High Accuracy GPS Performance using a Digital Adaptive Antenna Array

Alison Brown, *NAVSYS Corporation*

BIOGRAPHY

Alison Brown is the President and CEO 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 GPS-III Independent Review Team and Scientific Advisory Board for the USAF and serves on the GPS World editorial advisory board.

ABSTRACT

NAVSYS' High-gain Advanced GPS Receiver (HAGR) has been designed to take advantage of digital adaptive antenna array spatial-processing to enhance the accuracy of the GPS observations. The HAGR has the capability to create an optimized digital antenna pattern for up to eight GPS satellites simultaneously. This is used to perform dynamic beam-forming to the GPS satellites, in both static and mobile environments, providing over 10 dB of additional signal gain on each satellite tracked. The additional gain reduces the receiver noise on both the code and carrier tracking loops. This paper includes test results comparing the performance of the HAGR phased array antenna versus two conventional surveying GPS antennas.

NAVSYS have also developed an adaptive spatial processing algorithm that minimizes the antenna pattern in the direction of any detected multipath signals. This adaptive spatial processing minimizes the effect of multipath errors on the code and carrier tracking loops. Preliminary test results showing adaptive multipath beam-forming/nulling using a 7-element antenna array are also included.

INTRODUCTION

The precision provided by current generation GPS receivers, and the use of high accuracy processing methods such as differential and kinematic GPS to remove GPS system errors, leaves multipath as the dominant remaining error source affecting GPS performance.

Multipath errors are caused by the receiver tracking a composite of the direct GPS signals and reflected GPS signals from nearby objects, such as the ground or nearby buildings, as illustrated in Figure 1.

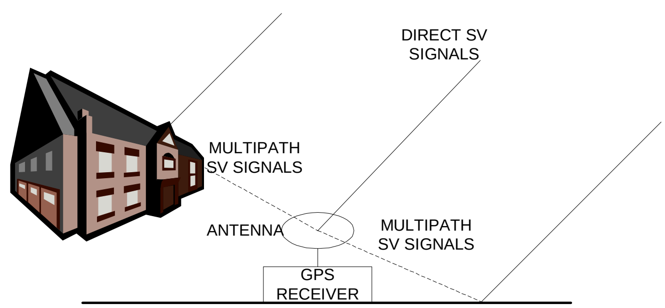


Figure 1 GPS Multipath Errors

Previous techniques for minimizing the multipath effect have used either antenna designs, to cut-off low elevation GPS signals, and signal processing to minimize the multipath tracking loop errors. Antennas that have large ground planes or choke rings provide low elevation signal rejection which will reduce the power of low elevation multipath signals. However, this technique has no effect on errors introduced by high elevation multipath from sources such as buildings. Signal processing techniques include the use of multiple correlators for correlation shape correction or temporal filtering using code/carrier smoothing. These effects can reduce the effect of multipath on the pseudo-range errors but they have no effect on carrier multipath errors.

In this paper, test data is presented that compares the performance of a digital adaptive antenna array for high accuracy GPS applications against these previous approaches.

DIGITAL BEAMFORMING GPS RECEIVER (HAGR)

The test results presented in this paper were collected using NAVSYS' High-gain Advanced GPS Receiver (HAGR)[1]. The reprogrammable digital spatial processing capability inherent in the HAGR allows GPS signals to be combined from as many as 16 antennas and create a multi-beam antenna pattern to apply gain to up to eight GPS satellites simultaneously.

The test results presented were collected with the HAGR operating with the C/A code. A Precise Position System (PPS) version of the HAGR (the HAGR-200) is also in development with 12 channel L1 and L2 capability.

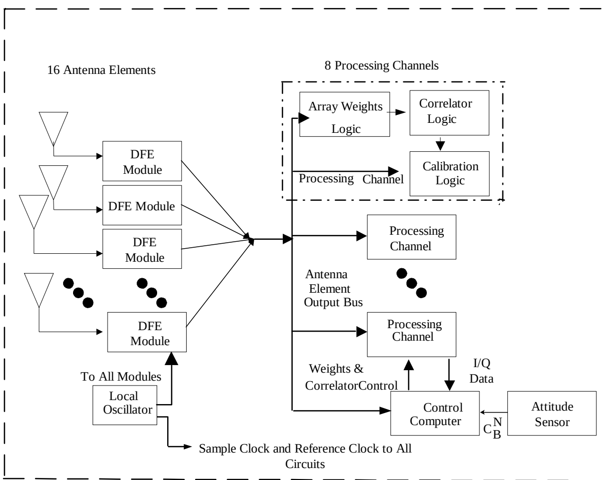


Figure 2 HAGR System Block Diagram

The HAGR system architecture is shown in Figure 2. 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 the composite digital beam-steered signal input for each of the receiver channels. The weights for each channel are dynamically downloaded through software control. The reprogrammable digital spatial processing approach adopted by the HAGR also enables adaptive beam and null-forming to be applied which can be used to reduce the effect of multipath errors, improving the GPS performance for high accuracy applications [2,3,4,5].

MULTIPATH COMPARISON TESTING

To further characterize the test environment and provide comparison data between the different multipath mitigation approaches considered, the test set-up shown in Figure 5 was used.

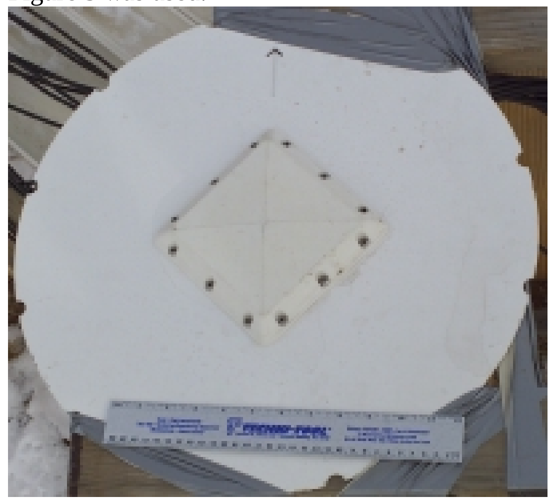


Figure 3 Trimble Antenna (provided by NOAA)

Figure 4 Ashtech Antenna (provided by NOAA)

HAGR receivers were configured to operate with a 16-element antenna array, and also two 7-element antenna arrays. Data was also collected from a Trimble antenna (Figure 3), with large ground plane, and an Ashtech antenna (Figure 4) with a choke ring, using two Novatel receivers. These antennas were provided to us on loan by NOAA. Data was collected over a 24 hour test period to characterize the multipath errors from the different antennas and antenna arrays tested.

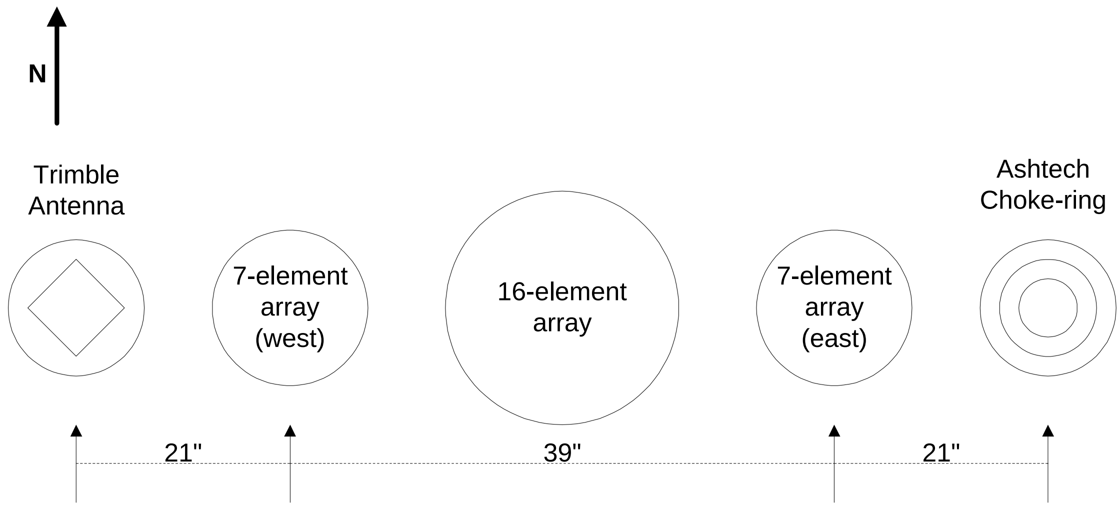


Figure 5 Multipath Comparison Testing Antenna Separation

Figure 6 Test Set-up Showing Trimble, HAGR and Ashtech Antennas

Over the 24 hour period where data was logged, 28 GPS satellites were in view. The individual observations plots for the satellites in view for the HAGR (blue), Ashtech (green) and Trimble (red) antennas for selected satellites are shown in Figure 14 for selected satellites. The following observations were used to illustrate the magnitude of the multipath errors over the test period.

Signal/Noise Ratio When multipath is present the signal/noise ratio magnitude varies due to the constructive and destructive interference effect. The peak-to-peak variation is an indication of the presence of multipath signals, as shown by the following equation and Figure 7, where A is the amplitude of the direct signal, A_M is the amplitude of the reflected multipath signal, θ is the carrier phase offset for the direct signal and θ_M is the carrier phase offset for the multipath signal.

$$\tilde{A} = \left|A + A_M e^{\Delta\theta}\right| - A$$

$$\tilde{\theta} = \angle(A + A_M e^{\Delta\theta})$$

$$\Delta\theta = \theta - \theta_M$$

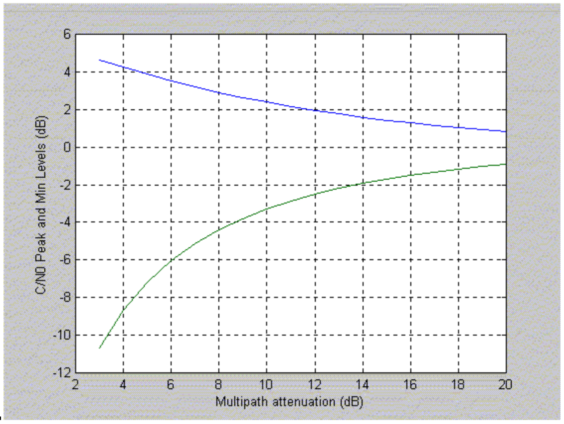


Figure 7 Multipath Amplitude Effect

Code-carrier phase difference Since the multipath error is much larger on the pseudo-range observation than on the carrier-phase, the short-term code phase (pseudo-range) – carrier-phase difference provides an indication of the multipath error. The longer term effects observed are due to ionospheric divergence on the code and carrier. These longer term effects should be common on the data logged from all of the GPS receivers. The individual PR+CPH plots for the HAGR (blue), Ashtech (green) and Trimble (red) antennas are also shown in Figure 14.

From the plots in Figure 14, the 16-element beam-steering array provides a significant improvement in C/N0 due to the antenna gain. The cyclic variation in C/N0 due to the constructive/destructive interference caused by the multipath signals (see Figure 7) is also significantly reduced in the HAGR data as opposed to the Trimble and Ashtech antenna data. The PR+CPH observations show a similar reduction in the cyclic variation indicating the presence of pseudo-range multipath errors. The HAGR pseudo-range data was unsmoothed by carrier range. The plots show that the pseudo-range errors are essentially "white noise" indicating that carrier range smoothing could be applied without introducing the bias errors present in the other receiver data due to fact that the multipath errors are correlated over many minutes.

The peak-to-peak C/N0 variation indicates the strength of the multipath returned signal relative to the direct signal (M/S in dB), as illustrated in Figure 7. The maximum-to-minimum observed C/N0 was estimated over a 1-hour period for each satellite tracked and for each antenna observed. This variation in C/N0 was then used to predict the multipath power present. The predicted M/S power plots for each satellite are included in Figure 15.

In Figure 9, the average M/S power for each satellite is plotted for the HAGR (blue), Ashtech (green) and Trimble (red) antennas.   Both the GPS survey antennas experienced (on average) multipath errors of around – 6 dB (Table 1). From Figure 8, this would result in peak carrier phase errors (on average) of +/-2 cm from the multipath signals. The HAGR, with an average multipath level of –13 dB, would experience peak carrier phase errors (on average) of +/-7 mm.

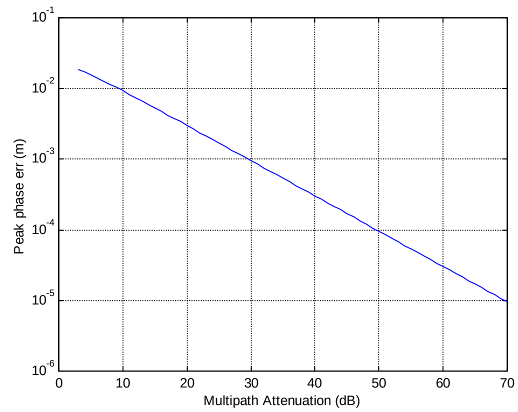


Figure 8 Multipath Peak Phase error vs Attenuation (dB)

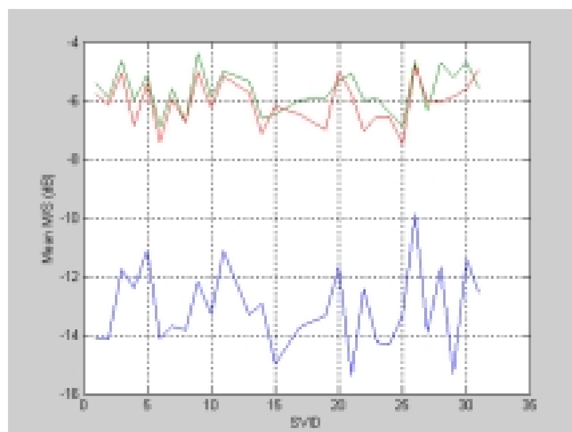


Figure 9 Mean M/S Power Observed per Satellite (dB)

Table 1 Mean M/S (dB) for HAGR, Ashtech and Trimble Antennas

HAGR	Ashtech	Trimble
-13.1 dB	-5.7 dB	-6.1 dB

GPS KINEMATIC POSITIONING TEST

The two 7-element HAGRs shown in Figure 5 and Figure 6 were used to compute a kinematic GPS solution between the two antenna arrays using the HAGR beam-steering mode. The 7-element array used 7 conventional GPS antennas configured ½ L1 cycle apart in a hexagonal pattern (Figure 10). A small version of this array is also being developed using NAVSYS' Mini-Array technology[6].

Figure 10 7-Element Antenna and Next Generation Mini-Array

The kinematic solution results are shown in Figure 12 and Figure 11. In Figure 13 the fault vector (f) magnitude is shown. This is equivalent to (Nsv-4) times the carrier phase noise. During this period, 6 satellites were in view. Figure 13 indicates that except for a few brief excursions, the carrier-phase noise was within 2-3 mm when the beam-steering solution was used. The mean offset between the two antennas, as observed by the kinematic solution, is [0.90 -98.72 4.95] cm (North, East, Down) or 38.92 inches apart.

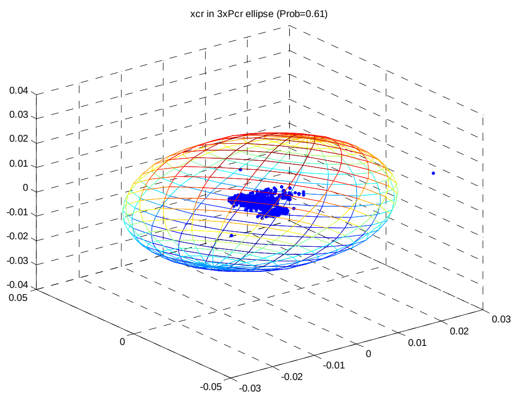


Figure 11 Kinematic Solution 3-D Position Variation

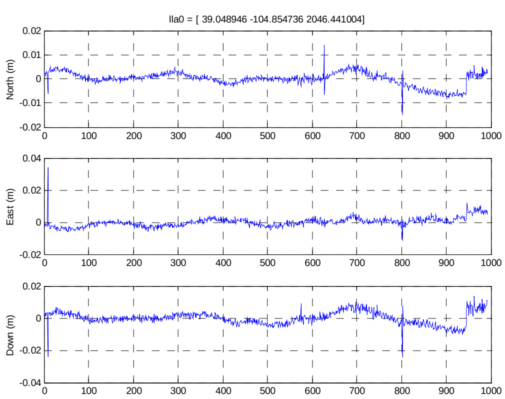


Figure 12 Kinematic Solution - NED variation (m)

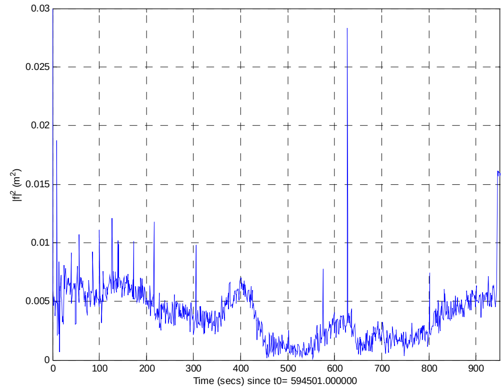


Figure 13 Fault Vector from Kinematic Solution

ADAPTIVE MULTIPATH SPATIAL PROCESSING

To minimize the effect of the multipath signals, the digital antenna array can be used to dynamically adjust the antenna array pattern to provide gain towards each of the satellites tracked, and also detect and place nulls in the direction of observed multipath signal sources. This approach has the following advantages over other multipath reduction techniques employing fixed antenna patterns or temporal signal processing methods.

<u>Array electronics estimates the presence of multipath sources</u>. The multiple signals from the antenna elements are processed to dynamically estimate the presence of multipath. This provides a measure of the magnitude and effect of this error source that can be used to optimize siting of GPS reference stations to achieve high accuracy performance.

<u>Array electronics adapts the antenna pattern to optimize the relative direct signal to multipath signal power</u>. The beam steering is used to provide antenna gain to reinforce the direct signals and to apply nulling to minimize the effect of the received multipath signals.

The test set-up shown in Figure 6 was used to evaluate the effectiveness of the multipath spatial processing algorithms. Two 7-element antenna arrays were configured at each end of a precisely measured baseline. The 7-element arrays, were each connected to two HAGR GPS receivers which were run in calibration mode to track each of the antenna elements independently. This calibration data was processed to estimate the presence of any multipath signals.

In Figure 16, the detected multipath spatial patterns are shown for each of the 7-element (East and West) phased arrays. These plots also show the detected "direct" signal from each of the GPS satellites tracked. The presence of multipath is indicated in each of these cases by detected signals arriving from directions other than the direct paths.

The detected multipath spatial data was used to create an adaptive satellite beam-steering/multipath nulling antenna pattern post-test using a maximum likelihood spatial processing algorithm [5]. The resulting antenna patterns for the 7-element arrays are shown in Figure 17. These figures show that the antenna array will provide gain in the direction of the GPS satellite direct path and will attenuate the signals received from other directions where multipath signals were detected.

Work is continuing on the HAGR design to allow real-time multipath calibration and satellite tracking to operate in parallel. Currently the HAGR implements both modes but cannot run them concurrently.

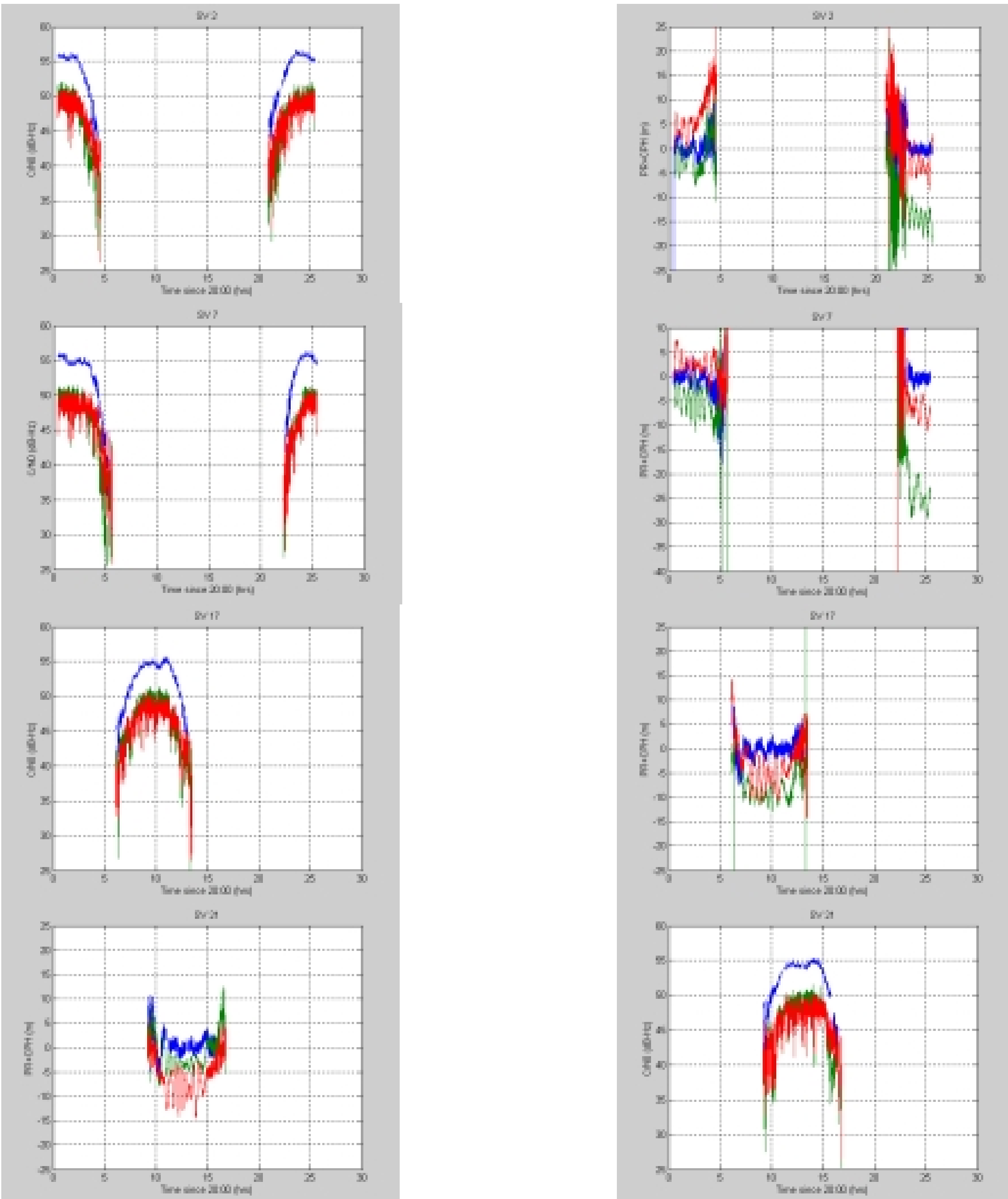


Figure 14 Multipath C/N0 and PR+CPH Comparison Plots (7-element)

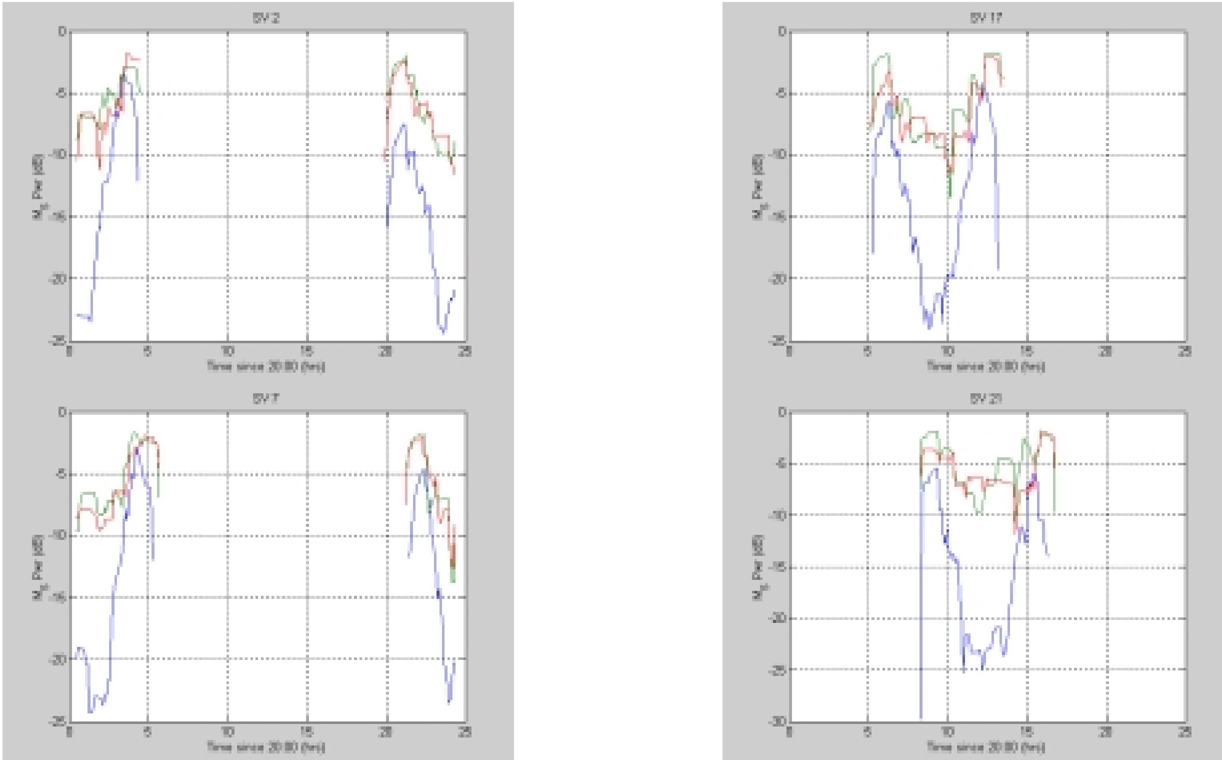
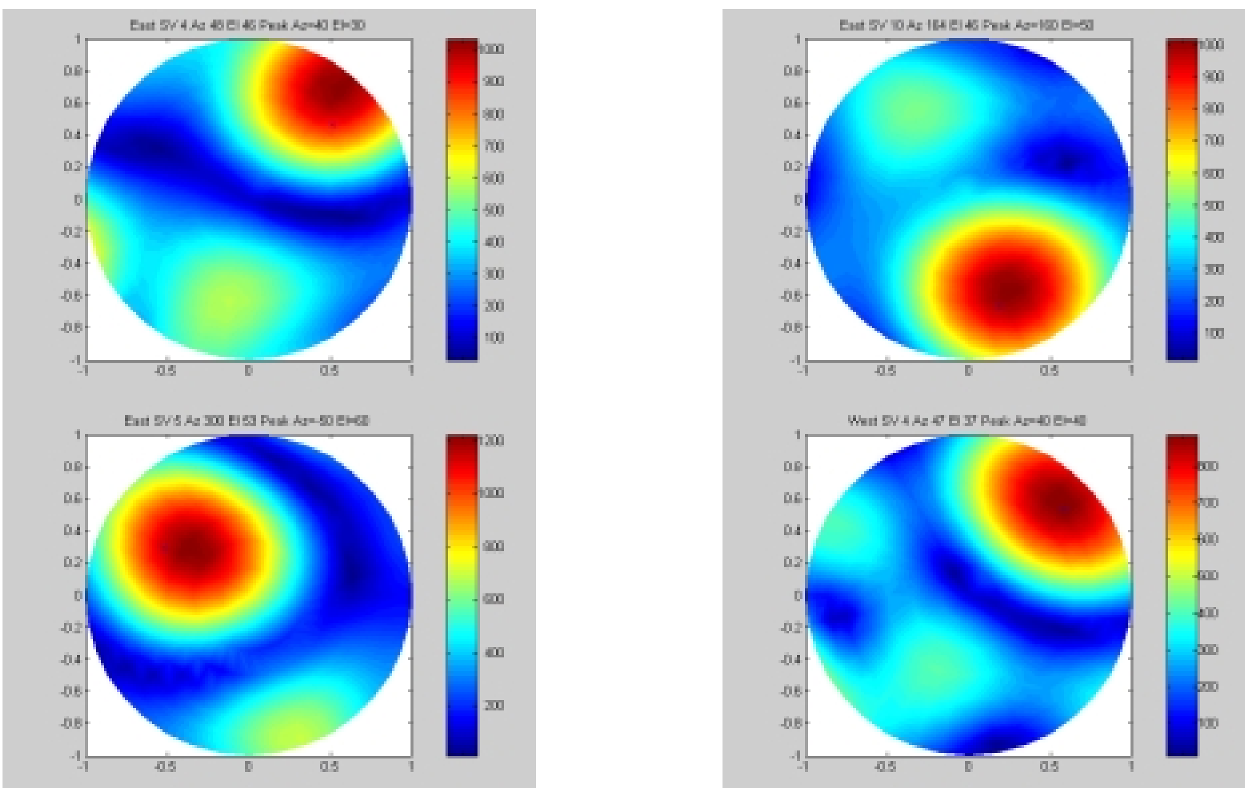


Figure 15 Estimated Multipath/Signal Level



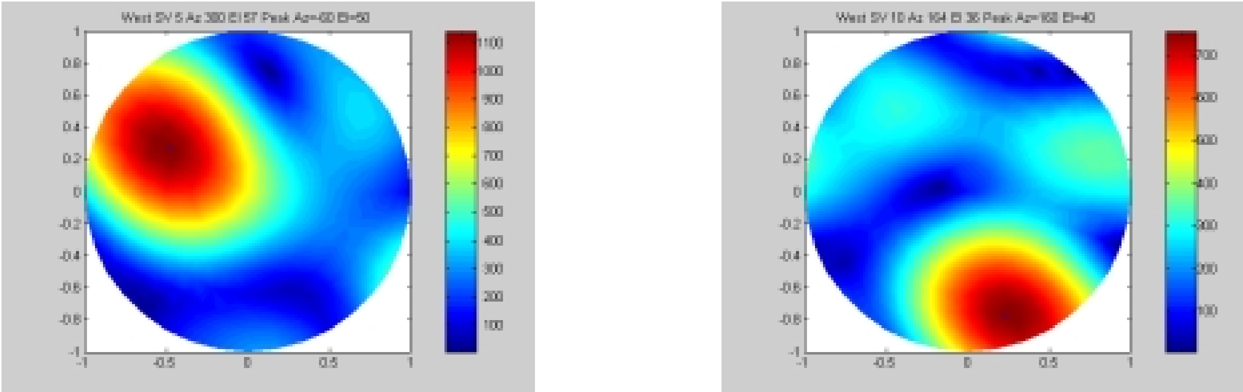


Figure 16 Phased Array Detected Multipath

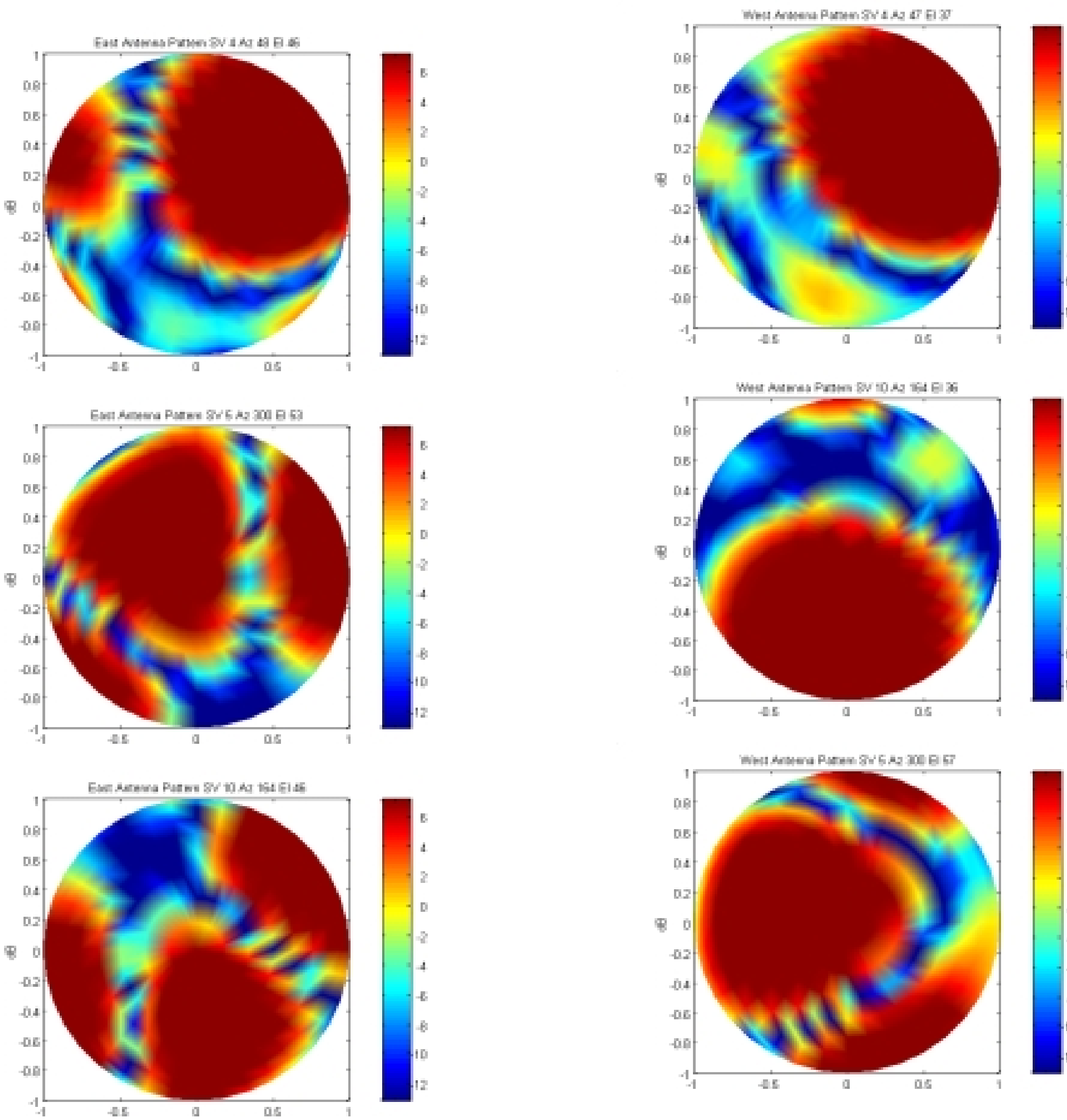


Figure 17 Beam/Null-Steering Antenna Patterns

CONCLUSION

The test data presented in this paper has demonstrated that the HAGR digital spatial processing reduces the effect of multipath on the code and carrier phase measurements. Test data collected using conventional GPS survey antennas measured a mean Multipath/Signal power level of -6 dB. This would imply carrier phase errors of +/-20 mm would be present. Pseudo-range errors of +/-5 meters were also observed from the multipath sources. With the HAGR digital phased array, the observed mean Multipath/Signal power was reduced to -13 dB which implies less than +/- 7 mm peak phase errors would occur.

Using dual 7-element antenna arrays, a kinematic GPS solution was computed over a known baseline. This test showed that the carrier phase noise was within 2-3 mm (1-sigma). Testing was also performed using the HAGR built-in calibration mode to dynamically estimate the spatial presence of multipath signals. Antenna patterns were presented showing how the detected multipath sources could be attenuated.

In the next phase of our development program we plan to implement the multipath spatial estimation modes and the adaptive spatial processing algorithms in our core HAGR products. Testing is also planned of the high accuracy performance of the digital spatial processing array using our 7-element Mini-Array antenna (Figure 10).

ACKNOWLEDGEMENTS

The author would like to thank Knute Berstis of the National Geodetic Survey for the loan of the GPS survey antennas used in these tests and for providing financial support for this effort. [7]

REFERENCES

[1] Dr. Alison Brown, Randy Silva, Gengsheng Zhang, "Test Results of a High Gain Advanced GPS Receiver," ION 55th Annual Meeting, Cambridge, Massachusetts, June 1999

[2] A. Brown, K. Taylor, R. Kurtz, H. Tseng, "Kinematic Test Results Of A Miniaturized GPS Antenna Array With Digital Beamsteering Electronics," Proceedings of ION National Technical Meeting, Anaheim, California, January 2000

[3] A. Brown, J. Wang, "High Accuracy Kinematic GPS Performance using a Digital Beam-Steering Array," Proceedings of ION GPS-99, Nashville, Tennessee, September 1999.

[4] A. Brown, H. Tseng and R. Kurtz, "Test Results Of A Digital Beamforming GPS Receiver For Mobile Applications," Proceedings of ION National Technical Meeting, Anaheim, California, January 2000

[5] A. Brown, "Multipath Rejection Through Spatial Processing", ION GPS-00, Salt Lake City, UT, September 2000.

[6] C. Manry, K. Rouzbehani, D. Nathans, A Brown, H. Tseng, S. Atterberg; "Advanced Mini Array Antenna Design using High Fidelity Computer Modeling and Simulation," Proceedings of ION GPS 2000, Salt Lake City, UT, September, 2000.