An Array of Digital Antenna Elements for Mitigation of Multipath for Carrier Landings

Kenn Gold, Alison Brown, *NAVSYS Corporation*

BIOGRAPHY

Kenn Gold is the Chief Technology Officer at NAVSYS Corporation. He previously was the Product Area Manager for the Advanced Systems and Simulation Tools group, and led the development of the Advanced GPS Hybrid Simulator. Prior to coming to NAVSYS, he was a Professional Research Associate at the Colorado Center for Astrodynamics Research. He received his PhD in Aerospace Engineering from CU Boulder in 1994.

Alison Brown is the President and Chief Executive Officer of NAVSYS Corporation. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge University. In 1986, she founded NAVSYS Corporation. Currently, she is a Member of the Interagency GPS Executive Board Independent Advisory Team (IGEB IAT), and an Editor of GPS World Magazine. She is an ION Fellow.

ABSTRACT

NAVSYS has developed a new Digital Antenna Element design for integration with a Controlled Reception Pattern Antenna (CRPA) which offers significant advantages over conventional Digital Antenna Electronics for high integrity GPS applications such as the Joint Precision Approach and Landing System (JPALS). Instead of performing spatial processing within the Digital Antenna Electronics, the Digital Antenna Elements each output the raw sampled digital data from each of the CRPA antenna elements. This allows the GPS receiver to perform embedded spatial integrity monitoring and optimize the spatial processing for each internal receiver channel to maximize the signal/jamming ration (S/J) or to minimize the signal/multipath levels (S/M).

This paper describes the Digital Antenna Element and Receiver design and includes test results collected onboard the USS Truman to evaluate the improvements possible using digital beam forming for multipath mitigation in this environment.

INTRODUCTION

The Joint Precision Approach and Landing (JPALS) Shipboard Relative GPS Concept (SRGPS) is illustrated in Figure 1. The goal of the SRGPS program is to provide a GPS-based system capable of automatically landing an aircraft on a moving carrier under all sea and weather conditions considered feasible for shipboard landings. The presently utilized Aircraft Carrier Landing System (ACLS) is a radar-based system which was developed more than 30 years ago and has a number of limitations that make the system inadequate to meet present and future ship-based automatic landing system requirements. The goal of SRGPS is to monitor and control up to 100 aircraft simultaneously throughout a range of 200 nautical miles from the landing site[1]. Integrity monitoring is especially important for the last 20 nm of an approach, and accuracy requirements are 30 cm 3-D 95% of the time.

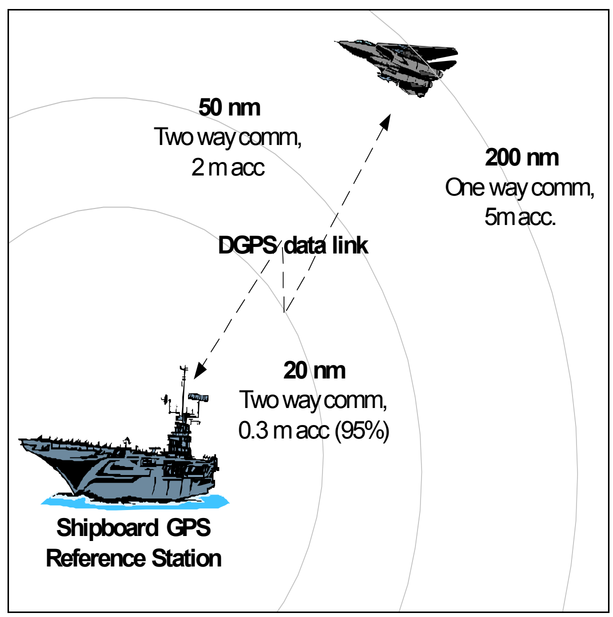

Figure 1 JPALS Shipboard Concept

The SRGPS architecture provides a precision approach and landing system capability for shipboard operations equivalent to local differential GPS systems used ashore, such as the Federal Aviation Administration's (FAA's) Local Area Augmentation System (LAAS). A relative navigation approach is used for SRGPS with the "reference station" installed on a ship moving through the water and pitching, rolling, and yawing around its center of motion. In addition, the ship's touchdown point may

Proceedings of ION 2005 National Technical Meeting, San Diego, CA, January 2005.

translate up/down (heave), side to side (sway), and fore and aft (surge). These more stringent requirements necessitate the need for integrity monitoring to assure that the GPS data used in the solutions is not corrupted.

INTEGRITY MONITORING CONCEPT

Next generation GPS systems designed for JPALS and SRGPS operations are expected to have performance advantages over previous generation user equipment (UE). While these designs will meet the objective of high anti-jam (A/J), high accuracy performance, they must also implement integrity monitoring to be able to support precision approach and landing. Some of the elements of a high A/J aircraft receiver and the integrity monitoring components that must be addressed are illustrated in Figure 2. The shaded boxes in this figure highlight the areas of focus for NAVSYS integrity monitoring efforts.

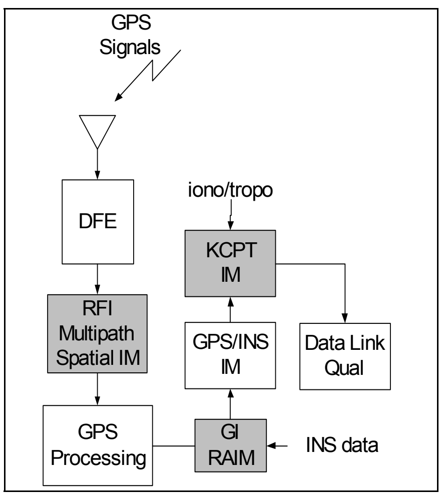

Figure 2 Integrity Monitoring Concept[2]

A component of the integrity monitoring solution is the Spatial Integrity Monitor (IM) which must be designed to address the following potential failure modes: (1) RFI or jamming; (2) multipath errors and (3) antenna electronics failures. In a high A/J digital beam forming receiver, the RF signals from each antenna are first converted to an intermediate frequency (IF) signal and digitally sampled. The digital samples from the multiple antenna elements are then combined in the digital spatial processor to create the inputs to each channel of the GPS user equipment where the code and carrier correlation are performed.

Our integrity monitoring design includes a Spatial Environment Estimator/Integrity Monitor to monitor for failure modes within the antenna electronics or receiver spatial processing and also detect out-of-tolerance RF interference or multipath errors. This is accomplished through spatial signal processing on the raw digital outputs of each antenna element. As described in the following section, the use of these raw Digital Antenna Element outputs provides the ability to perform robust integrity monitoring within the aircraft's JPALS receiver. This capability cannot be provided when only using the Digital Antenna Electronics which currently only outputs the processed beam/null-steered composite antenna signal outputs.

DIGITAL ANTENNA *ELECTRONICS* VS. DIGITAL ANTENNA *ELEMENTS*

With the current generation analog controlled reception pattern antenna (CRPA) and digital antenna electronics in use by the DoD, a single composite RF signal is generated from the combined antenna inputs adapted to minimize any detected jammer signals. This modified signal is then passed into the digital GPS receiver as shown in Figure 3.

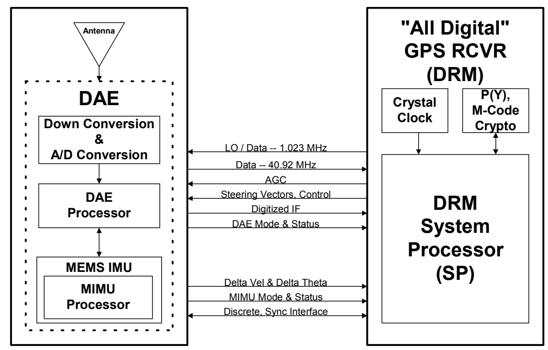

Figure 3 Current Generation DOD Digital Antenna Electronics

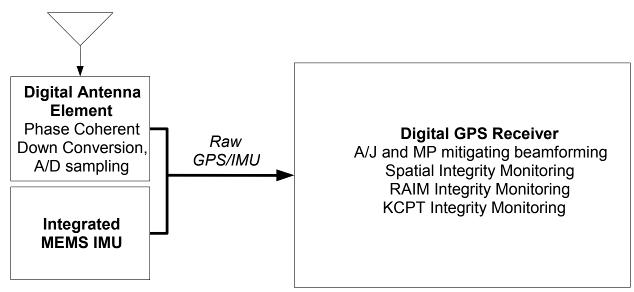

Figure 4 NAVSYS Digital Antenna Element and receiver

The approach taken with the NAVSYS Digital Antenna Elements is to pass the raw A/D sampled signal from each of the antenna elements directly into the digital receiver. It is within the software GPS receiver architecture that the adaptive spatial processing is applied for anti-jam and multipath mitigation, as shown in Figure 4. This approach allows for embedded integrity monitoring features within the GPS receiver to detect RFI, multipath and antenna electronics failures, It also offers significant possibilities for increased algorithm performance, and reduces the requirements for certification to one unit rather than two, since the DAE is a passive module rather than performing active spatial processing that could result in hazardous misleading information.

GPS SPATIAL SIGNAL PROCESSING

NAVSYS' High-gain Advanced GPS Receiver (HAGR)[3] is a software reprogrammable, digital beam forming GPS receiver. The HAGR components are illustrated in Figure 5. With the HAGR digital beam forming implementation, each RF input from an antenna element is converted to a digital signal using a DAE. The HAGR can be configured to operate with up to sixteen antenna elements (L1 and L2), with the antenna elements installed in any user-specified antenna array pattern.

Each DAE board in the HAGR can convert signals from eight antenna elements. The digital signals from the DAE modules are then provided to the HAGR digital signal processing cards with the cross-correlation matrix (R) for use in the digital beam forming algorithms.

The HAGR can be configured to track up to twelve satellites providing L1 C/A and L1/L2 P(Y) observations when operating in the keyed mode. The digital signal processing is performed in firmware downloaded from the host computer. Since the digital spatial processing is unique for each satellite channel, the weights are optimized for the particular satellites being tracked. The digital architecture allows the weights to be computed in the HAGR software, then downloaded and applied pre-correlation to create a digital adaptive antenna pattern to optimize the signal tracking performance.

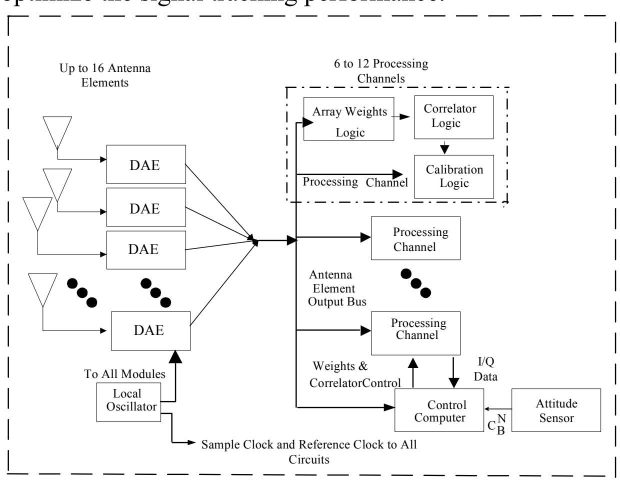

Figure 5 HAGR Spatial Signal Processing

ADAPTIVE DIGITAL SPATIAL PROCESSING

The HAGR architecture utilizes digital beam forming to provide additive gain in the direction of the GPS satellite tracked and nulling in the direction of undesired signals, such as jammers or multipath. The digital signal from each of the HAGR antenna elements can be described by the following equation.

$$y_k(t) = \sum_{i=1}^{Ns} s_i(\underline{x}_k, t) + n_k(t) + \sum_{k=1}^{Nj} j_j(\underline{x}_k, t)$$

where $s_i(\underline{x}_k,t)$ is the ith GPS satellite signal received at the kth antenna element

$n_k(t)$ is the noise introduced by the kth DAE

$j_j(\underline{x}_l,t)$ is the filtered jth jammer signal received at the kth antenna element

The GPS satellite signal at each antenna element ($\underline{x}_k$) can be calculated from the following equation.

$$s_i(\underline{x}_k, t) = s_i(0,t)\exp\{-i\frac{2\pi}{\lambda}\underline{1}_i^T\underline{x}_k) = s_i(0,t)e_{sik}$$

where $s_i(0,t)$ is the satellite signal at the array center and

$\underline{1}_i$ is the line-of-sight to that satellite

e_{sik} are the elements of a vector of phase angle offsets for satellite i to each element k

The combined digital array signal, z(t), is generated from summing the weighted individual filtered digital antenna element (DAE) signals. This can be expressed as the following equation.

$$z(t) = \underline{w}'\underline{y}(t) = \underline{w}'\left[\sum_{i=1}^{Ns} s_i(t)\underline{e}_{si} + \underline{n}(t) + \sum_{l=1}^{Nj} j_j(t)\underline{e}_{jl}\right]$$

Since the weights are generated through software control, a variety of different beam forming algorithms can be used to compute the optimum weights depending on the receiver's mode of operation.

In Figure 6 and Figure 7, the antenna patterns created by the digital antenna array are shown for four of the satellites tracked. The HAGR can track up to twelve satellites simultaneously. The antenna pattern provides the peak in the direction of the satellite tracked (marked 'x' in each figure). The beams follow the satellites as they move across the sky. Since the L2 wavelength is larger than the L1 wavelength, the antenna beam width is greater for the L2 antenna pattern than for the L1

With beam forming, the information provided by the spatial integrity monitor is used to adapt the weights to minimize the array gain in the direction of undesired signals. The integrity spatial monitor is designed to monitor for signal anomalies and adapt the spatial processing using both the pre-correlation signal power (R) and also the post-correlation signal power (M).

The pre-correlation R matrix provides an estimation of the following parameters: DAE Noise Levels, indicating possible DAE failures which is used to deselect failed antenna elements; RFI or Jammer Signal levels, used to apply nulls to minimize the J/S levels. The optimized weights for the spatial processing are defined as those that reject any failed antenna elements and those that maximize the S/J for each satellite tracked.

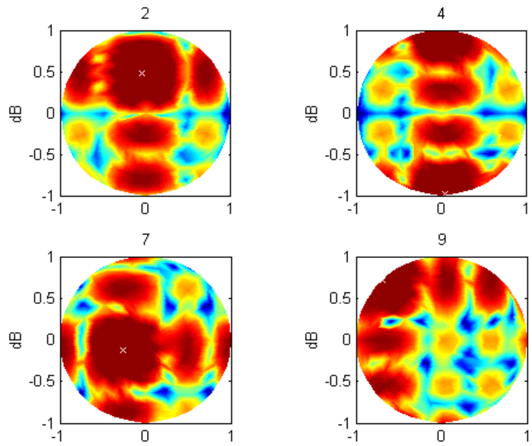

Figure 6 L1 Beam Steering Antenna Patterns

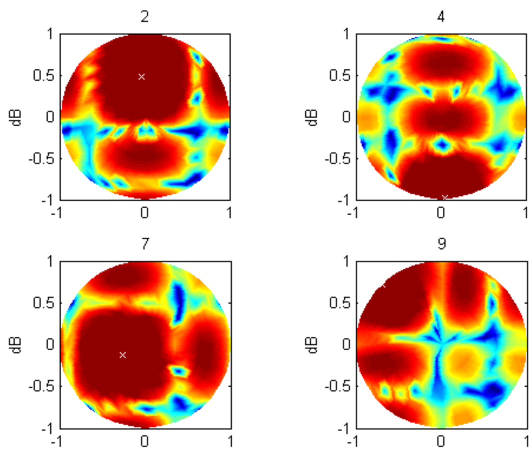

Figure 7 L2 Beam Steering Antenna Patterns

The post-correlation signal matrix, M, is used to detect strong multipath sources and estimate their direction. The direction of the multipath signals is used to compute the optimal weights to apply beam-forming to the desired GPS satellite, and place a null on the estimated multipath signal direction. The optimized weights for the multipath nulling algorithms are defined in the case as maximizing the S_i/M for each satellite being tracked.

The performance of the beam-former/multipath minimization algorithms is illustrated in Figure 8 assuming a single multipath reflection at azimuth 270, elevation 30. This figure shows that the multipath minimization algorithm applies nearly 40 dB of attenuation on the multipath signal in each of these cases. Moreover, the gain from the beam forming increases the C/No by 8 dB of gain on each satellite tracked. The combination of these effects significantly enhances the signal/multipath levels minimizing the code and carrier distortion. The multipath spatial monitoring feature also allows for the residual multipath error on the spatially corrected beam forming output to be estimated providing a quality figure of merit for the code and carrier observations.

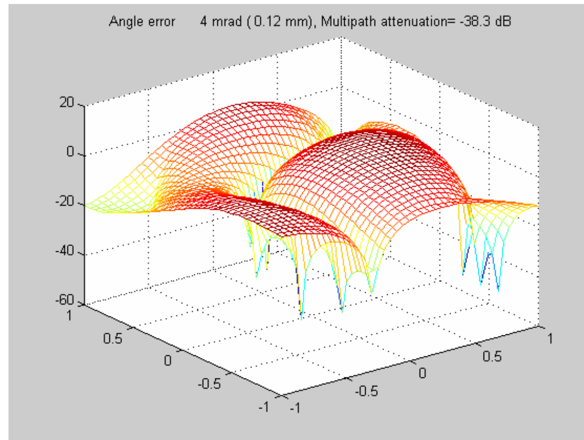

Figure 8 Antenna Pattern with Multipath Mitigating Beam Forming

NAVSYS HARDWARE USED FOR JPALS DATA COLLECTION

The NAVSYS HAGR receiver was used to collect data in a representative JPALS environment to quantify the effects of interference and multipath on the GPS observation quality. The HAGR has been designed as a software GPS Receiver to track both the military and civil GPS signals. The architecture that is being used to host the SGR application is illustrated in Figure 9. The SGR architecture consists of FPGA programmed in VHDL (Very High Speed Integrated Circuit (VHSIC) Hardware Description Language) to implement the correlation and tracking functions, as well as to apply the spatial processing algorithms.

Figure 9 CPCI Form Factor HAGR receiver

The GPS DAE components shown in Figure 10 perform the RF to IF downconversion and A/D sampling on the

GPS. The DAE can currently accommodate either L1 or L2 signals and a future upgrade is planned to add the L5 signal. This provides the digitized received GPS signals to the FPGA firmware where these signals are processed. The PC test bed is designed to allow inputs to be provided from multiple antenna elements. This allows the test bed to perform spatial processing from an antenna array[4], or to receive signals at different frequencies, such as L1, L2 and L5. Each DAE board includes eight separate RF channels, as shown in Figure 10. The input frequency of each individual channel is selected through the front-end filters. The input RF signals are mixed to a 70 MHz IF where they are sampled using a 12 bit A/D converter. The IF filter bandwidth can be selected from 2 to 24 MHz and the sample clock can be adjusted up to 56 MHz. The digitized signal is converted to a low voltage differential signal for transmission to the FPGAs

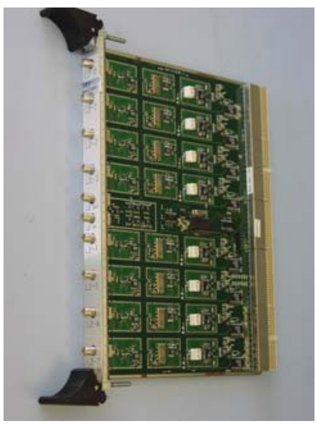

Figure 10 Digital Antenna Element card

The DAEs were connected to a GAS-1 CRPA for the JPALS data collection efforts described in this paper. Additionally, a Digital Storage Receiver was used to capture the raw data from each antenna element for subsequent processing in the lab environment. Figure 11 shows the Digital Storage Receiver with its eight data recording drives installed.

Figure 11 Digital Storage Receiver

Figure 12 shows the placement of the DSR in the HAGR SGR architecture. The raw digital signals are output directly from the Digital Antenna Elements, and are sampled and stored. The signals are also passed through to the normal HAGR processing functions. The DSR can log data at up to 200 MB/s, and with 8 storage drives, the DSR can log 1.44 TB of data. The unit is reconfigurable for number of channels and number of bits per channel that can be logged. Additionally, the DSRs are configured with dual-XEON processors so that data analysis can be carried out directly on the units.

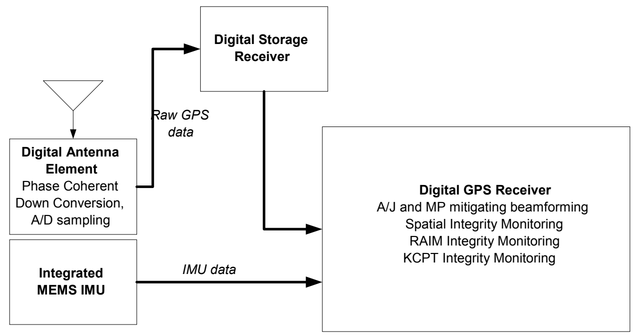

Figure 12 DSR in the HAGR Architecture

JPALS DATA COLLECTION EFFORTS

In February of 2004, NAVSYS personnel took a HAGR receiver, and two digital storage receivers aboard the USS Truman during flight deck certification operations. L1 and L2 GPS data was collected with the DSRs using a GAS-1 CRPA. Figure 13 shows the location in which the NAVSYS equipment was placed on the ship. The HAGR and DSRs were placed in a room under the LSO platform, with 60 foot cables running through the hull of the ship, and up onto the flight deck. Figure 14 and Figure 15 show the location of the CRPA near the LSO platform. Significant multipath sources were present from an aircraft parked near the CRPA, and from the LSO platform itself which was raised during part of the data collection.

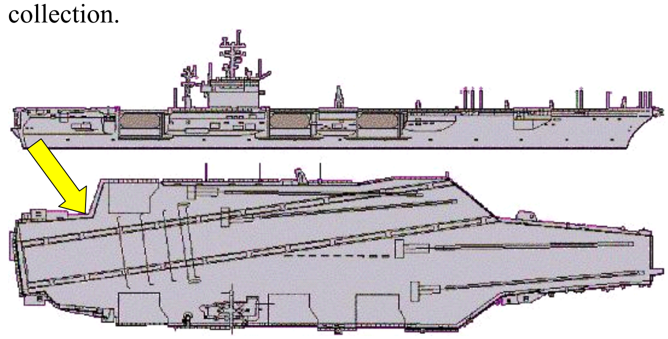

Figure 13 Location of CRPA on the USS Truman

Approximately 5.3 TerraBytes of raw GPS data was collected and brought back with the DSRs for subsequent processing and algorithm development.

Figure 14 CRPA and Gain Stage on the Flight Deck

Figure 15 CRPA with LSO Platform Raised

PSUEDO-RANGE MULTIPATH

In order to determine the magnitude of the multipath error on the pseudorange data, a technique was used in which the code and carrier data are differenced. This code minus carrier (CMC) observable removes common errors, but leaves multipath, ionosphere and receiver noise. Figure 16 shows this observable for one satellite.

The curve in the data is due to ionosphere error. This is removed in Figure 17 by fitting and removing a polynomial from the data. Figure 18 shows a close up of the previous figure, and also shows a fit of the data smoothed to 1 minute. This has the effect of reducing high frequency receiver noise in the observable. The 1-sigma value of these fits are the effective result of multipath error on the pseudorange data.

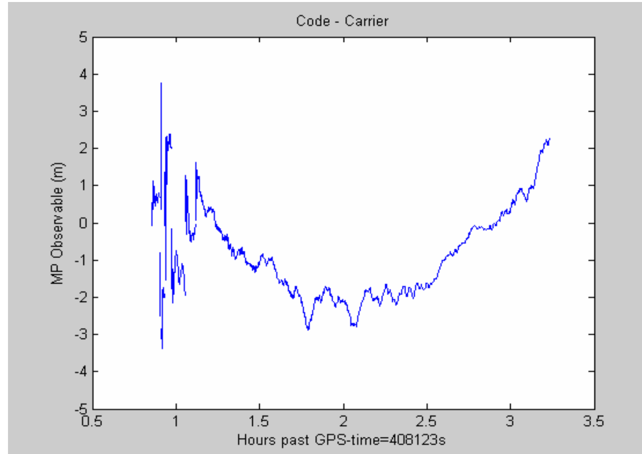

Figure 16 CMC Observable

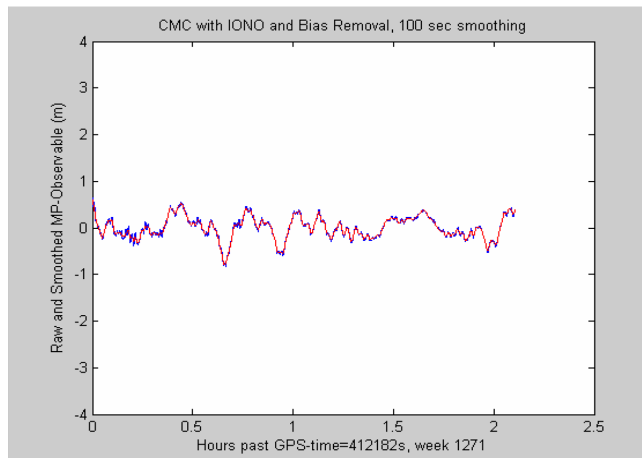

Figure 17 CMC with Ionosphere Error Removed

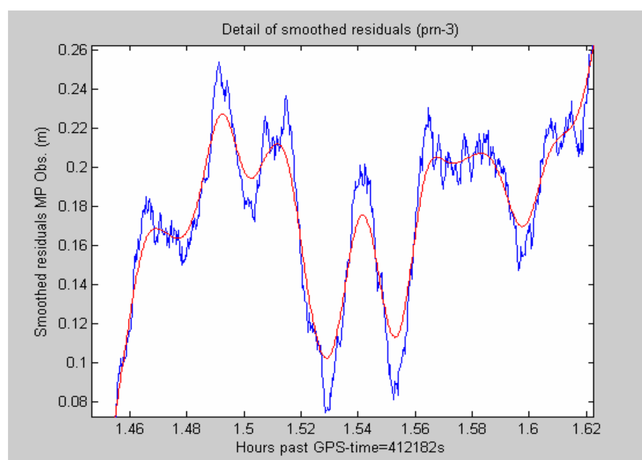

Figure 18 CMC with Fit to Smooth Receiver Noise

Once the CMC fits were generated for each satellite used during the data collection period, the results were sorted by elevation angle of the GPS satellite at the time the data was collected. These values were binned over 10 degree elevation increments and averaged. These results are shown in Figure 19 compared to pre-mission checkout data collected on the NAVSYS roof. From this data it is apparent that the multipath error on the ship is much higher than that collected on the building, as was expected. It can also be seen that beam steering removes significant multipath error at all elevations. Multipath error mitigation at lower elevations is not as effective as that at higher elevations. On future ship trips, the multipath mitigating beam-forming approach will be used to demonstrate the ability to improve multipath mitigation at lower elevations.

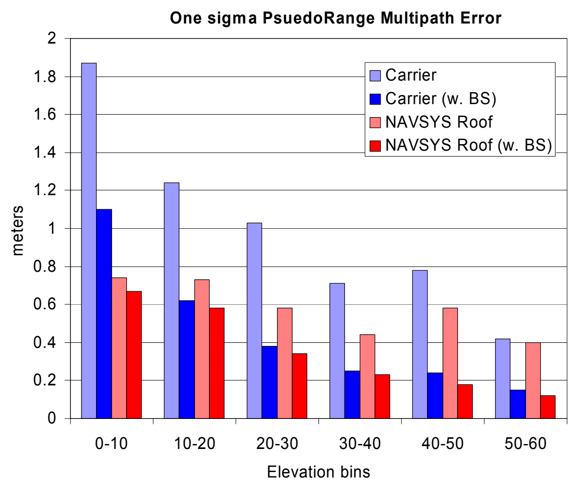

Figure 19 Pseudorange MP Error as a Function of Elevation

CONCLUSIONS

The NAVSYS Digital Antenna Element approach used in the HAGR receiver architecture passes raw sampled data directly into the receiver spatial processing and integrity monitoring electronics. The beam forming weights are applied to these digital data in the receiver. This approach is different from that used in modern DoD Digital Antenna Electronics in which the beam forming anti-jam algorithms are applied in the Antenna Electronics and the processed signal is then sent to the digital receiver. The NAVSYS approach offers more versatility in algorithm design and allows for robust spatial integrity monitoring to assure the quality of the GPS observations.

The NAVSYS HAGR and Digital Storage Receiver technology have been used to capture data from the deck of an aircraft carrier, for analysis of the multipath error content. It was demonstrated that the digital beam-steering approach significantly reduces pseudorange multipath at all elevations. Digital beam forming, in which a composite antenna pattern is formed both to maximize gain towards satellites, and to minimize gain towards detected multipath sources will be used on subsequent carrier trips. This technique shows promise to reduce multipath at all elevations to levels that will be acceptable for JPALS processing.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the U.S. Navy's Naval Air Warfare Center for supporting this research. However, the views expressed in this paper belong to the authors alone and do not necessarily represent the position of any other organization or person.

REFERENCES

[1] System makes historic flight for naval aviation, "http://www.cnrma.navy.mil/news/june2001/2060701/2060701.html"

[2] K. Gold and A. Brown, "A Hybrid Integrity Solution for Precision Landing and Guidance", Proceedings of IEEE Plans, Monterey, CA, Apr. 2004

[3] K. Gold and A. Brown, "A Software GPS Receiver Application for Embedding in Software Definable Radios" Proceedings of ION GPS/GNSS 2003, Portland, OR, Sept. 2003

[4] A. Brown and N. Gerein, "Test Results from a Digital P(Y) Code Beamsteering Receiver for Multipath Minimization," Proceedings of ION 57th Annual Meeting, Albuquerque, NM, June, 2001.