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PRELIMINARY RESULTS OF THE GPS FLIGHT EXPERIMENT ON THE HIGH EARTH ORBIT AMSAT-OSCAR 40 SPACECRAFT

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The GPS flight experiment on the High Earth Orbit (HEO) AMSAT-OSCAR 40 (AO-40) spacecraft was activated for a period of approximately six weeks between 25 September and 2 November, 2001, and the initial results have exciting implications for using GPS as a low-cost orbit determination sensor for future HEO missions. AO-40, an amateur radio satellite launched November 16, 2000, is currently in a low inclination, 1000 by 58,800 km altitude orbit. Although the GPS receiver was not initialized in any way, it regularly returned GPS observations from points all around the orbit. Raw signal to noise levels as high as 9 AMUs (Trimble Amplitude Measurement Units) or approximately 48 dB-Hz have been recorded at apogee, when the spacecraft was close to 60,000 km in altitude. On several occasions when the receiver was below the GPS constellation (below 20,000 km altitude), observations were reported for GPS satellites tracked through side lobe transmissions. Although the receiver has not returned any point solutions, there has been at least one occasion when four satellites were tracked simultaneously, and this short arc of data was used to compute point solutions after the fact. These results are encouraging, especially considering the spacecraft is currently in a spin-stabilized attitude mode that narrows the effective field of view of the receiving antennas and adversely affects GPS tracking. Already AO-40 has demonstrated the feasibility of recording GPS observations in HEO using an unaided receiver. Furthermore, it is providing important information about the characteristics of GPS signals received by a spacecraft in a HEO, which has long been of interest to many in the GPS community. Based on the data returned so far, the tracking performance is expected to improve when the spacecraft is transitioned to a three axis stabilized, nadir pointing attitude in Summer, 2002.

INTRODUCTION

There is widespread interest in the extension of GPS-based spacecraft navigation to high Earth orbit missions; however, due to reduced GPS observability at high altitudes and limitations of existing receivers, the use of GPS in space has been limited primarily to regions where point positioning is always possible, typically below altitudes of 3000 km. A number of papers have appeared in the literature examining the reception of GPS signals from above the GPS

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constellation and presenting expected navigation accuracies based on simulation [1,2,3,4,5]. Within the last several years, the concept of GPS tracking above the GPS constellation has actually been demonstrated by some of the first flight experiments to operate a GPS receiver on a HEO spacecraft. While these experiments have achieved some important milestones, the total amount of data returned and available to the civilian community regarding HEO GPS signal levels has been extremely limited.

This paper presents the preliminary results from the GPS experiment onboard the HEO AMSAT-OSCAR 40 (AO-40) spacecraft, launched 16 November 2000. Some of the original goals for the AO-40 GPS experiment included: demonstrating the operation of a GPS receiver in a HEO with very minimal interaction from ground controllers; returning sufficient observations to map the GPS satellite antenna patterns above the constellation; and ultimately generating orbit and attitude solutions for the AO-40 spacecraft from the GPS data. In the mid 1990s when this experiment was conceived, there were no currently available GPS receivers suitable for direct application to HEOs. Like other early HEO flight experiments, AO-40 uses an existing early-1990s-era LEO GPS receiver, in this case the Trimble TANS Vector. Even though this receiver has inherent design limitations at high altitudes, a significant amount of data has already been returned since the GPS experiment was first activated in September 2001. This paper will provide additional background on the AO-40 spacecraft, the design of the GPS experiment, and an overview of previous GPS experiments in HEO. Subsequent sections will present some examples of the GPS data returned from the first six weeks of operation.

PREVIOUS FLIGHT EXPERIMENTS

Table 1 provides a summary of all of the known examples of GPS receivers operated on HEO spacecraft. In late 1997, three separate high altitude GPS experiments were launched within a period of several months. Two of these satellites, TEAMSAT/YES [9] and EQUATOR-S [10] utilized existing GPS receivers with LEO heritage. Limitations in the receivers acquisition functions at high altitudes were overcome by manually commanding the receiver to track specific GPS satellites, and in this manner some of the first GPS observations were returned from above the GPS constellation. Notably, EQUATOR-S tracked a GPS satellite from an altitude of 61,000 km and demonstrated tracking of GPS side lobe signals from within a very high eccentricity orbit. The US Air Force Academy-sponsored Falcon Gold satellite took a different approach, using a "sampling receiver" built by NAVSYS Corporation to record sparse samples of the GPS spectrum from a geostationary transfer orbit. The normal receiver processing functions were then performed on the ground in post-processing [11]. At the time, these experiments were assumed to be the first ever examples of GPS tracking in a HEO, or from above the GPS constellation. Then in September 2000 the first public disclosure was made of a restricted US Department of Defense satellite program that has been using GPS measurements to perform the operational orbit determination for a Geostationary satellite for at least the last several years [8]. Similar to the Falcon Gold approach, this program used a distributed GPS receiver architecture comprised of an analog translator on the spacecraft coupled with a ground-based receiver and processing system. GPS signals are translated from the L1 frequency to a convenient intermediate frequency, and transmitted to the ground where they are combined with data from a ground receiver and used to compute the navigation solution.

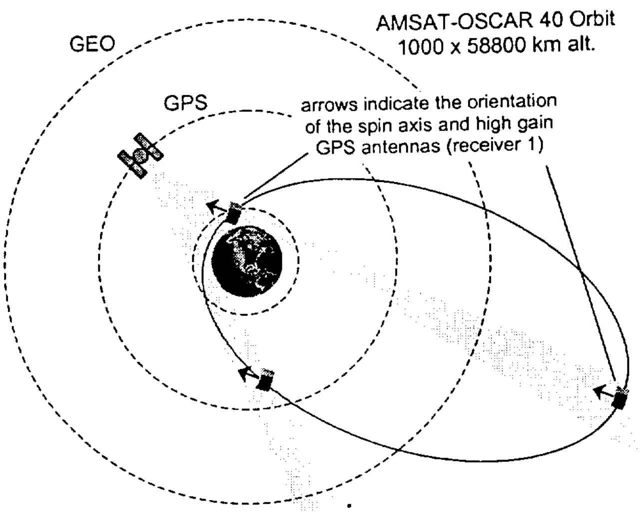
Table 1: HEO Flight Experiments

Mission	Orbit/Date/Duration	Architecture	Comments
US DoD Satellite [8]	Geostationary GPS based OD system dates to early 1990s, ongoing program.	Distributed architecture using a transponder on the spacecraft and a ground based receiver.	Operational GPS-based OD system for GEO satellite, uses specialized high-gain antenna design utilizing an array of patch antennas.
TEAMSAT-YES [9]	GEO transfer orbit Launched Oct 1997 Operated ~2 weeks	Trimble TANS-II	Tracked GPS signals up to ~26000 km altitude. Mission length limited by several week life span of s/c battery.
Equator-S [10]	500x67000 km alt. Launched Dec 1997 Operated several months	Motorola Viceroy	GPS experiment operated intermittently over several months. Tracked PRN 30 from an altitude of 61000 km and tracked GPS side lobe signals. Satellite failed prematurely.
Falcon Gold [11]	GEO transfer orbit Launched Oct 1997 Operated several weeks	NAVSYS TIDGIT sampling receiver	Receiver returned digitized samples of GPS spectrum, processed on the ground. Experiment operated for a couple of weeks.
STRV 1c&d [12]	GEO transfer orbit launched Nov 2000	microGPS II sampling receiver	No GPS data returned due to spacecraft failure.
AO-40 [13]	1000x58800 km alt. Launched Nov 2000 Currently operating	Two Trimble TANS Vectors	Spacecraft currently spin stabilized, GPS Receiver 1 activated from 25 Sept. to 2 Nov, 2001. Uses "high gain" receiving antennas.

The primary objectives of these early experiments were to validate the concept of GPS tracking at high altitudes, and to return actual measurements of GPS side-lobe and back-lobe transmissions, data that is generally unavailable. Obviously the Department of Defense program has gone a step further and demonstrated an operational GPS based orbit determination system based on a distributed system architecture. This system could potentially return a wealth of data on the transmitted GPS signal levels; unfortunately, due to the restricted nature of this satellite program, the data is simply not available to the civilian GPS community. The Falcon Gold satellite used a similar architecture; however the experiment operated for only a couple of weeks before the spacecraft battery was depleted, and a minimal amount of data was ultimately extracted from the measurements [11]. The experiments utilizing conventional space receivers demonstrated closed-loop tracking of GPS signals at high altitudes, an important step for users interested in autonomous GPS navigation in HEO; however, due to limited battery life of the TEAMSAT experiment and premature failure of the spacecraft on EQUATOR-S, only a limited amount of GPS data was returned from these missions as well. Although it was originally intended to launch in 1997, the AO-40 spacecraft did not reach orbit until late 2000 due primarily to the wait for a slot on the Ariane 5 launch vehicle. Like TEAMSAT and EQUATOR-S, AO-40 uses a receiver with LEO flight heritage, but the high altitude receiver (receiver 1) is set up to operate autonomously. Receiver 2 is expected to be capable of returning point and attitude solutions around perigee, which would be a first in a HEO. There is still a need for additional measurements of the GPS transmissions at high altitudes, and for operational experience using GPS observations for HEO navigation.

AMSAT-OSCAR 40 SPACECRAFT

The AMSAT-OSCAR 40 satellite is the latest in a series of low-cost spacecraft built by the Radio Amateur Satellite Corporation, or AMSAT. The Orbiting Satellites Carrying Amateur Radio (OSCAR) series of small satellites was initiated for radio amateurs to experience satellite tracking and participate in radio propagation experiments. The primary payload consists of an array of antennas and transponders intended to provide communications with direct access by radio amateurs all around the world. The GPS experiment is one of several secondary payloads on the spacecraft. AO-40 is in a low inclination, 1000 by 58,800 km altitude orbit, as indicated in Figure 1. Ultimately AO-40 will be placed in a three-axis stabilized, Earth pointing attitude mode to maintain the antenna arrays directed towards the Earth; however, the spacecraft is currently in a passive/spin stabilized attitude with the spin axis parallel to the nadir vector when the vehicle is at apogee. The antenna array points in the same direction as the spin axis, as indicated in Figure 1, allowing amateur radio access to the spacecraft during the high altitude portions of each orbit.



semimajor axis	36286 [km]
eccentricity	0.79684
inclination	6.04 [deg]
period	19.1 [hrs]
perigee altitude	1000 [km]
apogee altitude	58800 [km]

Figure 1: AMSAT-OSCAR 40 orbit parameters and attitude.

AO-40 GPS EXPERIMENT

The GPS experiment onboard AO-40 consists of two independently operated Trimble TANS Vector, L1 C/A code GPS receivers, each connected to four receiving antennas. The antennas for each receiver are mounted on opposite sides of the spacecraft; in the nominal Earth-pointing attitude, receiver 1 was intended to provide GPS coverage during the high altitude portions of each orbit, while receiver 2 would be operated near perigee. With AO-40 currently spin stabilized, the receiver 1 antennas are oriented in the same direction as the communications antennas and the spin axis, as indicated by the arrows in Figure 1. The GPS antennas essentially have a fixed field of view since they point in the same direction as the spin axis. Only receiver 1 has been activated to date since its antennas are oriented favorably both at apogee and perigee.

In order to compensate for the increased path lengths and reduced GPS signal levels expected at high altitudes, receiver 1 uses an additional pre-amplifier stage and "high gain" antennas that are more directional than typical GPS patch antennas, providing approximately 10 dB peak gain. Figure 2 shows a picture of the nominal "nadir" pointing spacecraft face with the four high gain GPS antennas and the other RF antennas clearly visible. The primary or master receiving antenna is indicated by an "M", with the other antennas numbered 1 through 3.

Additionally, a minor yet important software modification was made to disable the satellite selection logic normally employed in the TANS Vector receiver to allow receiver 1 to operate in a "blind search" acquisition mode. Ordinarily this acquisition strategy is not very reliable for a six-channel receiver operated in space. It creates the possibility that the receiver will miss some of the visible GPS signals it might otherwise be capable of tracking, simply because it is not searching in "the right place at the right time." Unfortunately, the normal satellite selection logic in the Vector assumes that the receiving antennas are always oriented towards zenith, so without the ability to make this minor software modification it would have been impossible for the TANS Vector to track any satellites above the GPS constellation. While the acquisition performance will be somewhat degraded, it has the advantage that receiver 1 requires no initialization or intervention from the ground in order to operate.

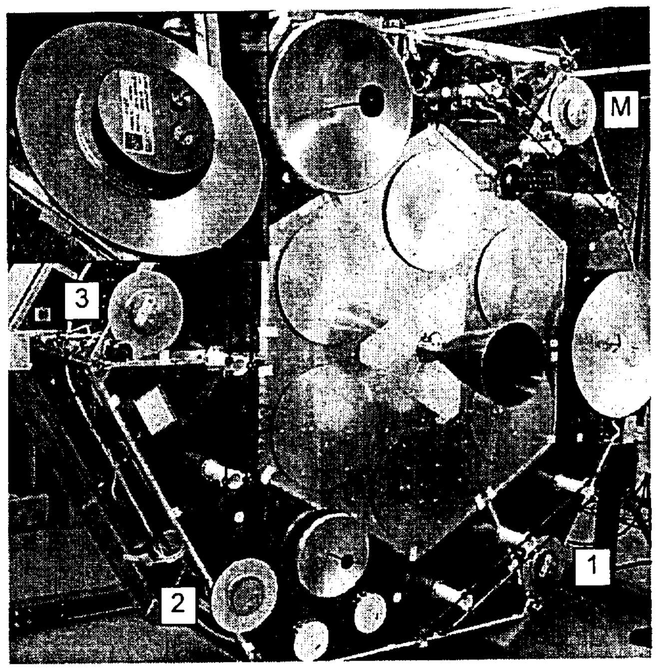


Figure 2: A picture of the nominal Earth-pointing face of the AO-40 spacecraft showing the layout of the receiver 1 (high gain) GPS antennas (close-up view inset). The master antenna is indicated by "M." Receiver 2 antennas are mounted on the opposite side of the spacecraft, pointing in the opposite direction.

Receiver 2 (the perigee receiver) is installed and operated in much the same way it would be on a LEO spacecraft. The four hemispherical patch antennas are installed 180 degrees opposed from the receiver 1 antennas; oriented in the zenith direction when the spacecraft is in Earth-pointing mode. It was intended to provide GPS tracking as the spacecraft passed through perigee. Receiver 2 is capable of being initialized with an a priori state estimate that is used in the satellite selection and acquisition process.

The TANS Vector is capable of tracking up to six satellites simultaneously, and when four or more satellites are tracked, it is capable of producing real-time position, velocity, and attitude solutions. Of particular importance for a HEO spacecraft, the receiver also provides the raw GPS code phase, carrier phase, Doppler, and SNR (signal to noise ratio) measurements for all satellites tracked. At the time this experiment was conceived, there were no existing GPS receivers well suited for operation in HEO. Like most GPS receivers originally designed for terrestrial use, the TANS Vector has fundamental limitations that hinder its performance at high altitudes; however because of previous LEO flight experience with this receiver, NASA GSFC was in a unique position to make the minor software modifications described above to enable the tracking of GPS signals even when high above the GPS constellation.

The digital communications processor on AO-40 (RUDAK) provides digital store and forward capabilities for users of the spacecraft, and serves as the primary communications path for interacting with the GPS (and other) experiments. The binary data streams from the GPS receivers are binned into one-hour files by the RUDAK that can be downloaded via a suitably equipped ground station. Some additional steps are required to reconstruct the actual observation and solution data from the receiver.

FLIGHT DATA RESULTS

Overview

GPS Receiver 1 was operated for the first time from approximately September 25th through November 2nd, 2001. GPS Receiver 2 has not been activated yet. The binary data from the receiver is parsed by the spacecraft into separate one-hour files that are downloaded via the RUDAK. The volume of data actually returned from the spacecraft each day is shown in Figure 3. On the best days only 16 one-hour blocks of binary data were downloaded from the spacecraft. In many cases these missing files were deliberately not downloaded from the RUDAK because they appeared not to contain any data. In these cases it is likely that no satellites were actually tracked by the receiver. However in some instances, files may have been deleted from the RUDAK before they could be downloaded due to memory limitations. The larger gaps in the data covering several days are believed to correspond to periods when either the RUDAK processor or the GPS receiver itself crashed and had to be restarted. Because the ground stations are not constantly monitoring the status of the receiver in real-time, these lock ups are not necessarily detected immediately.

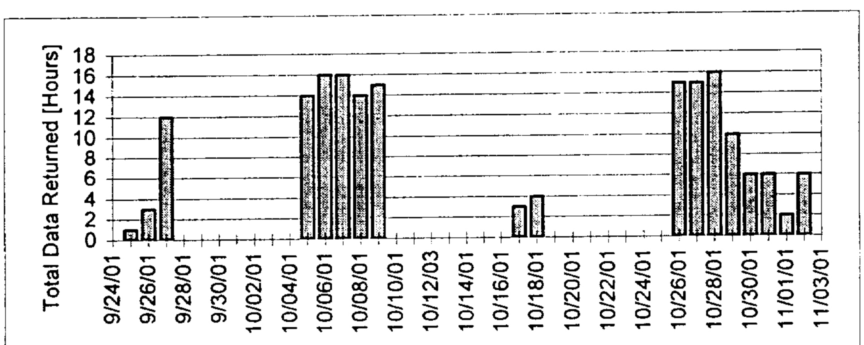


Figure 3: Volume of GPS data returned from AO-40 GPS receiver 1.

Receiver 1 operates in a blind search mode using each of its six channels to search sequentially through the 32 possible GPS satellite PRNs. As described earlier, this allows the receiver to track GPS satellites even when it is above the GPS constellation, but introduces the possibility that some satellites will be missed. The approximate 5 RPM spin rate has a noticeable effect on the measurements and makes the acquisition and tracking problem more difficult.

Despite these limitations, receiver 1 has successfully tracked GPS satellites throughout all parts of the orbit, including near apogee (when signal levels are reduced) and perigee (when the spacecraft velocity is high). During one perigee pass, it acquired four satellites simultaneously for a short time; however, the receiver never returned a point solution. The high gain antennas and pre-amplifier design provides sufficient link margin even at apogee, where C/N_0 levels as high as 48 dB-Hz were common. The following sections present more details regarding several aspects of the data received thus far.

Analysis Procedure

Several pre-processing steps are necessary to reformat the one-hour duration binary files downloaded from the RUDAK into a form that could be decoded with existing TANS Vector post processing tools. Following this procedure it was possible to reproduce the original TANS Vector binary output or to produce ASCII formatted output containing individual raw data or solution packets from the receiver. Of primary interest were the 'e4' data packets containing the raw GPS observations. The e4 packets contain a GPS time tag, code phase, Doppler, carrier phase, and SNR measured through the master antenna, followed by carrier phase and SNR measured from each of the three secondary antennas [7].

The SNR reported by the TANS Vector is given in units of AMUs. The following expression, derived from experimental data, was used to convert the SNR in AMUs to the more commonly used carrier to noise spectral density, C/N_0 expressed in dB-Hz, [6]

$$\mathbf{C/N_0}\ [\text{dB-Hz}] = 10*\log_{10}(\text{BW}*\mathbf{AMU}^2)$$

where AMU is the raw SNR measurement reported by the receiver in Trimble AMUs, and BW is the noise equivalent bandwidth of the receiver.

The code phase measurements reported by the TANS Vector are the actual measurements of the fractional C/A code epochs made by the receiver, not the full pseudorange that is used by the receiver in a navigation solution. In order to produce a full GPS pseudorange, as required by the standardized RINEX GPS observation format, an integer number of one millisecond (300 km) C/A code epochs must be added to the fractional code phase reported by the receiver.

One final peculiarity associated with the TANS Vector data is related to the data and solution time tags. When solutions are available, the receiver periodically adjusts its local clock by ±1 millisecond to keep the current time within ±0.5 milliseconds of GPS system time. As a result, data time tags are biased by up to ±0.5 milliseconds; however, by subtracting the clock bias solution from the reported time tag, it is possible to obtain the corrected data time tags. Since receiver 1 was operated for long periods of time without a position (or clock) solution, it is believed that the local oscillator is drifting freely and the clock bias continues to accumulate, which means time tag errors can become very large, potentially even as large as several seconds. An additional uncertainty is related to the initial setting of time in the receiver based on the handover word from the GPS navigation message. Before this event happens, the local oscillator error is completely unknown.

GPS visibility and link analysis tools were developed previously to predict GPS observability, expected signal levels, and dynamics for HEO users [5]. Similar tools were used in the analysis of previous HEO GPS data [10], and are useful to determine which GPS satellites were actually visible to the HEO spacecraft at the time of the observations. In the analysis of the

AO-40 GPS data, they were also used to estimate a variety of parameters associated with the measurements that were not available from the receiver such as signal reception geometries, spacecraft altitude, etc. Of particular interest for the analysis of the GPS signal levels was the angle measured between the line-of-sight and the boresight of either the transmitting or receiving antennas, called the transmitted or received boresight angles, respectively. Since a precise reference orbit for AO-40 was not readily available, NORAD Two Line Elements (TLE) were used to generate reference state vectors for the spacecraft that could then be propagated forward in time. GPS satellite ephemerides were computed using either almanac or broadcast ephemeris as initial conditions, depending on the accuracies required. GPS signal levels were estimated using the model for the receiving antenna gain pattern given in Figure 4, and the model for the gain pattern of the GPS satellite transmitters given in Figure 5 [15].

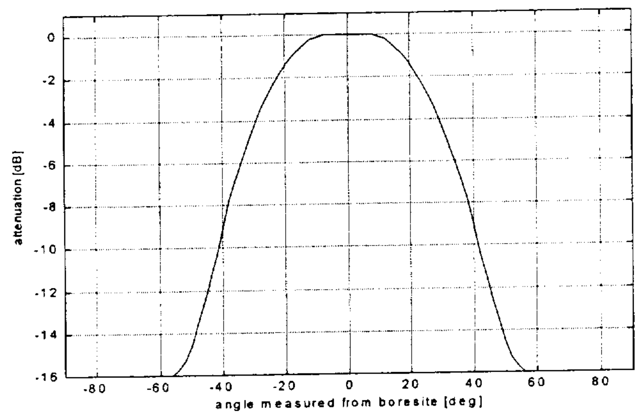


Figure 4: Modeled gain pattern for "high gain" GPS antennas used with receiver 1. Peak gain is approximately 9.2 dBiC.

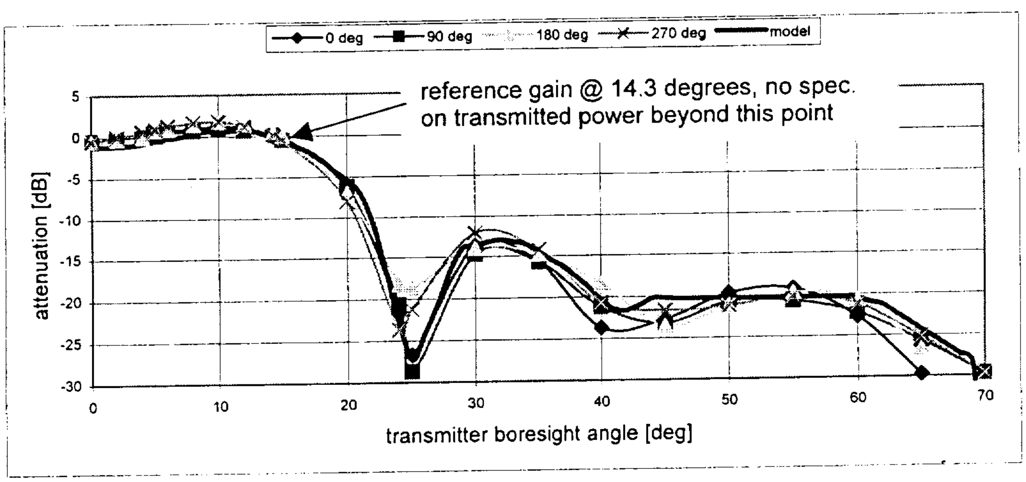


Figure 5: Model of the GPS transmitting antenna pattern assuming reference EIRP=29.8 dBW, based on the measured gain pattern from a GPS Block IIA satellite [14].

GPS Measurements

Figure 6 illustrates the tracking performance and GPS data outages for receiver 1 on October 5, 2001. These results are representative of the data that was returned on the other days as well. The GPS satellites that were predicted to have signals levels above 35 dB-Hz and an unobstructed line-of-sight to the AO-40 spacecraft are plotted next to the actual satellites tracked by receiver 1. It is impossible to tell if the receiver actually tracked any satellites during the hours when no data was obtained from the spacecraft. During the periods when data was returned, the receiver was able to acquire and track at least part of 17 of the 24 predicted GPS satellite passes shown. There are also two cases in which a satellite was tracked for a short time even though it was not predicted to be visible. Typically, the duration of time satellites were actually tracked is shorter than the duration of the predicted passes for two reasons. First, using the blind search acquisition technique, the receiver may not start to search for the signal until some time after it became visible. This also explains why some satellites are missed altogether. Second, the threshold at which the receiver loses lock on the signal is not necessarily equal to the predicted threshold of 35 dB-Hz.

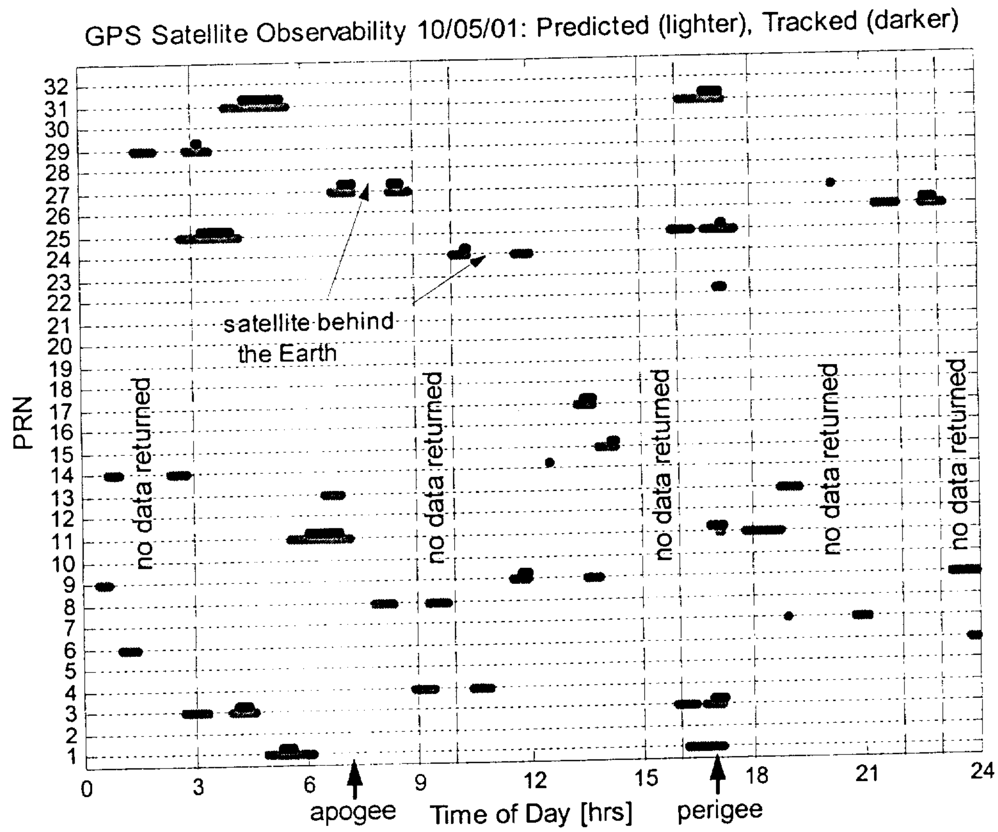


Figure 6: Comparison of predicted GPS visibility and actual satellites tracked on 5 October, 2001, showing typical tracking performance of receiver and data outages.

There are a few other interesting features in Figure 6. The acquisition performance was fairly consistent regardless of whether the spacecraft was near apogee or perigee. Between approximately 07:00 and 09:00 hours (UTC time), the tracking of PRN 27 is actually interrupted as the satellite passed behind the earth, but the receiver successfully reacquired the signal when it reappeared on the other side. This geometry in which the GPS satellites pass behind the earth is common for a high altitude user. During the perigee pass at approximately 17:00 hours, the signals from four GPS satellites were tracked simultaneously for a short time. Some of these effects are examined more closely in the subsequent discussion.

The approximate five revolutions per minute (RPM) spin rate of the AO-40 spacecraft has a significant effect on all aspects of the GPS tracking performance, particularly for satellites at lower elevations. The direct effect, as shown in Figure 7, is a on the GPS signal levels measured by the receiver. The antennas for receiver 1 are oriented in the same direction as the spin axis (Figure 1), so they essentially have a fixed field of view; however, the gain patterns are not completely symmetrical in azimuth. This asymmetry is actually more pronounced for the high gain antennas because of the steeper attenuation curve. As the spacecraft rotates, the null region (where the antenna gain is reduced) rotates causing an oscillation in the measured signal levels. Figure 7 shows five minutes of measured signal levels for three different satellites tracked at different altitudes and with varying received boresight angles. These variations can be very significant, particularly if the received boresight angle is large. For PRN 4, tracked when AO-40 was near apogee and the line-of-sight was only 6.2 degrees off the boresight, the signal levels only vary approximately 2 dB peak-to-peak. In contrast, PRN 31 was tracked close to perigee when the line-of-sight was approximately 40 degrees down from the boresight, and the signal levels vary by approximately 12 dB peak-to-peak.

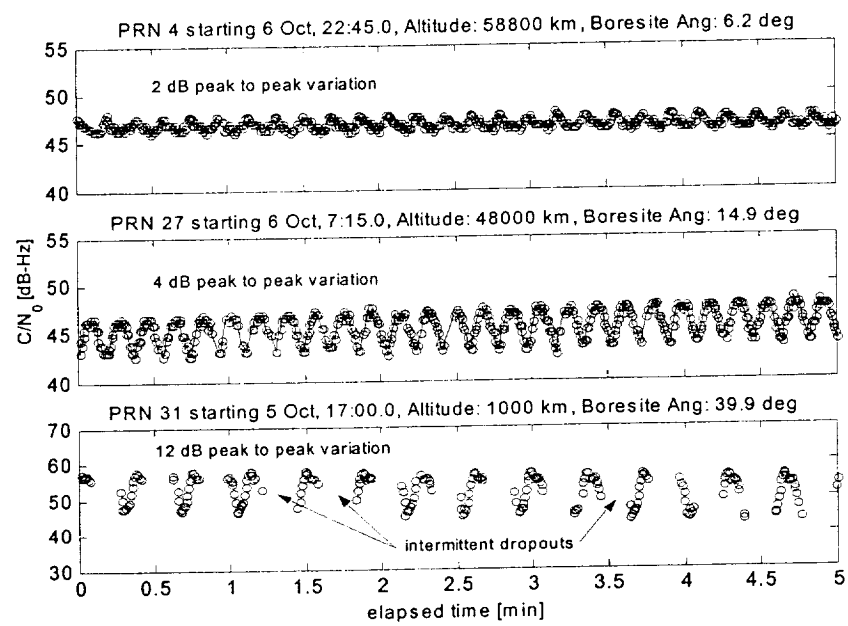


Figure 7: Effects of the AO-40 spin rate on the observed GPS signal to noise levels.

The indirect effect of the oscillations in the signal levels is reduced tracking performance. Clearly the receiver is having difficulty tracking PRN 31 as evidenced by the data dropouts on this plot. In this case, while measurements are returned periodically, the dropouts make it impossible for the receiver to receive the broadcast navigation message modulated on the GPS data, so the receiver is not able to use PRN 31 in a solution during this span. The spin has the effect of reducing the effective field of view of the receiving antennas. At high altitudes, the effects are reduced because most of the GPS signals are located close to the boresight direction. Unfortunately, these effects significantly reduce the chances of receiver 1 computing a point solution while the spacecraft is spin stabilized. The oscillations in the signal levels provide a direct measure of the AO-40 spin rate, which was derived to be 5.4 RPM on October 5th. It is also possible to obtain a measure of the asymmetry of the receiving antenna gain pattern by correlating the magnitude of the oscillation with the received boresight angle.

Figure 8 provides plots of the measured signal to noise levels and Dopplers during a six hour span near apogee on October 5, 2001. The spin rate effects discussed above are clearly present. The peak signal levels measured near apogee were typically 48 dB-Hz or 9 AMUs (the raw signal to noise measurement reported by the receiver). Even though the spacecraft is close to 60,000 km altitude, the high gain antennas provide about 6 dB of additional signal gain relative to a typical patch antenna, which helps to offset the additional path losses and accounts for the good signal levels reported by the receiver. There were two times during this span when two satellites were tracked simultaneously (PRN 3 and PRN 31, PRN 31 and PRN 1). The measured signal Dopplers never exceeded ±7 kHz, as compared to Dopplers that range between ± 45 kHz in a low Earth orbit.

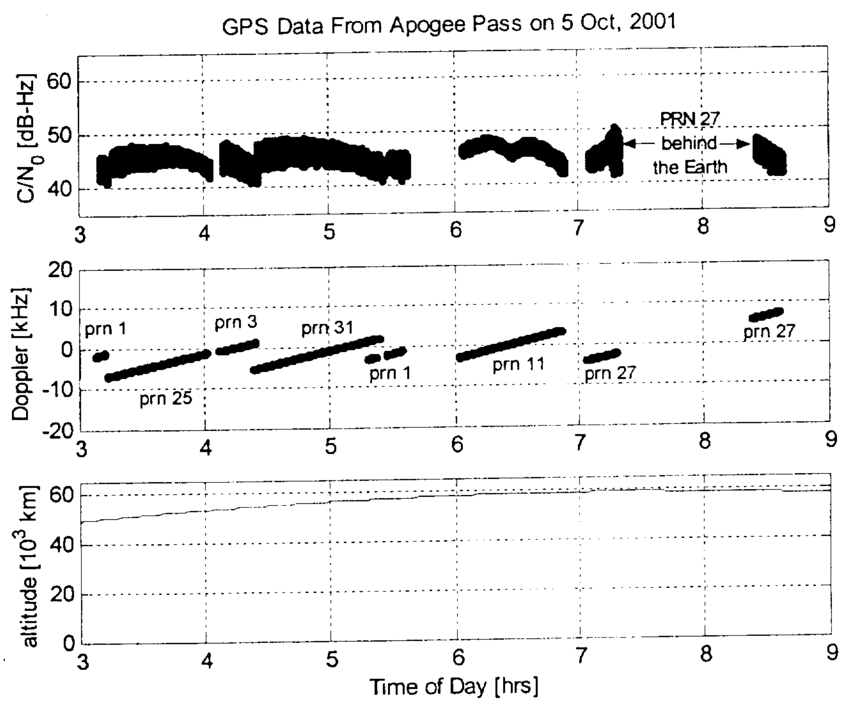


Figure 8: Measured Signal Levels and Dopplers from apogee pass on October 5, 2001.

Figure 9 is provides a similar view of a one-hour period around perigee. The spacecraft is moving must faster and measured Dopplers are almost an order of magnitude higher than measured at apogee. The oscillations in the signal levels are more pronounced near perigee, which makes it difficult to interpret the measured signal levels. Figure 10 separates the measured signal levels for each of the satellites tracked during this span. Although there is a period lasting approximately five minutes when it appears that four satellites are tracked simultaneously, the receiver did not generate a point solution. Actually, the receiver indicated that there were never more than two usable satellites during this entire period. Due to the variations in the signal levels, the receiver was not able to continuously track the other satellites long enough to obtain the broadcast navigation message.

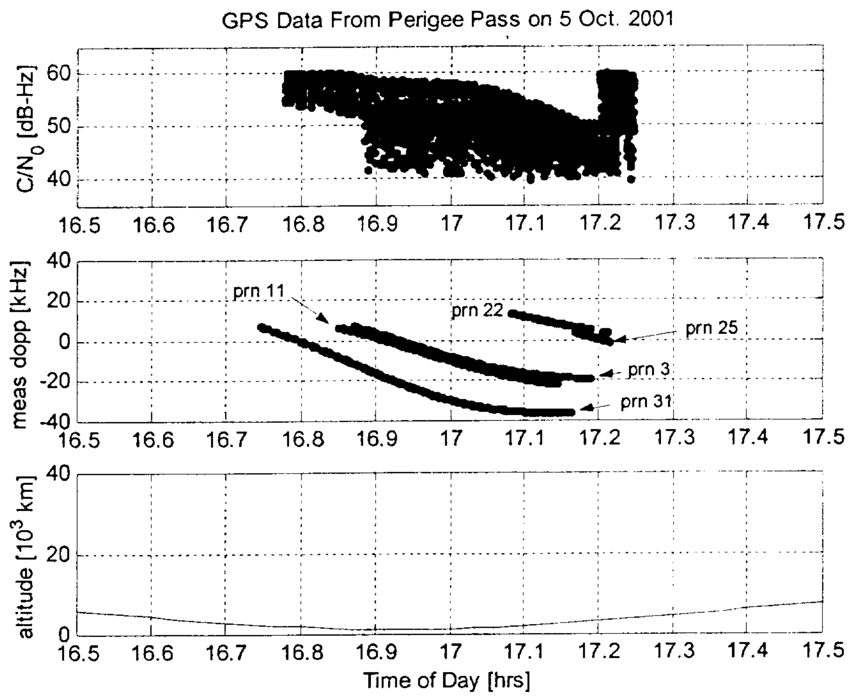


Figure 9: Measured Signal Levels and Dopplers from perigee pass on October 5, 2001.

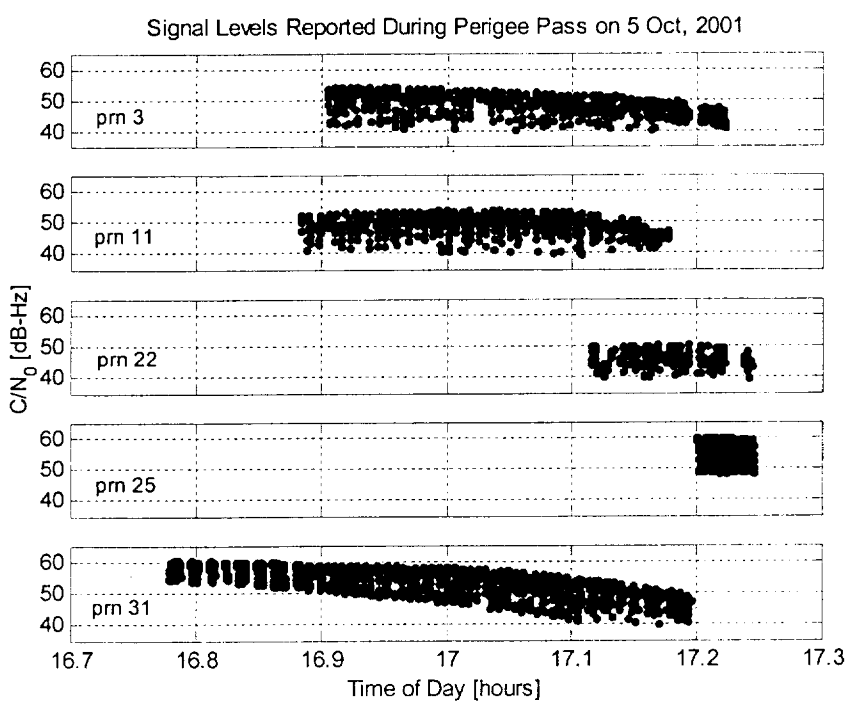


Figure 10: Signal levels reported for the five satellites tracked during the perigee pass on October 5, 2001.

On several occasions when the receiver was below the GPS constellation (between altitudes of approximately 10-20,000 km), observations were reported for GPS satellites tracked through side lobe transmissions. Figure 11 is a plot of the raw GPS SNRs reported by the receiver plotted versus the transmitted boresight angle. Transmitter boresight angles greater than approximately 24 degrees correspond to side lobe signals. Measurements of the transmitted power from the GPS satellites were made covering a large range of transmitted boresight angles, but only a small number of side lobe passes were recorded from a couple of GPS satellites. These are precisely the types of measurements that are of interest to many in the GPS community to determine what contribution the side lobes will make to GPS observability, if a sufficient number of measurements can be made to effectively map out the transmitted power levels from the GPS satellites for high transmitted boresight angles. Unfortunately, it is difficult to directly infer transmitted power levels from this limited amount of data since it also contains spin rate effects, variations in the power levels due to path losses, the receiving antenna gain pattern, etc. The receiver has demonstrated the ability to record these signals, even while spinning, and once the AO-40 transitions to a three-axis stabilized pointing mode, the quality and quantity of these measurements should improve greatly.

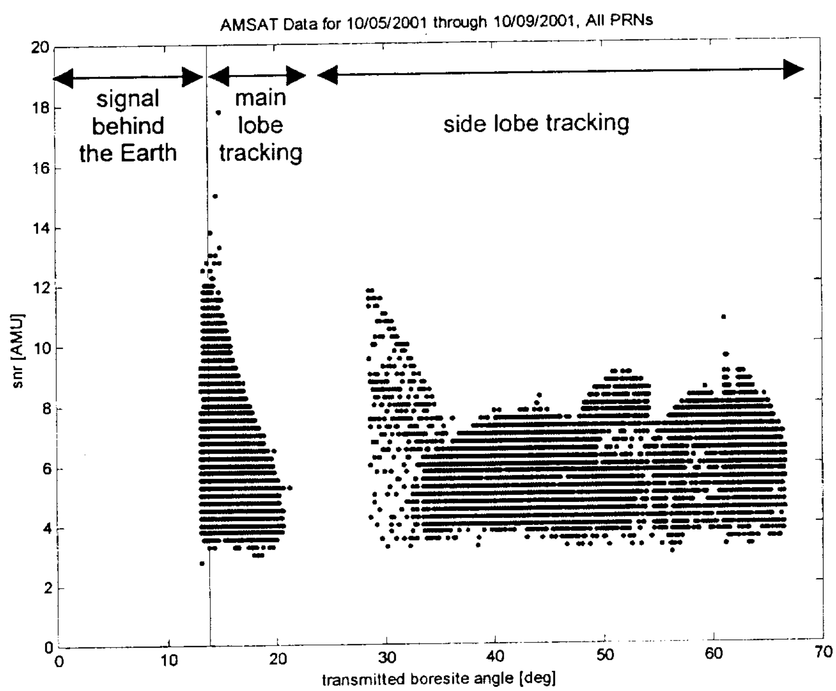


Figure 11: Raw GPS signal levels plotted versus transmitted boresight angle.

Preliminary Orbit Determination Efforts

Although the receiver has not returned any point solutions, there was a period lasting approximately five minutes shown in Figure 10 where four satellites were tracked simultaneously. This was the only time during the six weeks the receiver was operated that four satellites were tracked at the same time, although there were several instances when three satellites were tracked. This short arc of data near perigee on October 5th was used to compute point solutions after the fact. As described earlier, since the TANS Vector only reports a fractional code phase measurement, the full pseudorange must be computed before such a solution can be obtained. The aforementioned unknown time tag bias further complicates this process. The resulting point solutions compared to the TLE-based reference trajectory to within approximately 100 kilometers, differing mostly in the along track direction. This magnitude of error could be partially attributed to the unknown clock error in the receiver, or the errors in the TLE-based ephemeris itself, but with only a very limited amount of data and no precise "truth" orbit for the AMSAT spacecraft, it difficult to separate these effects. If the receiver had been able to compute a single point solution internally, the clock error would be known at that time and the problem would be greatly simplified. Some progress has been made towards fitting a precise orbit to the sparse GPS observations received to date, using the solution described above as a starting point.

CONCLUSIONS AND FUTURE WORK

The apogee GPS receiver on the AMSAT-OSCAR 40 spacecraft has demonstrated the ability to operate autonomously and track GPS signals anywhere within its 1000 by 58,000 km altitude orbit. Peak signal levels measured when the spacecraft was near apogee and at an altitude close to 60,000 km were approximately 9 AMUs or 48 dB-Hz. The receiver has tracked many of the satellites in view, even though the satellite acquisition strategy is not well suited for a receiver operating in space. These results are even more impressive considering the AO-40 spacecraft is currently in a spin stabilized attitude, which reduces the effective field of view of the GPS antennas and makes the GPS acquisition problem more difficult. No position or attitude solutions were computed by the receiver during the six week period when receiver 1 was operated; however point solutions were computed after the fact using a five minute arc of data when four satellites were tracked simultaneously.

The tracking performance is expected to improve when the spacecraft is transitioned to a three axis stabilized, nadir pointing attitude in Summer 2002 as planned. This will also allow the operation of receiver 2, increasing the chance of obtaining position or attitude solutions from within this orbit. Already AO-40 has demonstrated the feasibility of recording GPS observations in HEO using an unaided receiver. Furthermore, it is providing important new information about the characteristics of GPS signals received by a spacecraft in a HEO. These results have exciting implications for using GPS as a low-cost orbit determination sensor for future HEO missions.

Efforts are ongoing to generate a precise orbit from the GPS data. This process has been complicated by the combination of the fractional code phase measurements with the potentially large, unknown time tag errors present in the data. Still the AO-40 GPS experiment has already provided some valuable insights into the unique problems of operating a GPS receiver in a HEO. A simulation that precisely duplicates the AO-40 orbit and attitude has been created using the high fidelity GPS signal simulator at NASA GSFC. Data is being collected using a TANS Vector receiver in the lab to compare to the measurements made on orbit. This provides a means to assess how closely the hardware in the loop test duplicates on orbit conditions, and provides additional insights into the timing issues when the TANS Vector is operated for long periods of time without a point solution.

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REFERENCES

1. Jorgensen, P., "Autonomous Navigation of Geosynchronous Satellites Using the NAVSTAR Global Positioning System," *National Telesystems Conference*, Galveston, TX, 1982.

2. Wu, S.C., T.P. Yunck, S.M. Lichten, B.J. Haines, R.P. Malla, "GPS Based Precise Tracking of Earth Satellites from Very Low to Geosynchronous Orbits," *National Telesystems Conference*, 1992.

3. Potti, J., P. Bernedo, A. Pasetti, "Applicability of GPS-based Orbit Determination Systems to a Wide Range of HEO Missions," *Proceedings of the Institute of Navigation GPS 95 Conference*, Salt Lake City, UT, September 1995, pp. 589-598.

4. Moreau, M.C., 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.

5. Moreau, M.C., *GPS Receiver Architecture for Autonomous Navigation in High Earth Orbits*, Ph.D. Dissertation, Department of Aerospace Engineering Sciences, University of Colorado at Boulder, July 2001.

6. Cohen, C.E., *Attitude Determination Using GPS*, Ph.D. Dissertation, Department of Aeronautics and Astronautics, Stanford University, December, 1992.

7. Trimble Navigation Limited, *TANS VECTOR Specification and User's Manual, May, 1995.*

8. Kronman, J.D., *Proceedings of the Institute of Navigation GPS 2000 Conference*, Salt Lake City, UT, September 2000.

9. ESTEC, TEAMSAT Results, April 1998, http://www.estec.esa.nl/teamsat/page_menu_results.htm

10. Balbach, O., et al., "Tracking GPS Above GPS Satellite Altitude: First Results of the GPS Experiment on the HEO Mission Equator-S," *IEEE PLANS*, 1998, pp. 243-249.

11. Powell, T.D., P. D. Martzen, S.B. Sedlacek, C. Chao, R. Silva, A. Brown, G. Belle, "GPS Signals in a Geosynchronous Transfer Orbit: Falcon Gold Data Processing," ION Nation Technical Meeting, January, 1999, pp. 575-585.

12. DERA, *STRV Microsatellite Research Vehicles*, Last Updated 20 July 2000, <http://www.dera.gov.uk/html/space/strv/home.htm>

13. Williamson, P., *Phase 3D Project*, Last Updated: 1/19/2000, The Radio Amateur Satellite Corporation, < http://128.54.16.15/amsat/sats/phase3d.html>.

14. Czopek, F., "Description and Performance of the GPS Block I and II L-Band Antenna and Link Budget," *Proceedings of the Institute of Navigation GPS 93 Conference*, pp. 37-43..