver through data outages, but also to accurately model the behavior of the local oscillator in the receiver when a clock solution is not available. Additionally, a different approach is required for the design of the receiver's initialization strategy to allow the receiver to initialize and begin tracking autonomously, even if point positioning is not possible. Many cold-start initialization algorithms set the first point solution as the point when the cold start is terminated and normal receiver operations can resume, but at high altitudes there may never be a point solution. Other miscellaneous modifications required in the HEO PiVoT receiver include modifications to how observations are time-tagged in the receiver to account for times when clock errors may be large (during periods of sparse visibility), considerations for modeling relativistic effects on the local oscillator, and a correction to avoid reporting of ambiguous pseudoranges for very high altitude orbits (when the receiver is above approximately 20 Earth radii altitude).

Finally, by taking steps to optimize the design of the code and carrier tracking loops within the receiver for the expected signal levels and dynamics expected in space, it is possible to increase the sensitivity of the receiver for tracking weaker GPS signals, at or just below the tracking threshold of typical receivers. Previous studies have shown that modest improvements in the tracking threshold of the receiver can significantly improve the GPS observability for certain HEOs [6]. The strategy being developed for the PiVoT receiver incorporates adaptive tracking loop filter gains that use the best settings for the operating altitude of the receiver [9]. Improved signal detection algorithms will speed up the acquisition process and provide improved performance for weaker GPS signals and in the presence of high dynamics.

One of the most challenging aspects of the design of a HEO receiver is the wide range of conditions that the receiver can encounter, sometimes over the course of a single orbit. A receiver operating in a geostationary transfer orbit is subject to good GPS observability but high dynamics near perigee, but sparse visibility and long signal outages near apogee.

In the PiVoT receiver, modifications have been made to address the basic HEO signal tracking concerns described in (1) above. Additional modifications to the acquisition algorithms and tracking loop design are being implemented currently. The algorithm modifications discussed above are intended to allow the receiver to function autonomously in HEO applications; however, many of the enhancements will provide improved performance for all spaceborne GPS applications. The PiVoT receiver has provided a platform to implement and test these software modifications. Although many of the algorithms have been developed specifically for PiVoT, the concepts are intended to be generally applicable to any GPS receiver. Other low lost GPS receivers developed by the Surrey Space Center [5] and the Applied Physics Lab [4], would be particularly well suited to implement these HEO enhancements since they share the same open architecture software and hardware heritage with the PiVoT receiver.

REALISTIC HARDWARE IN-THE-LOOP HEO TESTING CAPABILITY

Hardware in-the-loop testing is a powerful tool used to evaluate how a space receiver will actually perform subject to the dynamics, signal levels, and error sources on an orbiting spacecraft. In such a test, the RF input of the receiver is connected to a GPS simulator rather than a real antenna. The simulator models the motion of the receiver based on a specified trajectory and attitude and generates GPS signals with the same phase, Doppler, and power relationships as would be measured if the receiver were actually in motion. This realistic orbital testing can be used to evaluate aspects of the receivers performance that would be impossible through terrestrial, static tests.

NASA GSFC has a GSS model STR4760, dual frequency GPS constellation simulator, with 16 parallel channels available through each of four RF outputs. The multiple RF outputs can be used to simulate a receiver with multiple receiving antennas, or relative navigation scenarios with up to four vehicles moving in different trajectories simultaneously. The GSS simulator allows a great deal of flexibility to control virtually any aspect of the simulated GPS signal properties, the modeled error sources, and the motion and dynamics associated with the receiver. In the GSFC configuration, some of the key parameters specified by the user include the reference gain patterns and orientations of the receiving antennas, the reference gain pattern for the GPS satellite transmitter, the orbits and signal properties of the GPS satellites, and the motion and attitude of the receiver. The GPS orbits and signals can be based on real almanac or broadcast ephemeris data, which makes it possible for the simulated GPS orbits and clock parameters to closely match the actual GPS constellation at the time of the simulation. The trajectory and attitude of the receiver (host vehicle) can be generated externally in order that the same data can be used as an input to the simulator and for a truth data set to compare with results from the receiver. Software simulation tools developed independently are used for visualization of scenarios modeled by the simulator and analysis of data obtained from the receiver under test.

The GSS simulator at GSFC has been used extensively for GPS receiver testing in a variety of LEO scenarios [10]. Unfortunately, the simulator was designed under the assumption that the receiver under test is always on or near the surface of the Earth, a condition violated by many of the HEO scenarios of interest. For scenarios in which the receiver uses down-looking (Earth-pointing) GPS antennas and reaches altitudes above approximately 10,000 km, the simulator often models many of the wrong satellites. The result is that the few satellites that are capable of being tracked by the receiver are not simulated. Furthermore, small offsets in the simulated power levels greatly affect the number of visible satellites for a HEO user. Both of these factors can easily result in a completely unrealistic test for a HEO scenario if special steps are not taken to address these problems.

Augmenting the Satellite Selection Method used by the Simulator

The first problem encountered for HEO scenarios was the method used by the simulator to select which GPS satellites are modeled on the limited number of available channels. The simulator only models GPS signals for a subset of the GPS constellation simultaneously; up to 16 satellites on each RF output. The existing algorithm attempts to select those GPS satellites that are most favorable for tracking through the receiving antenna by eliminating satellites not physically in view, and then ranking the remaining satellites to obtain the combination that yields the best dilution of precision.

The simulator uses two mask angles, illustrated in Figure 2, to determine which satellites are visible. The horizon mask is used to evaluate which satellites are not obstructed by the Earth, and the aperture angle mask is used to determine which satellites are within the user-specified field-of-view of the receiving antenna. The combination of these two metrics is an effective means to determine the set of visible satellites at low altitudes (a). Unfortunately, it does not consider that many satellites physically in view from high altitudes are actually transmitting away from the receiver (b). With 25 or more satellites included in the simulators visible satellite list, most of which are not visible, the combination of 16 satellites modeled often does not include some of the satellites most favorable for tracking by the HEO receiver, i.e. those on the opposite side of the Earth.

In order to conduct HEO tests using the existing simulator, it was necessary to develop a method to manually force the simulator to model the correct satellites. This problem was corrected by using a feature in the simulator that allows the availability of GPS satellites to be manually toggled on and off during a simulation. By "turning off" many of the GPS satellites transmitting away from the receiver, the remaining visible satellite list is manually forced to be less than the 16 available channels. In this manner the correct satellites are always modeled. This process was automated by providing the satellite status commands to the simulator via an input command file. Using the truth ephemeris for the simulated vehicle and a GPS almanac, the visible GPS satellites were predicted for the entire time of the simulation. The GPS signal visibility analysis tools used to do this were discussed in a previous paper [8]. A list of the 16 most favorable GPS satellites for tracking was created at 60-second intervals for the entire simulation, and the list of commands to toggle the necessary satellites on and off was created. The input file then becomes part of the simulation so the process is repeatable.

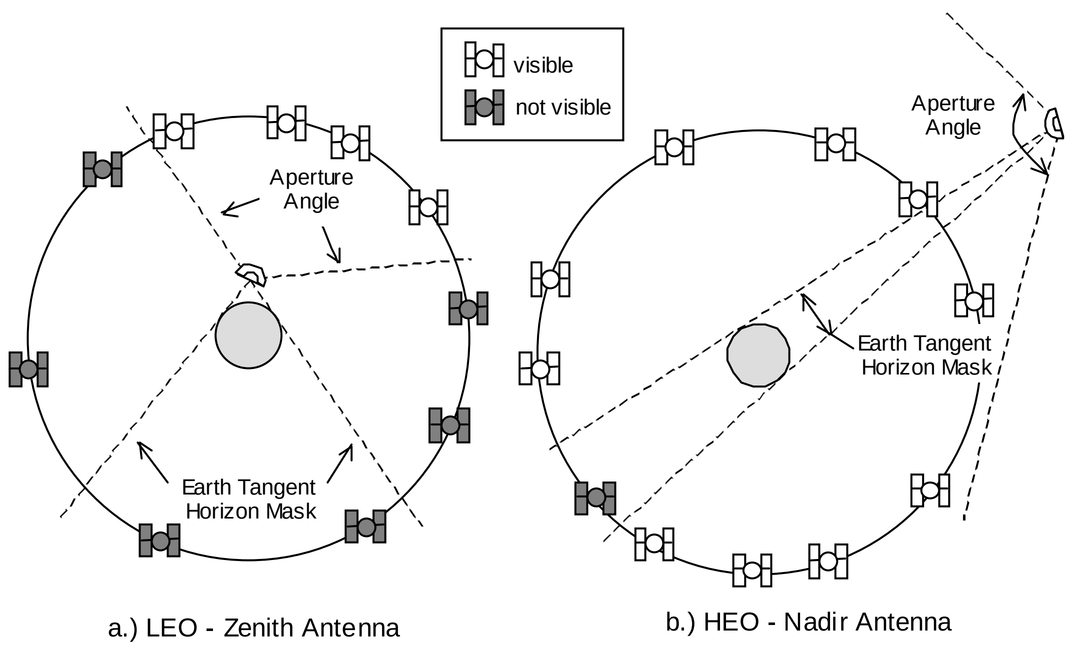

Figure 2: Evaluation of GPS signal visibility by the simulator for a LEO (a) and HEO (b) user. The two constraints, "horizon mask" and "aperture angle," correctly select the visible satellites for a LEO user, but for a HEO user, they fail to distinguish satellites that should not be considered visible due to the transmitting beam pattern of the GPS satellites.

This method completely corrected the satellite selection problem; however, a new input command file must be generated whenever a new scenario is set up. A straightforward way that the simulator vendor could use to eliminate this problem in future versions of the software/firmware would be to rank the visible satellites based on the simulated power levels. The signal power is already computed for each satellite, and this would ensure all of the correct satellites would be modeled for a HEO simulation without the special steps described here. Only HEO scenarios in which the user antenna is oriented in the nadir direction and the host vehicle is above roughly 10000 km altitude (when there are more satellites in the visible satellite list than channels) require this manual intervention to ensure the correct satellites are modeled.

Calibration of Simulated Power Levels

A second area of concern for HEO scenarios is related to the modeled GPS signal levels. The simulator varies the power levels for each GPS satellite based on path losses, antenna patterns, and other optional offsets or error sources (such as multipath) that can be specified by the user. Additionally, the user must account for other unmodeled factors, for example the reference gain of receiving antennas, by including these values in the user specified signal strength offset. In LEO and terrestrial applications, as long as the signal levels are set a few dB above the receiver threshold, the receiver will be able to track all satellites in view. Increasing the simulated power levels improves the measurement noise, but does not significantly affect the number of satellites tracked. However for a HEO scenario, many of the visible signals may be very close to the tracking threshold of the receiver, and a change in signal levels of only 2-3 dB can have a large effect on the number of satellites that are tracked. For this reason, it is necessary to precisely calibrate the power settings in the simulator to the real-world power levels associated with the GPS constellation to obtain realistic results from a HEO test.

All GPS signal levels in the simulator are specified relative to the minimum guaranteed signal strength of –130 dBm (for L1, C/A code) specified in the GPS ICD-200, for a signal received on the ground from a GPS satellite at low elevation [7, 11]. Setting the signal strength in the GPS constellation file to zero corresponds to this -130 dBm level at the input of the receiver, and the antenna patterns and other models specified by the user will cause the power levels to fluctuate about this reference value as the simulation is run. The signal strength parameter, a user specified constant, must account for several additional factors in order to yield realistic signal to noise ratios (C/N_0) in the receiver. Some of the unmodeled parameters or losses that must be included are:

+3-5 dB	reference gain of a typical hemispherical receiving antenna (high gain antenna would be more)
+2-5 dB	difference between the minimum specified versus actual transmitted power from the GPS satellites
-0-2 dB	losses due to atmosphere (negligible for most space users)
+2-3 dB	difference in thermal noise between receiver RF input connected to the simulator RF output versus a real antenna
+0-3 dB	other losses in the simulator not present for live GPS tracking

Clearly, setting the signal strength offset to zero would result in power levels at the receiver significantly below the minimum specified levels. In practice, the signal strength has typically been set at about 10 dB for a LEO or terrestrial user with a hemispherical antenna, which is about at the middle of the ranges specified above. For a high gain receiving antenna (+9 dBic), the offset could be 17 dB or more.

In order to have confidence that the simulated power levels were realistic, tests were conducted to compare the signal levels measured from the simulator with signals from the actual GPS satellites tracked through an antenna. A passive antenna (without an internal LNA) was set up on the roof of Building 11 at GSFC. A static scenario was set up in the simulator to duplicate as closely as possible the conditions of the rooftop test. The same cabling and LNA were used for both the real test and the simulator, so the signal paths were identical up to the point of the antenna/simulator RF output. The gain pattern of the receiving antenna was modeled based on a pattern supplied by the antenna manufacturer. The signal strength in the simulator was set to a value of 10 dB, based on a receiving antenna peak gain equal to +4.9 dBic, +3.0 dB to account for transmitted satellite power levels above the minimum, and 2.1 dB to account for additional thermal noise in the simulator.

Several different receivers were used in these static tests, but the data presented here were recorded using the Mitel GPS Builder-2. Measured C/N_0 values for all satellites tracked were recorded over 10 to 12 hours from the rooftop antenna, and then the test was repeated on the simulator over the same time period to duplicate the satellite tracks. Figure 3 was produced by binning the recorded signal level data by received boresite angle (complement of elevation angle) for all satellites. The satellites tracked close to zenith (small boresite angles) are the best basis of comparison between the simulated versus real signals because unmodeled effects due to multipath, attenuation from the atmosphere, and azimuthal variations in the real antenna gain are smallest in this region. Based on this plot, the simulated GPS signals were consistently about 3 dB below the signal levels of the real GPS satellites.

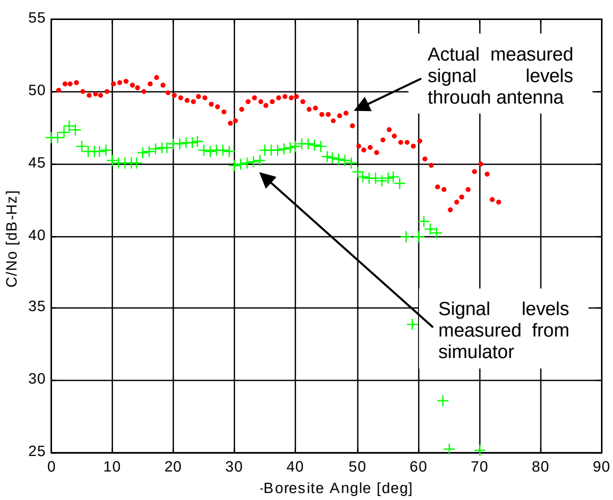

Figure 3: Comparison of real versus simulated signal levels for a static antenna. Plot shows the mean signal levels recorded versus received boresite angle for the real versus simulated GPS satellites.

This test indicates that the correct signal strength setting in the simulator to match the actual GPS power levels for this particular receiving antenna is 13 dB rather than the expected 10 dB. Unfortunately, the data provides little definitive insight as to where in the link budget the additional 3 dB of losses come into play. Assuming the manufacturer specified 4.9 dB peak gain of the receiving antenna is correct, additional losses in the simulator are most likely attributed to:

- The thermal noise temperature in the simulator being more than 2.1 dB higher than the noise temperature when a real antenna is used.
- The actual transmitted signals from the GPS satellites being on average more than 3 dB above the minimum specified levels.
- Other losses in the simulator that have not been properly accounted for.

Figure 4 shows the power levels recorded through the antenna and the simulator for PRN 22 during one of the tests in which the satellite was tracked for about 3 hours. The data between approximately 118.5 and 119.5 hours was recorded as the satellite passed close to the boresite of the receiving antenna. Within this region the 3 dB offset between the simulated versus real signals is apparent. One of the most obvious differences between the real versus simulated GPS signals in Figure 5 is the increased noise in the measured signal levels from the simulator. The thermal noise contributed by a GPS antenna varies based on the noise figure of the antenna and LNA, the sky noise temperature, and other factors. When the receiver is connected to the simulator, it is effectively a worst-case thermal noise condition, easily several dB worse than for a real antenna. Other differences between the two signals are attributed to errors in the modeled antenna gain pattern used in the simulator, and attenuation due to atmosphere and multipath (particularly at lower elevations).

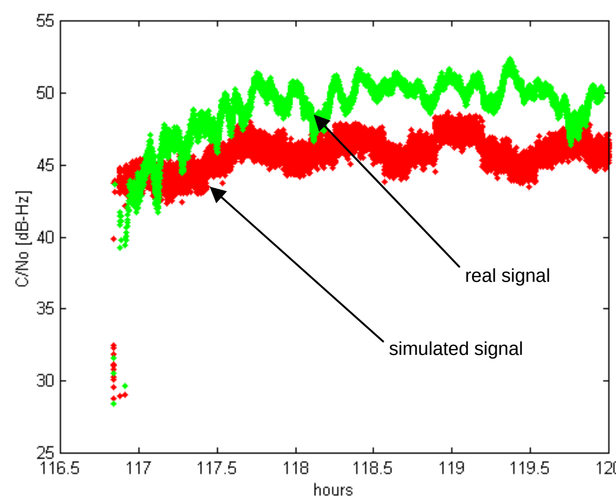

Figure 4: Comparison of measured signal levels for PRN 22 between simulator and real antenna.

With the satellite selection fix and the ability to set the modeled power levels properly, the simulator is now capable of producing a realistic simulation for all of the orbital scenarios of interest, including HEO scenarios utilizing down-looking antennas. With the HEO simulation capability in place, the next section describes some of the initial tests conducted with the PiVoT receiver.

HEO TRACKING PERFORMANCE

Initial tests were conducted with the PiVoT receiver in several HEO scenarios to assess its basic capabilities to track GPS satellites at high altitudes. The version of the PiVoT receiver used in these tests incorporated some basic changes to allow tracking of GPS satellites through a down-looking antenna across the limb of the Earth and modified satellite selection algorithms to allow the receiver to determine which satellites are visible for the HEO geometries. Since the other modifications discussed earlier to improve the weak signal tracking capabilities of the receiver had not yet been implemented, this test is in effect a measure of the performance of the existing tracking loop designs to acquire and track GPS signals subject to the conditions present at high altitudes. This section will present some of the results from the tests conducted for a geostationary orbit, in which the PiVoT receiver was operated for a period of 48 hours. The scenario assumes a single nadir-pointing, high gain receiving antenna with a peak gain of 9.6 dB.

Figure 5 shows a comparison of the number of satellites tracked by PiVoT versus the predicted number of satellites present above 33 dB-Hz. The difference between these two plots is effectively the number of satellites above 33 dB-Hz that were not tracked by the receiver. From this plot, PiVoT always tracked at least one satellite, and there were rare instances in which point positioning was possible, when there were four or more satellites tracked simultaneously. Figure 6 shows histograms of the same data indicating the percent of the time one or more, two or more, etc. satellites were tracked simultaneously. This plot indicates four or more satellites were tracked simultaneously about 11% of the time. The receiver did reasonably well at tracking GPS signals that were above its nominal tracking threshold. It would typically acquire a satellite when the signal went above 35 dB-Hz and loose signals that dropped below about 33 dB-Hz. These limits are determined by the nominal settings in the PiVoT source code used to determine acquisition and loss of lock of the signal.

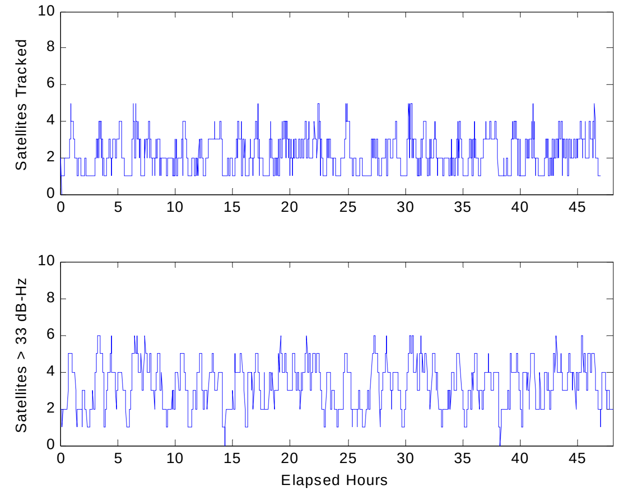

Figure 5: Comparison of number of satellites tracked versus number of satellites present above 33 dB-Hz.

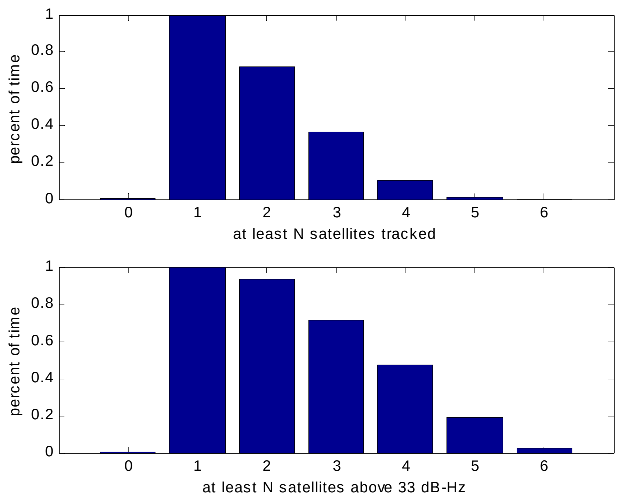

Figure 6: Comparison of number of satellites tracked versus number of satellites present above 33 dB-Hz.

Figure 7 provides a different prospective on this data by showing each satellite tracked versus time. The lighter shaded data points reflect the portions of passes when the signal was above 33 dB-Hz but was not tracked by PiVoT. For a geostationary user with a high gain antenna as modeled in this scenario, the typical GPS satellite will be acquired and lost four times as it passes behind the Earth; twice on side lobes and twice on the main lobe. The satellite is first picked up through the first side lobe and then is lost in the null between the main lobe and first side lobe. The satellites is picked up again when the receiver is radiated with the main lobe signal, but the main lobe pass is typically interrupted as the satellite passes behind the Earth. Finally there is another opportunity to track the satellite through the side lobe. This pattern can be observed in many of the passes illustrated in Figure 7.

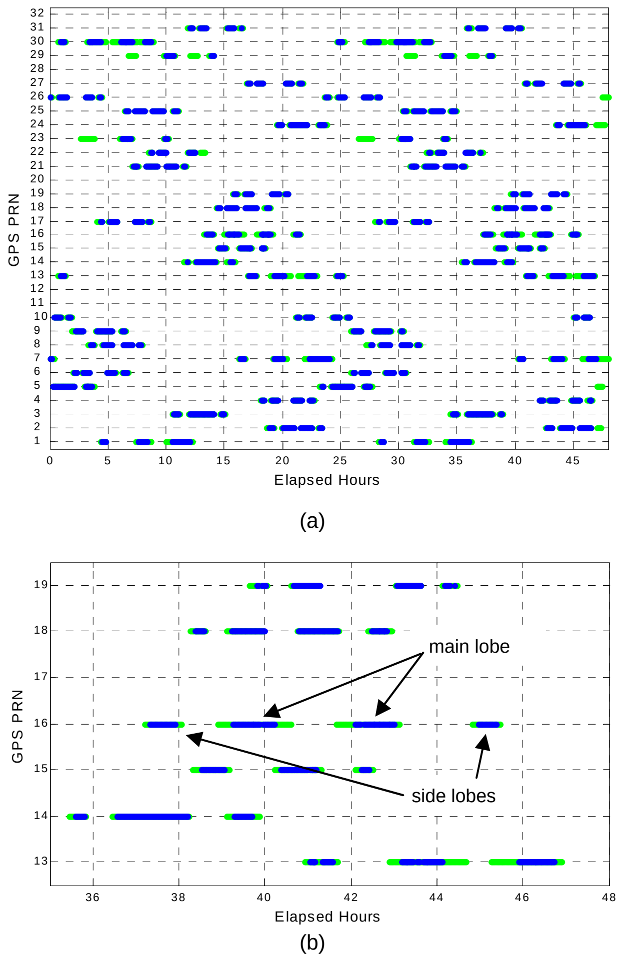

Figure 7: Individual satellite passes indicating tracked satellites (●) with respect to visible satellites (above 33 dB-Hz) (●) where (a) shows the passes for all satellites over a 48 hour period, while (b) shows a zoomed in view of the passes for several satellites.

There were very few instances when a pass was missed altogether, but it was fairly common for a small portion of each pass to be missed. This is in part because the receiver was found to acquire and lose signals within a range of power levels between 33-35 dB-Hz. Furthermore, there may be some additional latency between the time when the signal level is sufficient for tracking and the receiver actually acquires the signal. The well-designed acquisition process seeks to minimize this delay. Even missing just the ends of some of the passes here dramatically reduces the amount of time four satellites are visible simultaneously.

Figure 8 provides a way to visualize the GPS observability from the perspective of the geostationary user. As described earlier, the visible satellites are those on the opposite side of the Earth. The plot shows all of the satellite tracks of main-lobe and side-lobe signals above 33 dB-Hz. Here it is easy to see that many of the main lobe passes are actually interrupted as the signal passes behind the Earth. There is a null in transmitted power between the main-lobe and first side lobe. One can also get an idea of the relative duration of main lobe and side lobe passes. For a geostationary user, the visible satellites are all concentrated in one area of the sky contributing to poor solution geometry. The maximum received boresite angle for any of the side lobe signals shown here is 20.8 degrees. This geometry would be equivalent to a terrestrial receiver tracking only satellites at 69.2 degrees elevation and above.

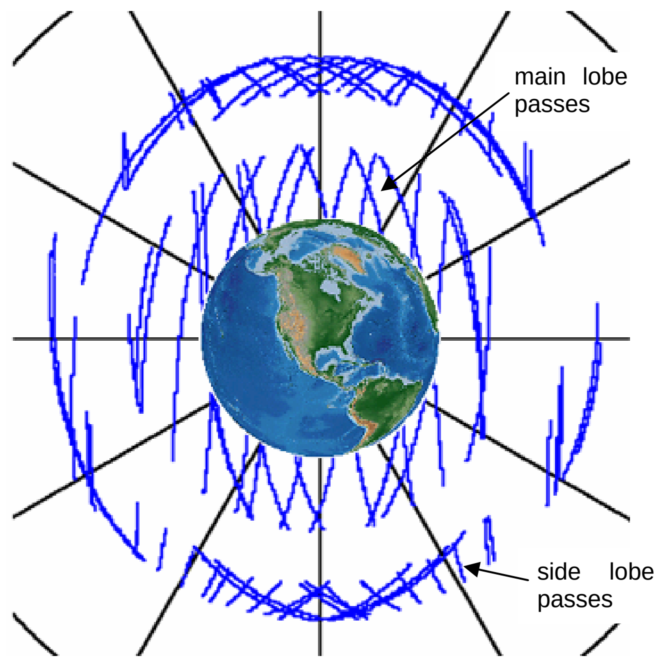

Figure 8: Plot of visible satellite passes from the perspective of the geostationary user.

The duration of passes are not as uniform for the HEO user as in other applications. Figure 9 shows histograms of the pass durations for the geostationary case. Most main lobe passes (~75%) are between 30 to 60 minutes in duration, however passes that are not interrupted by obstruction from the Earth can be over two hours long. Most side-lobe passes are shorter, with about 70% less than 45 minutes long; however, longer side lobe tracks are also possible. Most low Earth orbit passes are only 45 minutes or less in duration, so in many cases the HEO user has more time to track the available signals, even though the signal levels are reduced.

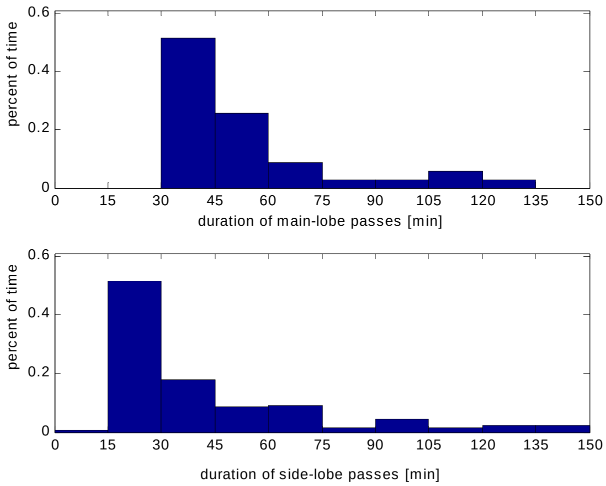

Figure 9: Duration of main-lobe and side-lobe satellite passes for geostationary user.

During the rare occasions when four or more satellites were tracked simultaneously (about 10% of the time) the receiver computed point solutions. The in-track and cross-track errors were typically within ±2 km of the truth; however, some outliers were significantly larger. The fact that the receiver was able to compute a solution in some cases was encouraging, but the errors were dominated by effects of the point solution algorithm and point solution based clock model not being equipped to operate through long data outages. For this reason, the first point solutions after an outage had large errors.

FUTURE WORK

Work is ongoing to implement an adaptive gain tracking loop design to allow for a lower loss of lock threshold when tracking at high altitudes. Additionally, modifications to the acquisition design will improve the speed of the acquisition process and help reduce the time required to acquire a signal after it comes into view.

The receiver is close to the point where it will be possible to run the real-time GEONS navigation filter with some of these HEO scenarios. Initial indications are that filtered solutions within several hundred meters of truth will be possible based on the signals tracked in the geostationary example presented here [8]. The enhancements to the acquisition and tracking design will improve the GPS observability and geometries and will make better navigation performance possible.

Some initial tests have been conducted in which the artificial tracking thresholds in the PiVoT receiver have been removed in order to assess the actual loss of lock performance in the carrier and code tracking loops subject to a variety of tracking conditions. Furthermore, tests are planned to assess the dynamic range of the receiver. In the geostationary case presented here, many side lobe signals were tracked. Particularly when attempting to track weaker signals, in some cases the difference in power levels between the peak main lobe signal and the weak side lobe signal may exceed the dynamic range of the receiver, preventing tracking of the weaker signal. This will also have an effect on the performance of the receiver subject to the near-far problem caused by temporary passes in close proximity to a single GPS satellite.

SUMMARY

A hardware in-the-loop GPS simulator is a powerful tool that can be used to evaluate the performance of a space GPS receiver in a full range of orbital test cases. However, before this tool could be used to conduct tests in HEO scenarios, some key steps were required to overcome inherent design assumptions in the simulator that assume the receiver is always near the surface of the Earth. The GSS simulator at GSFC is now capable of realistically simulating a variety of HEO scenarios.

Work is ongoing at NASA GSFC to implement software modifications to the in-house developed PiVoT GPS receiver to add the capability to operate in HEOs. With only minimal modifications to satellite acquisition algorithms, the existing PiVoT receiver was able to track main lobe and side lobe signals simulated for a geostationary orbit with a high gain, nadir-pointing receiving antenna. Enhancements currently being made to the PiVoT acquisition and tracking algorithms are expected to improve upon this performance. Many insights have already been gained into the behavior of the clock models and resulting measurement errors when the receiver attempts to operate in the sparse visibility environments at high altitudes.

REFERENCES

1. F.H. Bauer, K. Hartman, E.G. Lightsey, "Spaceborne GPS: Current Status and Future Visions," *Proceedings of the Institute of*

Navigation GPS 98 Conference, Nashville, TN, September 1998, pp. 1493-1508.

2. C. Mehlen, D. Laurichesse, “Real-time GEO Orbit Determination Using TOPSTAR 3000 GPS Receiver,” *Proceedings of the Institute of Navigation GPS 2000 Conference*, Salt Lake City, UT, 2000.
3. M. Mittnacht, W. Fichter, “Real Time On-board Orbit Determination of GEO Satellites Using Software or Hardware Correlation,” *Proceedings of the Institute of Navigation GPS 2000 Conference*, Salt Lake City, UT, September 2000.
4. W. Devereux et al., "The TIMED GPS Navigation System (GNS)," 49th International Astronautical Congress, Melbourne, September 1998.
5. M.J. Unwin, et al., "Preliminary Orbital Results from the SGR Space GPS Receiver," *Proceedings of the Institute of Navigation GPS 99 Conference*, Nashville, TN, September 1999.
6. M.C. Moreau, *GPS Receiver Architecture for Autonomous Navigation in High Earth Orbits*, Ph.D. Dissertation, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, August 2001.
7. Anon., “GPS Interface Control Document,” ICD-GPS-200, Revision C, U.S. Air Force, 10 October 1993.
8. M.C. Moreau, P. Axelrad, J.L. Garrison, A. Long, “GPS Receiver Architecture and Expected Performance for Autonomous Navigation in High Earth Orbits,” *Navigation*, Vol. 47, No. 3, Fall 2000, pp. 191-204.
9. J.L. Garrison, et al., “Tracking Loop Optimization for On-Board GPS Navigation in High Earth Orbit (HEO) Missions,” *Institute of Navigation Annual Meeting*, Albuquerque, NM June 2001.
10. J. Simpson, et al., “Testing of the International Space Station and X-38 Crew Return Vehicle GPS Receiver,” *Proceedings of the Institute of Navigation GPS 1999 Conference*, Nashville, TN, September 1999, pp 865-873.
11. P. Ward, “GPS Satellite Signal Characteristics,” Chapter 4 in E. Kaplan (editor), *Understanding GPS: Principles and Applications*, Artech House Publishers, 1996.