AAS 00-269

SPACE APPLICATIONS OF THE GLOBAL POSITIONING AND TIMING SERVICE (GPtS)

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ABSTRACT

Spaceborne Global Positioning System (GPS) technology is being widely accepted by both the commercial space industry and by NASA as a key enabler for improving space operations. The use of GPS for space missions has resulted in improvements in space vehicle autonomy and reduced design and operations cost.

The current GPS constellation includes 24 MEO satellites with spares. These satellites are launched and operated by the US Air Force. GPS users also have access to signals from GPS augmentation systems. The first of these augmentation systems to transition to an operational capability is the FAA's Wide Area Augmentation System (WAAS). Other organizations are actively developing augmentation services to GPS, and also developing follow-on satellite navigation capabilities. These include international variants of the WAAS service, planned for operation over Europe and the Pacific region, and new satellite navigation services, such as the proposed European Galileo satellite navigation constellation.

The concept of a Global Positioning and Timing Service (GPtS) proposes a networked approach that provides enhanced global services using an integrated system-of-systems architecture, coupling signals-in-space from different sources. This places challenges in tightly synchronizing different networks of satellite constellations to provide seamless service coverage.

GPtS applications for space users of the service include: autonomous orbit operations, accurate positioning and time synchronization, and attitude determination and accurate relative ranging between vehicles for formation flying. In this paper, some of the existing challenges for these applications are discussed and enhancements in GPS users' equipment and in the evolving GPtS architecture are described that could benefit space applications.

INTRODUCTION

NAVSTAR GPS is a space-based radio-positioning system nominally consisting of a constellation of 24 orbiting satellites that provide navigation and timing information to military and civilian users worldwide. In addition to the satellites, the system consists of a worldwide satellite control network and GPS receiver units that pick up signals from the satellites and translate them into position information. Delta II expendable launch vehicles are used to launch the GPS satellites from Cape Canaveral Air Station, Fla., into six circular orbits of nearly 11,000 nautical miles.

GPS provides the following services

- 24-hour, worldwide service
- Three-dimensional location information (providing latitude, longitude, and altitude readings)

Proceedings of the Richard H. Battin Astrodynamics
Conference, College Station, TX, March 2000.

- Accurate velocity information
- Precise timing services
- A worldwide common grid that is easily converted to any local grid
- Continuous real-time information
- Accessibility to an unlimited number of worldwide users
- Civilian user support at a slightly less accurate level

GPS satellites orbit the earth every 12 hours, emitting continuous navigation signals on two different L-band frequencies. The GPS worldwide satellite control system consists of five monitor stations and four ground antennas, as shown in Figure 1. The monitor stations use GPS receivers to passively track the navigation signals of all the satellites. Information from the monitor stations is then processed at the master control stations, operated by the 2nd Space Operations Squadron at Schriever Air Force Base, Colo., and used to very accurately update the satellites' navigation messages. Updated navigation information is sent to the GPS satellites from the Master Control Station at Schriever Air Force Base through ground antennas using an S-band signal. The ground antennas are also used to transmit commands to satellites and to receive the satellites' state-of-the-art telemetry data.

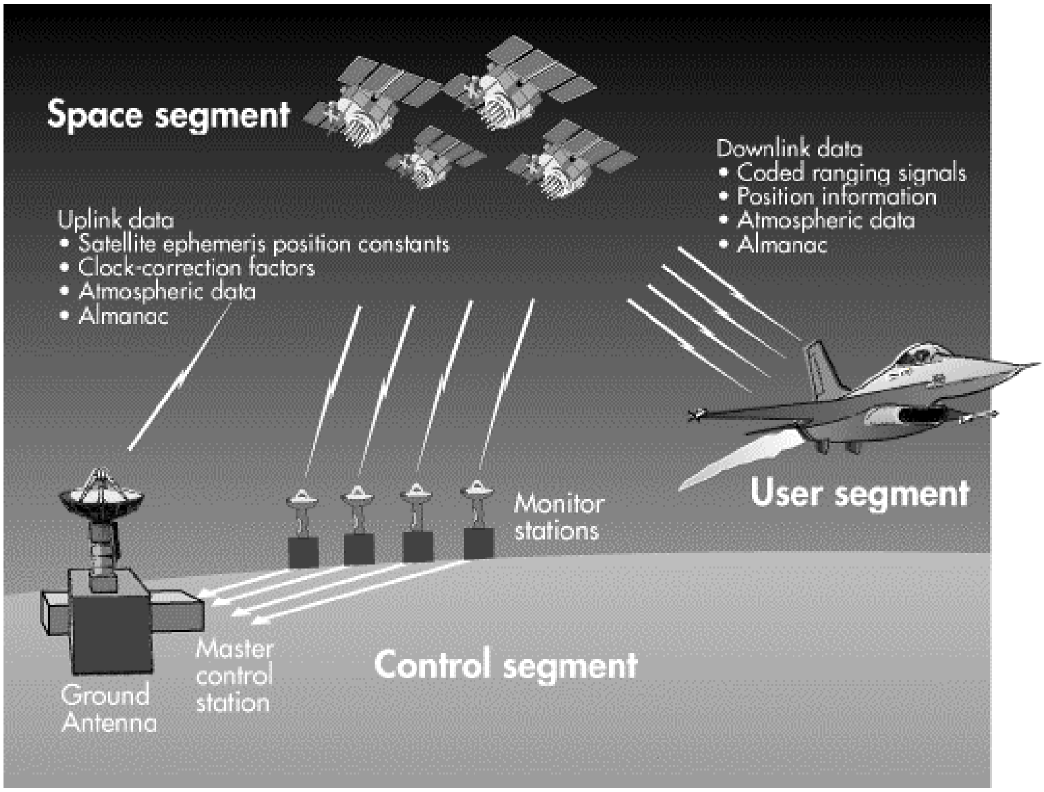


Figure 1 Global Positioning System (GPS)

The GPS positioning accuracy for military users is nominally 16 meters, while accuracy for civilian users is nominally 100m. Military users can access the encrypted Precise Positioning Service (PPS) which provides pseudorange measurements on two frequencies (L1 and L2), while civilian users are limited to the clear access Standard Positioning Service (SPS) which operates on the L1 signal only and is corrupted by Selective Availability (SA) errors to degrade the system accuracy. In the future, there are plans to discontinue the use of Selective Availability and to provide access to both the L2 frequency and possibly a third frequency (Lc) for civil users. With planned improvements to the GPS control segment to increase the accuracy of the GPS ephemeris and clock correction data, the GPS positioning accuracy is expected to improve to around 3 meters CEP[1].

The basic GPS service fails to meet the accuracy (the difference between the measured position at any given time to the actual or true position), availability (the ability of a system to be used for navigation whenever it is needed by the users, and its ability to provide that service throughout a flight operation), and integrity (the ability of a system to provide timely warnings to users or to shut itself down when it should not be used for navigation) requirements critical to safety of flight.

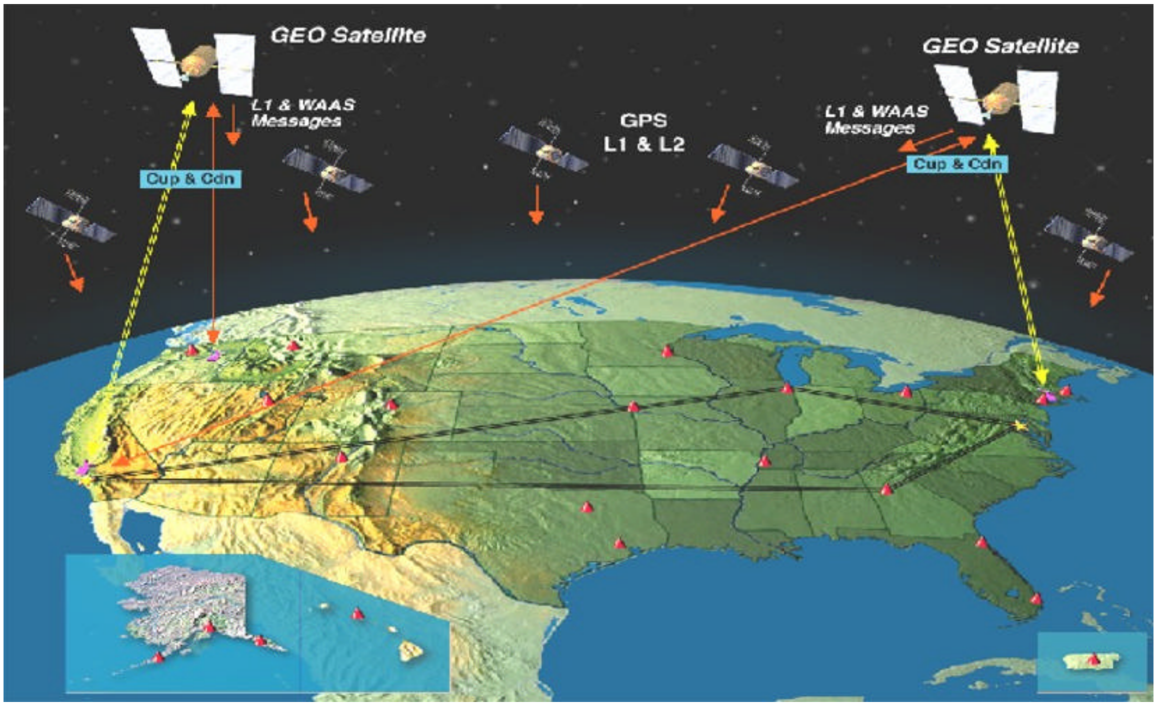


Figure 2 Wide Area Augmentation System (WAAS)

In order to meet these requirements the Federal Aviation Administration (FAA) is developing a space-based augmentation to GPS, the Wide Area Augmentation System or WAAS. WAAS is a safety-critical navigation system which improves the accuracy, integrity, and availability of the basic GPS signals. This system will allow GPS to be used as a primary means of navigation for enroute travel and non-precision approaches in the U.S., as well as for Category I approaches to selected airports throughout the nation. The wide area of coverage for this system includes the entire United States and some outlying areas such as Canada and Mexico.

The FAA's GPS Product Team is collaborating with international agencies who are also developing satellite-based augmentation systems (SBASs) to promote the goal of a single integrated Global Navigation Satellite System (GNSS). Both the European Space Agency and the Japanese Civil Aviation Authority are developing compatible augmentations systems that will shortly be available, providing global GPS augmentation coverage.

The FAA's WAAS architecture is based on a network of approximately 25 ground reference stations that covers a very large service area, as illustrated in Figure 2. Signals from GPS satellites are received by wide area ground reference stations (WRSs). Each of these precisely surveyed reference stations receives GPS signals and determines if any errors exist. These WRSs are linked to form the U.S. WAAS network. Each WRS in the network relays the data to the wide area master station (WMS) where correction information is computed. The WMS calculates correction algorithms and assesses the integrity of the system. A wide area differential GPS (WADGPS) correction message is prepared and uplinked to a GEO via a ground uplink system (GUS). The message is then broadcast on the same frequency as GPS (L1, 1575.42MHz) to receivers that are operating within the broadcast coverage area of the WAAS. The communications satellites also act as additional navigation satellites, thus providing additional navigation signals for position determination.

The WAAS will improve basic GPS accuracy to approximately 7 meters vertically and horizontally. Test data collected by Stanford University (see Figure 3) shows that the typical navigation errors when using the WADGPS broadcast corrections are less than 0.67 meters (2 feet).

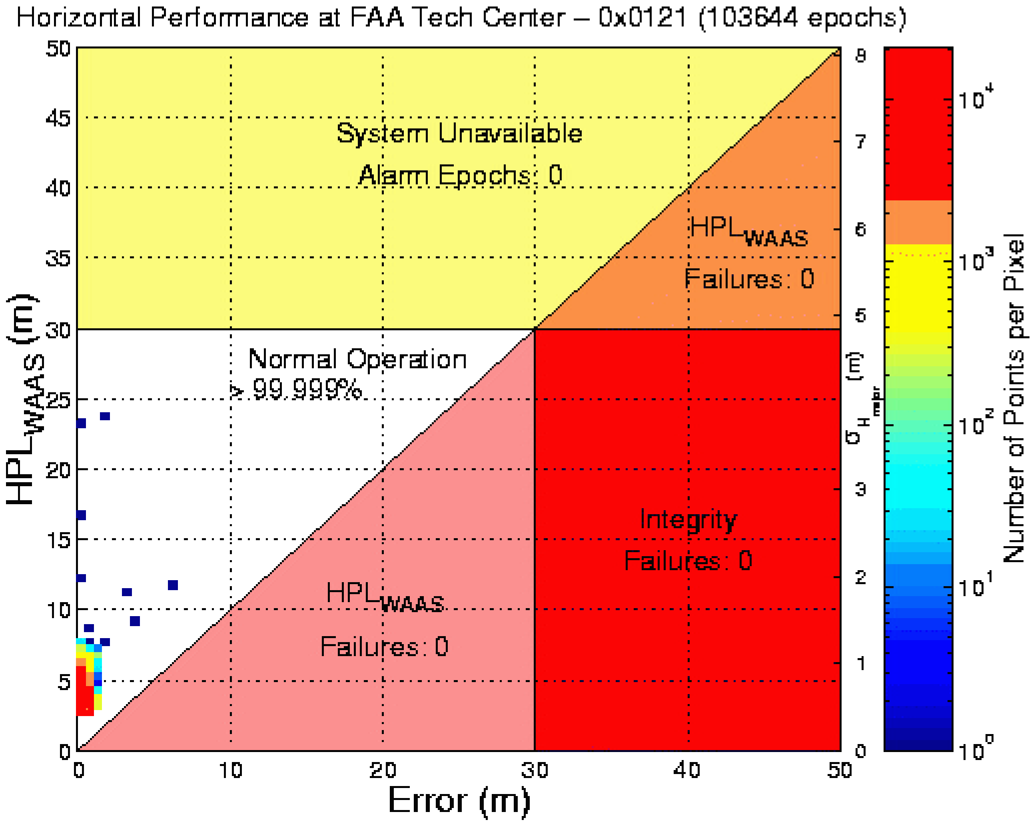
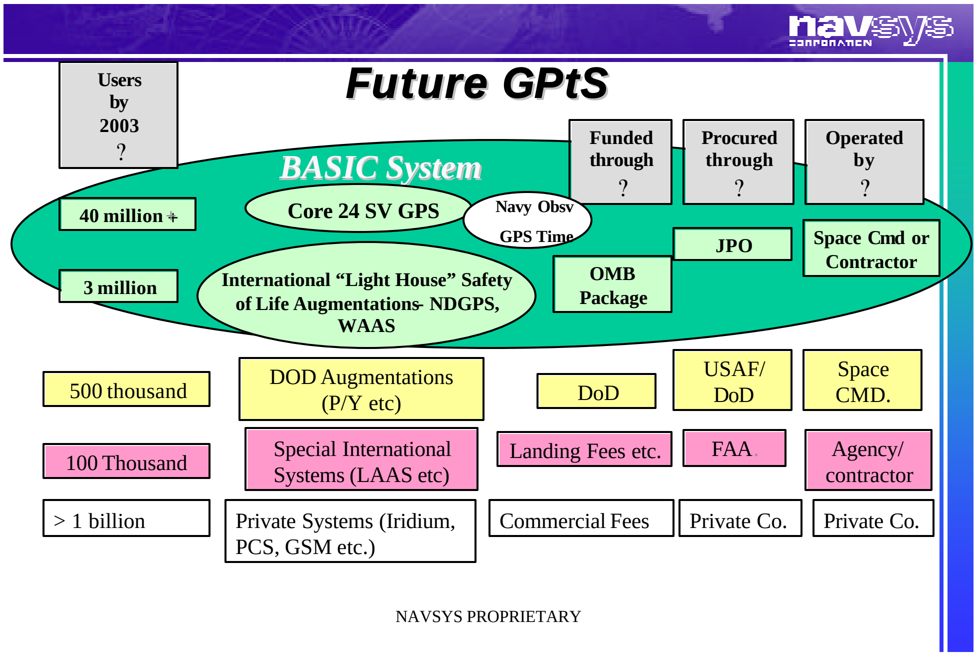


Figure 3 WAAS Demonstrated Performance

Since the WADGPS corrections are divided into the core GPS system error components, including satellite clock and ephemeris errors and ionospheric corrections[2], they can be applied equally well for spacecraft as well as aircraft navigation. The spacecraft GPS user equipment must be capable of receiving the corrections and applying only the error components that affect the navigation accuracy at the orbital altitude at which the spacecraft is operating.

GLOBAL POSITIONING AND TIMING SERVICE

The concept of a Global Positioning and Timing Service (GPtS) has been developed by the GPS-III Independent Review Team (IRT), which was chartered to provide strategic direction to the Air Force for a next generation satellite navigation service. The GPtS architecture proposes a networked approach that provides enhanced global services using an integrated system-of-systems architecture, coupling signals -in-space from GPS and other signal sources. As shown in Figure 4, this architecture relies on the core GPS constellation to provide the basic system capabilities and space based augmentation services, provide nationally and internationally to meet civil radionavigation requirements. Growth capability for further enhancements is also envisioned through the introduction of military augmentation systems, for example pseudolites to provide A/J protection in theater. Other local augmentation systems, such as the Local Area Augmentation System (LAAS) and Joint Precision Approach and Landing System (JPALS) are also considered to be part of the over all GPtS architecture providing precision approach and landing services. Digital communication services, such as the Personal Communication System (PCS), and mobile satellite services such as Iridium also provide basic timing information which can be used to provide radiolocation services, if tied back to a common time and geolocation standard. The GPtS architecture provides the foundation for these services to be linked together in a seamless fashion to provide a robust, precise global grid for distribution of positioning and timing services.



Future GPtS

BASIC System

Users by 2003 ?		Funded through ?	Procured through ?	Operated by ?
40 million +	Core 24 SV GPS Navy Obsv GPS Time	OMB Package	JPO	Space Cmd or Contractor
3 million	International "Light House" Safety of Life Augmentations- NDGPS, WAAS			
500 thousand	DOD Augmentations (P/Y etc)	DoD	USAF/ DoD	Space CMD.
100 Thousand	Special International Systems (LAAS etc)	Landing Fees etc.	FAA	Agency/ contractor
> 1 billion	Private Systems (Iridium, PCS, GSM etc.)	Commercial Fees	Private Co.	Private Co.

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Figure 4 Future Vision of a Global Positioning and Timing Service

This systems-of-systems architecture faces a challenge in tightly synchronizing different networks of satellite constellations and terrestrial services to provide seamless service coverage. Currently there are no direct connections for synchronization between GPS and the augmentation systems being deployed. The internationally accepted time standard is Universal Coordinated Time (UTC). The GPS control segment currently maintains the GPS Master Clock to within 8 nanoseconds of UTC-USNO. The FAA's WAAS control segment also maintains WAAS Network Time (WNT) synchronized to UTC-USNO, but only to within around 20 nanoseconds. These time offsets between the systems are not apparent when only GPS or GPS+WAAS signals are used to compute a navigation solution, since the master clock error will be absorbed within the GPS receiver clock error. However, if signals are used from more than two systems (e.g. from GPS, WAAS and EGNOS for example), the offsets between the SBAS master clocks will cause errors in the navigation solutions. If the master clocks differ by only 1-nanosecond between these constellations, this will introduce 1 foot of error between the system observations.

The purpose of GPtS network interoperability standards is to allow the different SBAS systems to operate together in a seamless fashion. This will result in a robust global grid that promises the capability to significantly improve the level of services currently provided by the stand-alone GPS satellite constellation in terms of availability, coverage and performance. Time transfer techniques have been demonstrated that will allow synchronization between GPS and the SBAS master clocks to better than 1 nanosecond. The U.S. Naval Observatory is currently working on developing standards for distribution of time to allow different SBAS time standards to be synchronized in real-time to a common reference.

As illustrated in Figure 4, the GPtS network architecture can also be used to synchronize other signals, such as broadband communication broadcasts. This will allow pseudoranges to be observed from other satellite or terrestrial signals, such as mobile communication networks, further enhancing the GPtS coverage and availability.

BENEFITS OF GPtS APPLICATIONS FOR SPACE USERS

In the following section, some of the applications of GPtS for space users are described with the benefits provided by the current service and the future GPtS architecture envisioned which includes both GPS and multiple space based augmentation systems (SBAS).

Autonomous Orbit Operations

Low cost autonomous navigation, on board maneuver planning and autonomous constellation control all become feasible when GPtS is employed. Traditionally, spacecraft navigation has been accomplished on the ground through ranging and trajectory determination techniques. Planning and controlling the orbit of a single spacecraft from the ground is labor intensive, performing these functions on several spacecraft simultaneously is extremely complex and introduces an overwhelming ground personnel requirement.

The time, orbit, and attitude data obtained from GPS enables spacecraft system developers to accomplish autonomous orbit maneuver planning and autonomous stationkeeping maneuvers on board the spacecraft[3]. This results in a substantial reduction in mission operations costs.

The majority of GPS experiments to date have been performed at orbital altitudes below the GPS satellite constellation. In these orbits, there is good reception from the GPS satellites located above the spacecraft. When operating from orbital locations above the GPS spacecraft, the GPS signals can only be tracked from satellites that fall within the beam pattern transmitted by the GPS satellites. Early experimenters worked on the assumption that the GPS satellites could only be viewed from behind the earth, when the signals “grazed” past the earth’s surface, as illustrated in Figure 5.

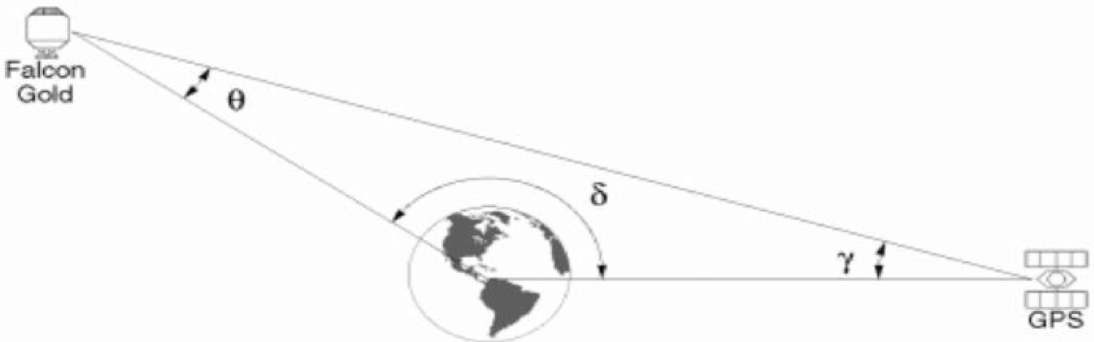

Figure 5 GPS Satellite Visibility

A later experiment showed that it was in fact possible to track the side lobes as well as the main lobe of the GPS antenna signals (see Figure 6), which significantly increases the visibility of the GPS satellites from space platforms. This experiment was performed by the Air Force on the Falcon Gold satellite using NAVSYS’ TIDGET GPS sensor, shown in Figure 7.

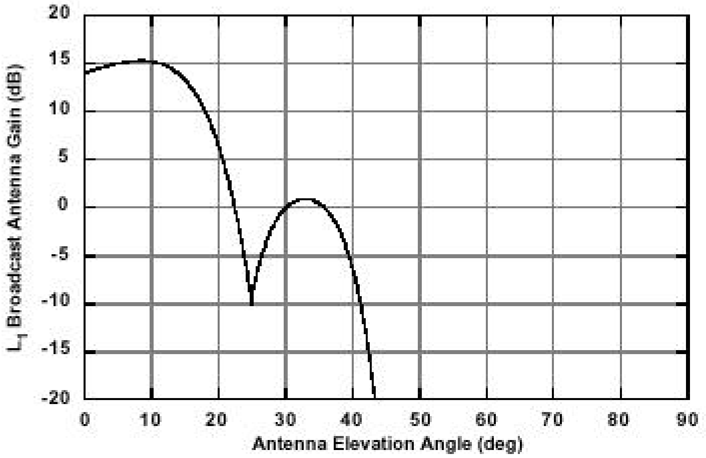

Figure 6 GPS II/II-A Gain Pattern

Figure 7 Falcon Gold Hardware

The TIDGET sensor collects snapshots of the GPS information and relays this to the ground for processing[4,5]. In the Falcon Gold experiment, the TIDGET sensor was used to provide orbit information for a Centaur geostationary orbit transfer vehicle. In Figure 8, data collected from this experiment is shown which proved the capability to track the GPS satellites throughout all phases of the transfer orbit (the periods of the orbit where GPS data was not downlinked were due only to the geometry of the telemetry system not the on-board sensor).

The Falcon Gold experiment showed that GPS signals could be received from Low Earth Orbit (LEO) to Geostationary Earth Orbit (GEO) orbits[6]. This capability opens up the opportunity for GPS to be used to provide orbit information in support of orbit entry operations for LEO, Highly Eccentric Orbits (HEO) or GEO satellites. As discussed later in this paper, a specifically designed GPS receiver and antenna system is needed to take full advantage of the signals provided by both the core GPS constellation and the SBAS geostationary satellites

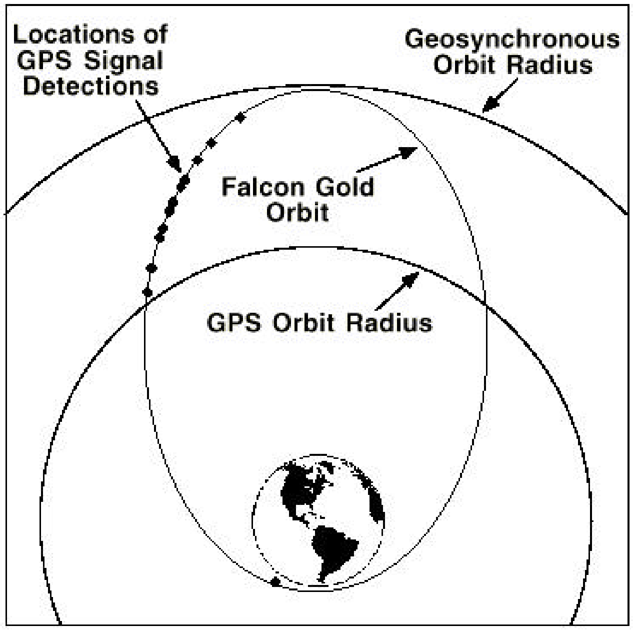

Figure 8 Falcon Gold GPS Signal Reception

Launch and Orbit Entry

"Cost-effectiveness" plays an important role when planning a space mission. Both commercial and Air Force space systems have a requirement for accurate, reliable satellite position determination during launch and in-orbit. The position of a satellite during launch is currently tracked by ground monitor stations using an S-band signal. Low-cost tracking systems can help to reduce the overall mission costs. The Global Positioning System (GPS) is an ideal source for providing accurate positioning data, which could then be down-linked to the ground monitor station.

Since during launch and orbit entry, the satellite can be spinning at up to 60 revolutions/minute, this places a challenge on the antenna system design to enable continuous tracking of the GPS satellite signals. Current generation GPS user equipment is unable to deal with rapidly changing satellite visbility. To support reliable operations during orbit entry and maneuvers, all-around (4? steridian) visibility is a requirement for next generation GPS user equipment. As is discussed later in this paper, advances in low cost, digital, GPS phased array technology promise a solution for this problem.

Attitude Determination

There has been great interest in the community for many years in using GPS for attitude control of a space vehicle7. The impetus behind these activities is the expense of the current sensors flown in space to provide attitude control. For precision applications, star trackers are the preferred solution, however, these cost between $0.5 to $1M each. For a triply redundant system, this sensor component alone adds roughly $2-3M to the expense of a satellite.

There are two fundamental methods of using GPS to observe attitude information. Both are illustrated in Figure 9 and Figure 10. In the first method, multiple GPS antennas are used in an interferometric mode of operation. Using this method, carrier phase observations from two or more antennas are differenced to observe the attitude of the antenna baseline. The phase difference between these antennas then observes the relative attitude. The accuracy of this method of attitude observation is a function of the precision of the relative carrier phase observations. The attitude accuracy can be roughly approximated by the following equation (see Eq. (1)) where ?? is the carrier phase observation error and ? L is the baseline between the antenna elements.

$$\tilde{?} \; ? \; \frac{??}{?L} \tag{1}$$

This method of attitude control is used by the Loral GLOBALSTAR satellites[8]. This uses a four antenna solution with a GPS receiver that multiplexes between these antennas to observe the relative carrier phase (see Figure 10).

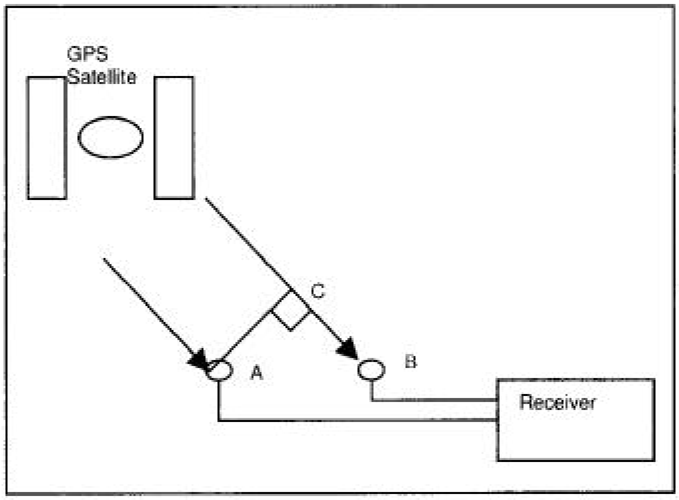

Figure 9 GPS Interferometric Attitude Determination

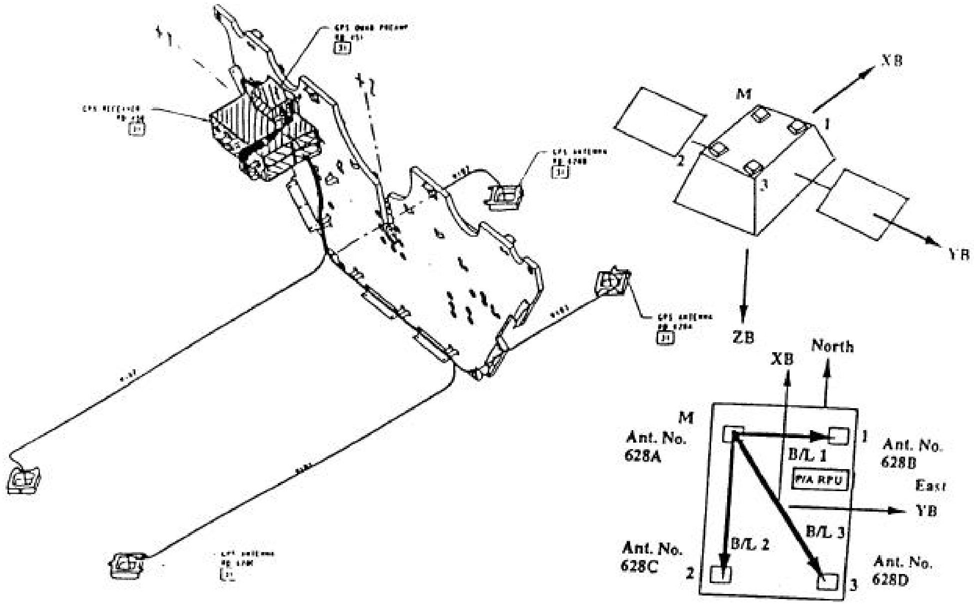

Figure 10 Globalstar GPS Tensor Installation

An alternative method of attitude determination has been demonstrated for spinning satellites where a single antenna element is used. In this implementation, shown in Figure 11 the observed cyclic variation in the Doppler offset on the GPS satellite signals is used to estimate the current attitude. The accuracy of this method can be approximated by the following equation (see Eq. (2)). This technique provides a rough estimate of attitude, with accuracy on the order of 2-3 degrees.

$$\tilde{?} \; ? \; \frac{?f}{? \, ? \, L} \qquad \textbf{(2)}$$

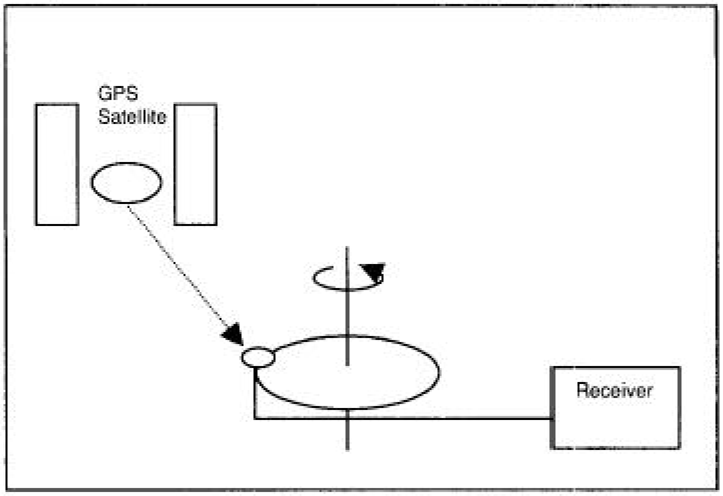

Figure 11 GPS Doppler Attitude Determination

To date, the best performance that has been achieved using GPS for satellite attitude determination is on the order of 1-2 degrees using GPS interferometric techniques. The limit on this performance has been shown to be caused by multipath signals reflected from different parts of the spacecraft structure. Surfaces, such as solar panels, have proven to be highly reflective for signals in the L-band range, which results in the GPS antennas receiving multiple signals from close-in surfaces from each satellite tracked. This results in significant phase errors on the GPS observations, which in turn corrupt the attitude information provided by a GPS interferometer. In Figure 12, the multipath errors from a Geosat Follow-On (GFO) satellite mock-up are shown illustrating this problem. This test data illustrating this problem was collected by Ball Aerospace on their antenna test range. A signal source was tracked from a test fixture rotated over 360 degrees in azimuth and 90 degrees in elevation and the observed carrier phase was compared with the ideal carrier phase based on the satellite's attitude. The residual error between these two data sources is plotted in Figure 12 showing the effect of multipath on an actual satellite vehicle in a simulated space environment. This test data observed a peak carrier phase error due to multipath of 19.7 degrees (1 cm). Over a 1-meter baseline this would result in an attitude error of roughly 10 mrad or 1 degree.

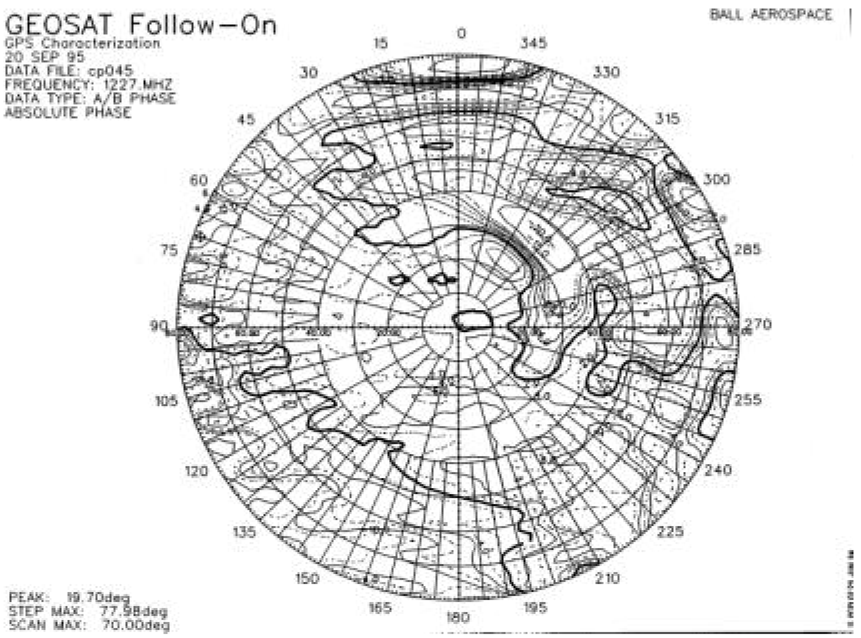

Figure 12 GFO Multipath Test Data

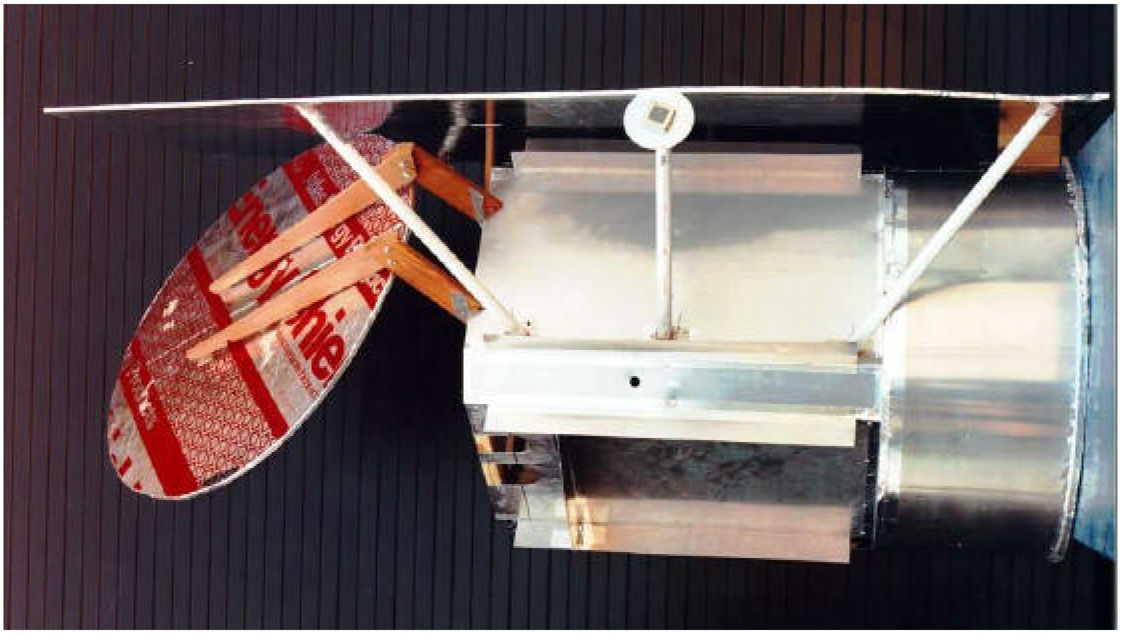

Figure 13 GEOSAT Follow-on Satellite Mock-Up

As is described later in this paper, recent advances in digital phased array antenna technology now enable multipath errors to be reduced by using digital beamforming to provide antenna gain towards the desired satellite signal. This technique shows promise for achieving high accuracy attitude determination for space applications, with performance approaching that possible today using star trackers.

Formation Flying

Precise relative positioning between spacecraft is essential for future missions which will involve formation flying of clusters of small satellites. This can be achieved by using relative kinematic positioning techniques using the GPS carrier phase signals. Relative Kinematic GPS positioning (RKGPS) is performed by observing the carrier phase difference on the GPS observations between the two satellites of interest. This phase difference observes the relative separation between the satellites, with an offset caused by an uncertainty in the number of carrier cycles in the phase observations (see Eq. 3).

(3)

$$CPH_1 \; ? \; CPH_2 \; ? \; R_1 \; ? \; R_2 \; ? \; b_1 \; ? \; b_2 \; ? \; ?N? \; ? \; \underline{1}^T \, ?\underline{x}_1 \; ? \; \underline{x}_2 \, ?? \; b_1 \; ? \; b_2 \; ? \; ?N?$$

where CPH is the observed carrier phase on each satellite (1 and 2), R is the range to the satellite, b is the receiver clock bias, ? is the L1 wavelength, ?? is the carrier cycle ambiguity; $\underline{1}$ is the line of sight vector of the satellite, $\underline{x}$ 1- $\underline{x}$ 2 is the relative position between the two satellites.

Estimation techniques involving filtering of the pseudorange observations and elimination using redundant observations can be used to deduce the integer ambiguities between the satellite observations. The relative carrier phase observations can then be used to solve for the precise relative position of the satellites, in real-time. Test data has demonstrated that accuracies of better than 1 cm can be achieved, if multipath errors can be reduced.[9]

Precise Time Transfer

For many space applications, precise time accuracy is also needed. This includes some of the experimental payloads planned for the International Space Station (ISS) and applications involving formation flying to coordinate observations between satellites or create stereo imaging.

The basic GPS standard positioning service will provide time accuracy to better than a microsecond. With the planned accuracy improvements to the GPS control segment, the GPS signals will be able to support time synchronization to within 20 nanoseconds [1]. When using signals from the space based augmentation systems, such as WAAS or EGNOS, the time accuracy can be provided to within 20 nanoseconds today. As discussed previously, tighter synchronization between these systems and the UTC time reference is also possible, enabling time transfer to within 1 nanosecond to be supported in real-time from the SBAS WADGPS broadcast corrections.

GPS carrier phase measurements provide the potential for much improved precision in time and frequency transfer [10,11,12]. Time-Transfer errors approaching 100 picosecond (ps) are expected using this approach. The main reason for this expected improvement is due to the GPS carrier phase measurement accuracy being 100 to 1000 times better than the code based pseudorange measurements. Typical carrier phase measurement noise can be on the order of ten picoseconds (ps) whereas the code measurement noise can be as high as ten nanoseconds (ns). Multipath errors are also much smaller on the carrier phase observations than on the code-based pseudorange measurements.

ADVANCED GPS RECEIVER DESIGN FOR SPACE APPLICATIONS

From the previous section, an ideal GPS receiver for space applications would have the following properties.

1. Directive gain towards the GPS satellites to allow tracking of both the main-lobes and the side-lobes of the GPS signals
2. 4? steridian field of view to assure continued operation when the spacecraft is tumbling or spinning
3. Multipath elimination for precise attitude estimation, positioning and timing
4. Coherent signal reception from multiple antenna elements to allow attitude estimation
5. Reception of both the GPS satellites and SBAS signals in space to increase accuracy, reliability and availability

These properties can now be achieved for a space-based GPS receiver by leveraging recent advances in digital phased array technology.

High-Gain Advanced GPS Receiver

In Figure 14, a 16-element array is shown designed to operate with a commercial digital GPS receiver, the High-gain Advanced GPS Receiver (HAGR). This uses digital spatial signal processing to combine the GPS signals from as many as 16 antennas and create a multi-beam antenna pattern to apply gain to up to twelve GPS satellites simultaneously.

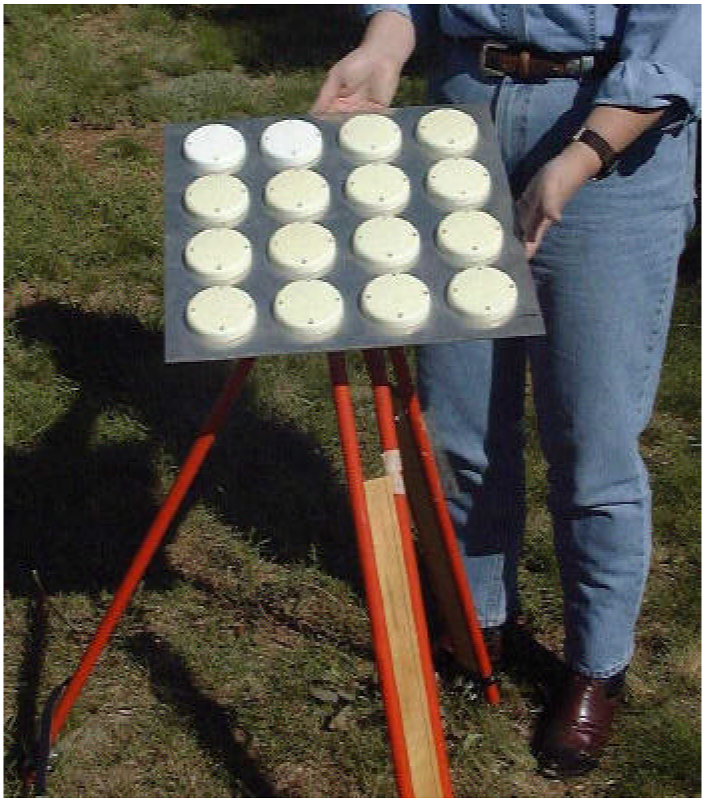

Figure 14 HAGR 16-element antenna array

The performance specifications for the HAGR for a 16-element, L1 C/A code version of this product are included in reference 13. Currently an L1/L2 Precise Position System (PPS) version of the HAGR (the HAGR-200) is also in development.

The HAGR system architecture is shown in Figure 15. The signal from each antenna element is digitized using a Digital Front-End (DFE). The bank of digital signals is then processed by the HAGR digital-beam-steering card to create a composite digital beam-steered signal input for each of the receiver channels.

If attitude data (pitch, roll, yaw) is provided from an inertial navigation system or attitude sensor, the HAGR will operate while the antenna is in motion[14].

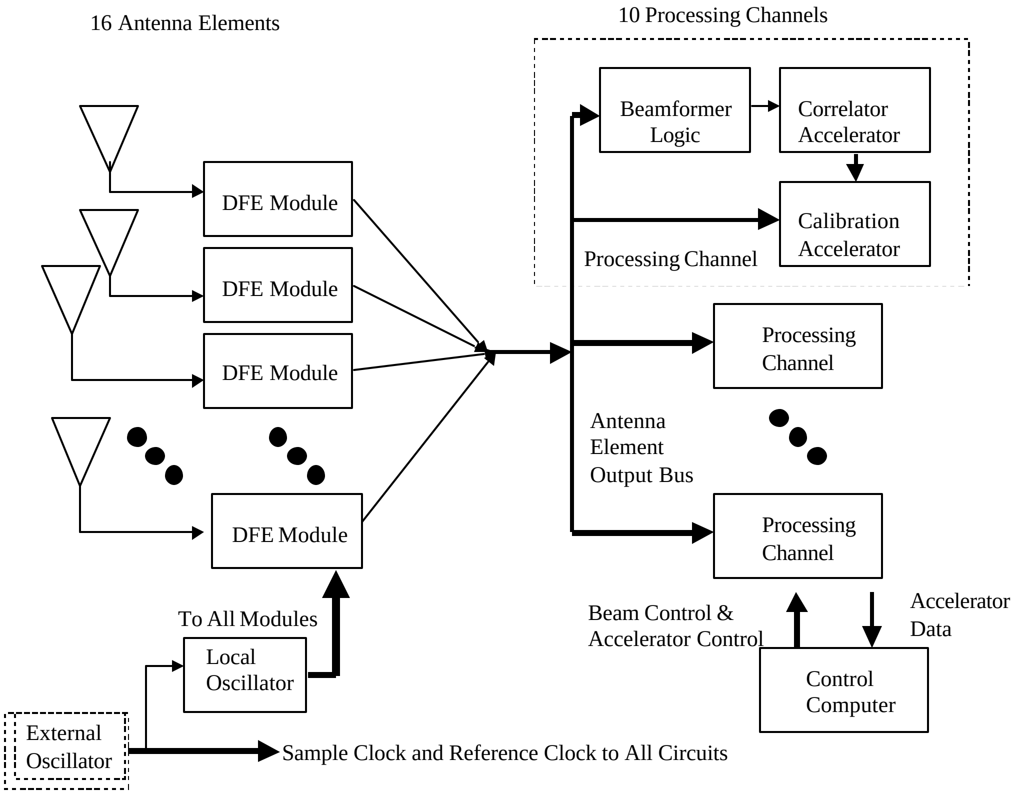

Figure 15 HAGR System Block Diagram

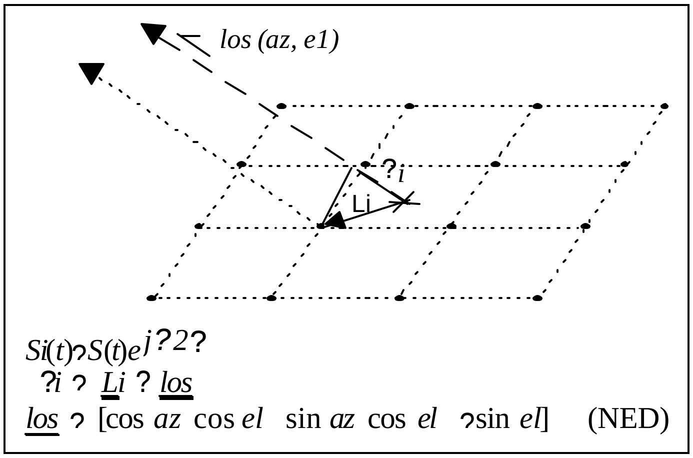

Figure 16 Beam forming satellite geometry

High-gain Benefits for Space Applications

The digital beam forming provides significant benefits in improving the measurement accuracy due to the narrow beam antenna pattern directed at each satellite tracked. As shown in Figure 17, a 16-element array will provide up to 12 dB of additional gain on each satellite tracked.

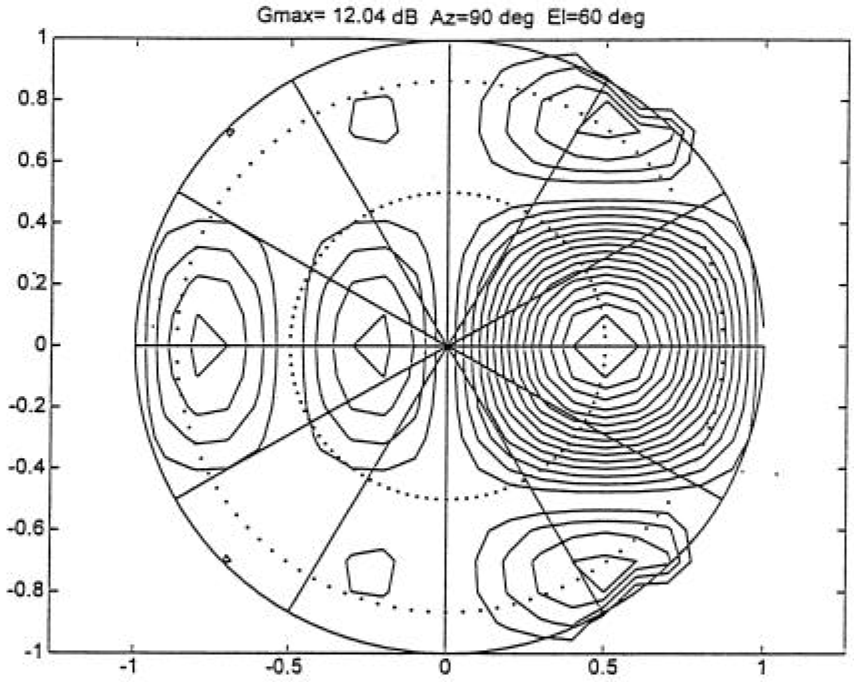

Figure 17 16-element array composite beam pattern

The HAGR digital beam forming has the effect of also increasing the signal-to-noise ratio from the GPS satellites. In Figure 18 to Figure 20, performance data is shown from a HAGR unit compared against two conventional GPS reference receivers. From these plots, it can be seen that the HAGR C/N_0 is generally 10 dB higher than the reference receiver, demonstrating the effect of the gain from the digital beam forming. This is important when tracking the GPS satellites from geostationary orbit, or when tracking the GPS sidelobes. As shown in Figure 5, the distance to the GPS satellites viewed behind the earth is roughly 3 times the normal distance. This means that the signal power received will be roughly 10 dB lower as the receiver power decreases proportional to the square of the distance to the signal source. Also, as shown in Figure 6, the sidelobes are as much as 15 dB weaker than the main-lobes. The additional gain from the digital antenna array is therefore extremely beneficial in allowing the weaker GPS signals to be tracked from orbits above the GPS constellation.

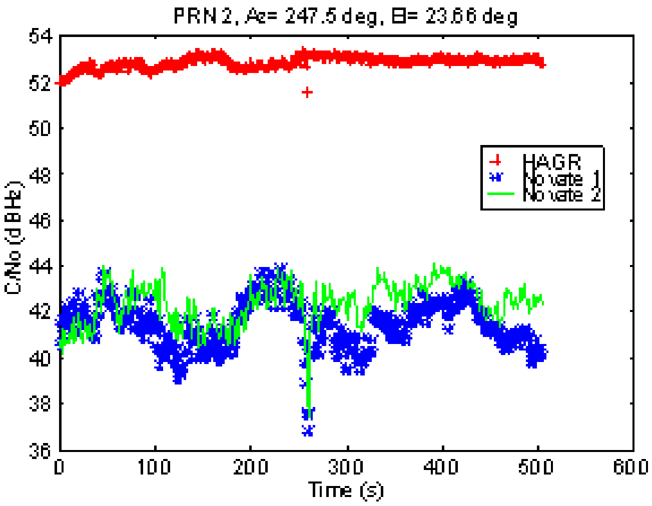

Figure 18 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 2

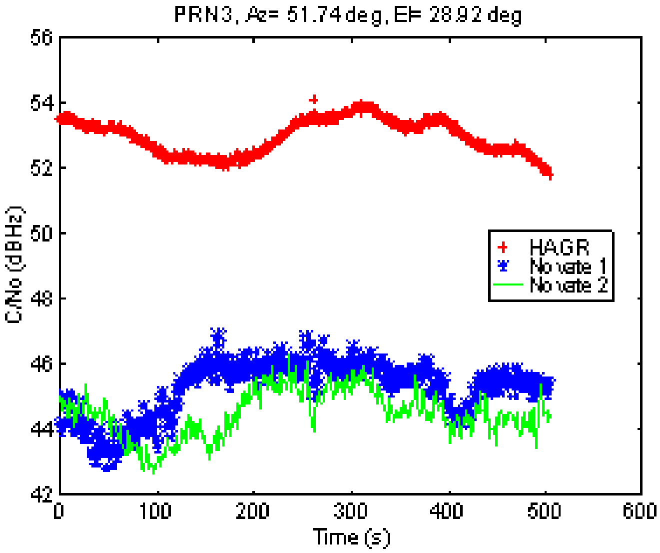

Figure 19 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 3

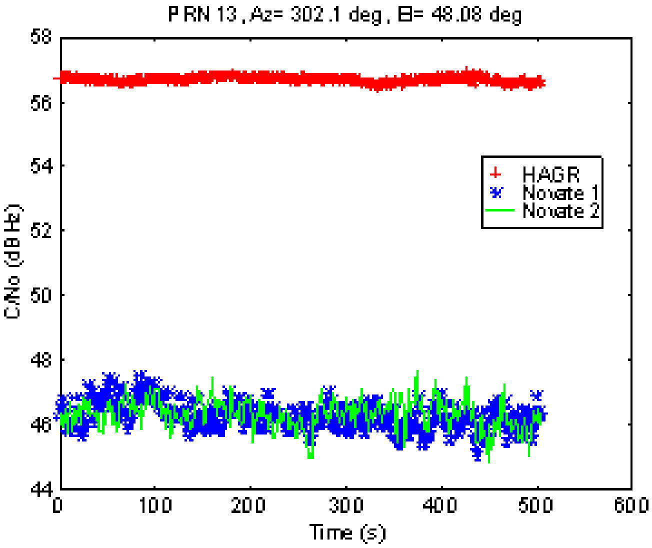

Figure 20 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 13

4? Steridian Field of View

A test fixture was assembled to show the capability of the HAGR to provide all-round (4? Steridian) visibility. Four antenna elements were assembled around a solid body, as shown in Figure 21, and the digital beamforming algorithms were reprogrammed to account for this 3-dimensional geometry.

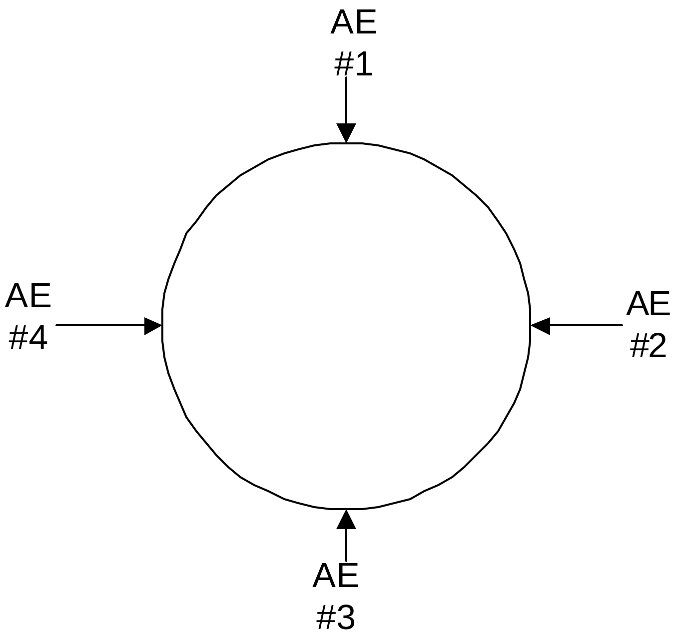

Figure 21 4-Element All-around Visibility Antenna Testing

In Figure 22 a sky plot is shown with the locations of the GPS satellites tracked during the test. In Figure 23 the satellite PRNs that were tracked during the test are plotted against time and in Table 1 the signal-to-noise ratios of the satellites tracked during the test are listed. From this test data, it is evident that the 3-D beam-forming is providing all-around visibility. All of the satellites above the horizon were tracked with the exception of satellites 8 and 10 which were not selected by the 8-channel GPS receiver. The signal-to-noise ratio is also comparable with normal GPS operation indicating no noticeable degradation from the 4? steridian signal combining.

Table 1
ALL-AROUND SATELLITE VISIBILITY TEST DATA SUMMARY

PRN	1	2	3	7	8	10	11	13	15	18	19	27	31
AZ	155	245	55	205	305	311	125	294	98	189	341	305	100
EL	23	19	31	13	13	10	10	51	12	60	72	45	53
C/N0	42	44	48	39	-	-	37	45	43	47	44	46	47

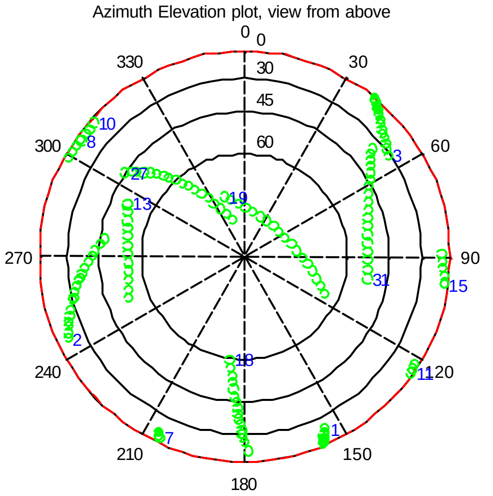

Figure 22 Skyplot of 3-D Beam-steering Satellite Visibility

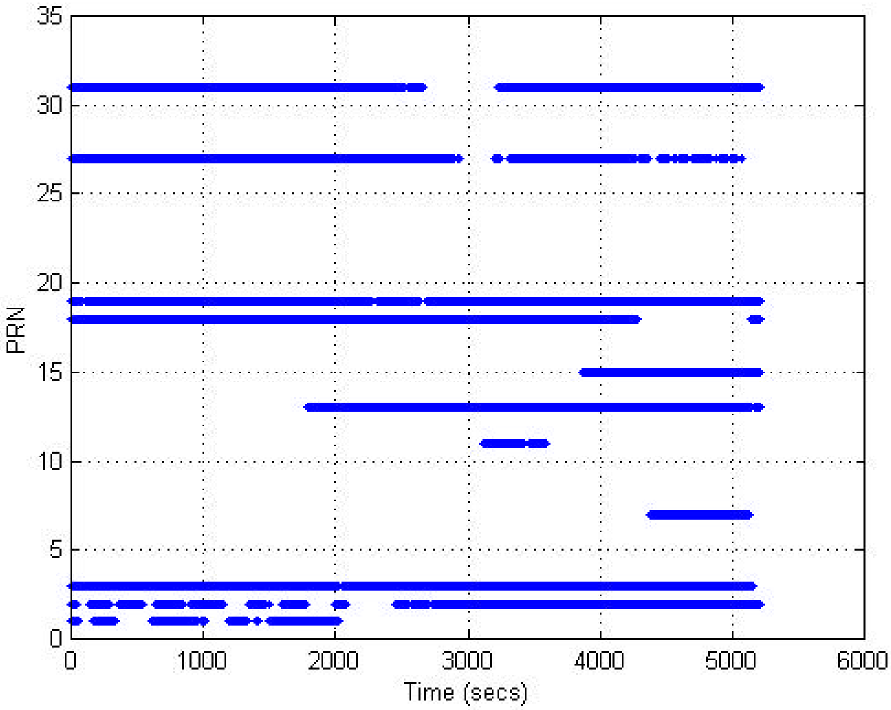

Figure 23 All-around Visibility Tests - SVs tracked

Improved Measurement Accuracy

The increased gain also results in improved pseudorange and carrier phase tracking performance, and the directionality of the beam-steering antenna array reduces the effect of multipath on the solution. In Table 2, the short term noise is listed for each of the two HAGR units tested. The gain provided by the beam steering has maintained the signal-to-noise generally above 50 dB-Hz, providing sub-meter level short term noise on the pseudorange performance. This increased accuracy also reduces the time needed to resolve the carrier cycle ambiguities that are needed for computing a kinematic GPS or relative kinematic navigation solution.

Table 2
HAGR PR NOISE PERFORMANCE DATA

SVID	**AZ**	**EL**	**C/N0 1**	$?_{PR}$	**C/N0 2**	$?_{PR}$
3	**285**	**36**	**49**	**0.89**	**51**	**0.46**
6	**173**	**18**	**44**	**0.60**	**44**	**0.48**
8	**134**	**21**	**48**	**0.46**	**45**	**1.05**
9	**90**	**28**	**50**	**0.50**	**48**	**0.77**
17	**113**	**57**	**55**	**0.21**	**55**	**0.19**
21	**291**	**50**	**54**	**0.26**	**53**	**0.31**
23	**21**	**66**	**55**	**0.35**	**54**	**0.47**
26	**43**	**13**	**49**	**0.33**	**52**	**0.27**
29	**212**	**40**	**52**	**0.38**	**53**	**0.36**

Kinematic GPS Performance

The kinematic performance of the HAGR antennas was tested by setting each of the antennas on two survey marks separated about 1.5 meter apart. Figure 24 and Figure 25 show the processing results. These test results show that the kinematic GPS positioning error achieved a standard deviation of 3 mm (1-sigma) in the north and east directions and 7 mm (1-sigma) vertically. This is consistent with a carrier phase measurement accuracy of 3 mm (1-sigma). These results also show that the multipath errors on the carrier phase are maintained on the order of a few millimeters by the HAGR beam forming. This will also improve the attitude determination accuracy when using interferometric techniques to better than 1 degree.

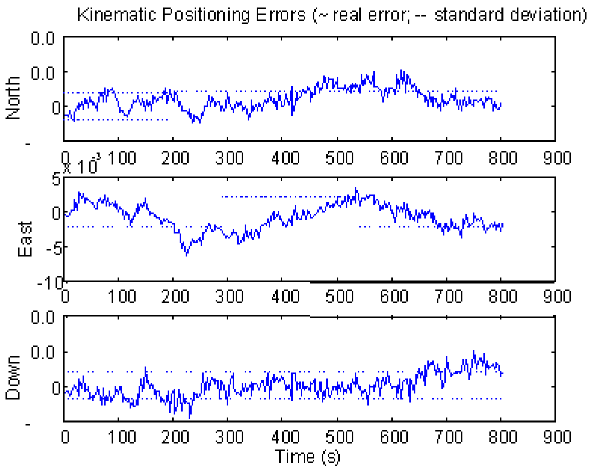

Figure 24 KGPS positioning errors

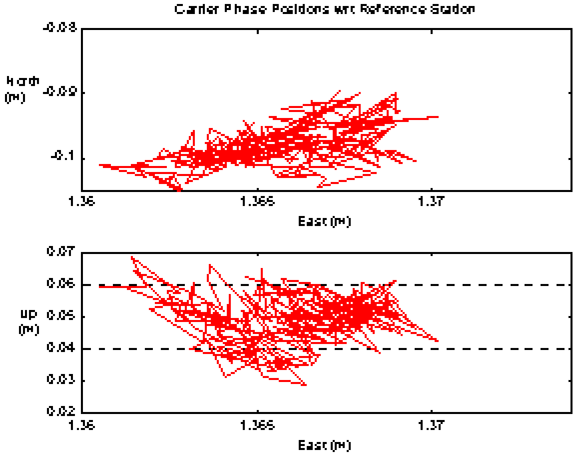

Figure 25 KGPS positioning error

High Accuracy Time Transfer

To test the time transfer performance of the HAGR receiver, two receivers were set up to operate using a common 10 MHz time reference and also a common antenna[15]. The raw carrier phase difference was computed between the two receivers for each satellite tracked. This was corrected for the integer ambiguity offset only. The residual error between two data sets for each satellite is plotted in Figure 26 and Figure 27. The HAGR was power-cycled between these two data sets. As can be seen, both data sets observed a common bias between the units of around 0.02 cycles and has a standard deviation of the carrier phase difference residual of 16 psecs. Each GPS satellite observation has a common offset between the units of 14 psecs +/- 3 psecs, indicating that the HAGR units should be able to be calibrated to this level by averaging the satellite observations.

Table 3
CARRIER PHASETIME DIFFERENCE ACCURACY

SVID	1	14	16	18	22	25
Mean offset (cycles)	0.022	0.020	0.022	0.026	0.022	0.020
Mean offset (psec)	14.3	12.4	14.1	16.8	13.7	12.4
Std Dev (psec)	15.1	17.6	16.3	16.4	15.4	9.2

This testing indicates that the HAGR units can provide carrier phase observations consistent with a time transfer performance of 16 psecs 1-sigma, post-calibration.

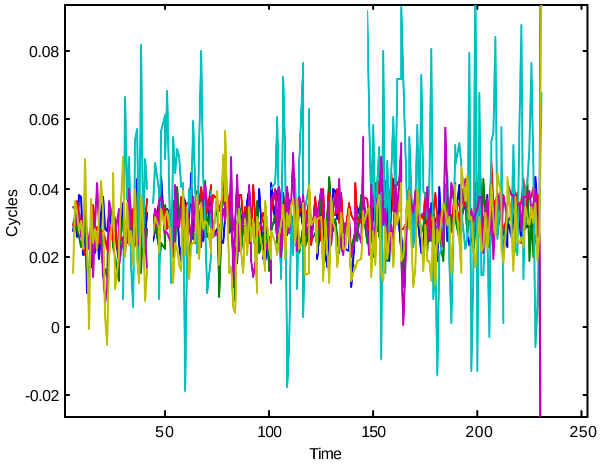

Figure 26 Unit1-Unit2 Time Offset (cycles) Time Set 1

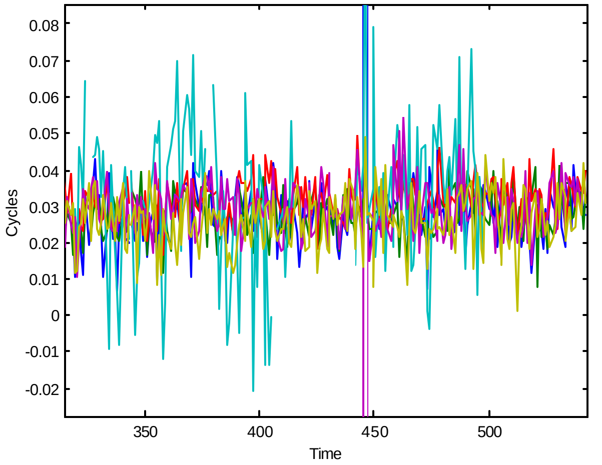

Figure 27 Unit1-Unit2 Time Offset (cycles) Data Set 4

CONCLUSION

In conclusion, advances in receiver technology and space-based augmentation systems will be able to provide enhanced Global Positioning and Timing Services (GPtS) for space applications. Based on the systems and hardware described in this paper, that are currently being developed, the following services for future space users are envisioned.

?? Precise real-time navigation (<1 m) using GPS and WAAS corrections to support autonomous orbit operations and position determination during launch and orbit entry

?? Reliable, full-sky (4? steridian) signal reception for spacecraft operating at LEO, HEO and GEO orbits using GPS receivers with digital beam-steering antenna arrays

?? Real-time attitude determination (<1 degree) using digital beam-steering antenna arrays for multipath minimization and interferometric attitude observation

?? Precise relative positioning (<1 cm) for formation flying of satellites using kinematic GPS positioning techniques

?? Precise real-time time synchronization using GPS and WAAS corrections (< 20 nanosecond) and high accuracy time transfer (<100 picosecs) using carrier phase observations.

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