Multipath Characterization using Digital Phased Arrays

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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.

Neil Gerein is a Product Manager for NAVSYS Corporation's Receivers Group and is responsible for the management and development of NAVSYS' next generation of GPS receivers. He is currently completing his M.Sc. in Electrical Engineering and holds a BSEE in Electrical Engineering from the University of Saskatchewan.

Lee Savage is a Senior Scientist of NAVSYS Corporation where he is involved with developing GPS signal processing algorithms. He has a MSEE from the University of Southern California and a BSEE from California State University Long Beach.

ABSTRACT

In this paper, a technique developed to spatially characterize the multipath environment using NAVSYS' 16-element GPS phased array, the High-gain Advanced GPS Receiver (HAGR), is described. The algorithms used to process the multi-element digital phased array data and characterize the multipath environment are presented with simulation results to demonstrate the performance of the multipath characterization algorithm in a simulated environment. Using the Digital Storage Receiver (DSR), field test data was recorded from each of 16 antenna elements for subsequent processing and analysis. The test results from analyzing the multipath spatial characteristics from this data are also included.

In this paper, we describe a method of using the multi-element digital phased array data to characterize the multipath environment. Results using simulated data are presented to demonstrate the performance of the multipath characterization algorithm. Test results are also presented using data recorded from a 16-element digital phased array.

INTRODUCTION

The multipath characterization method described in this paper was developed to analyze the spatial profile of the GPS multipath environment using a GPS phased array. 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. In the absence of any multipath signals, the wavefront of the GPS signals arriving at the antenna array are aligned with the line-of-sight to the GPS satellites. When multipath is present, the antenna array will receive signals from both the direct path direction and also from other directions due to near-by reflected signals. By spatially analyzing the data collected from the phased array, it is possible to determine the spatial directions from which the multipath originates. This information can be used to characterize a multipath environment.

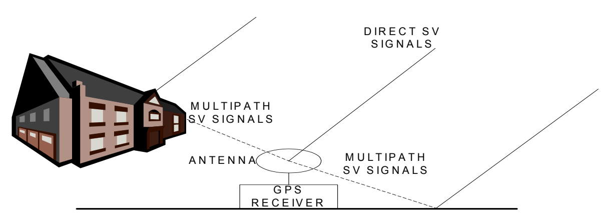

Figure 1 GPS Multipath Errors

HAGR DIGITAL STORAGE RECEIVER

The multipath characterization capability has been developed based on our HAGR and DSR capability. The DSR is designed to capture segments of digitally sampled

GPS data and record them to disk[1]. The recorded digital signals can be generated either through logging real-world GPS signals collected from the HAGR multi-element GPS receiver Digital Front End (DFE), or through digital simulation using our Advanced GPS Hybrid Simulator (AGHS)[2] (see Figure 2).

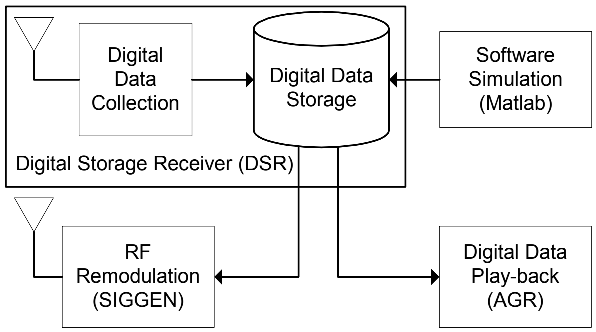

Figure 2 Advanced GPS Hybrid Simulator

The DSR can be configured to record data from up to 16 independent antenna elements (see Figure 3). This allows logging of real-world data from a digital phased array, such as the 16-element HAGR array shown in Figure 5. The data recorded from the multiple antenna elements can then be played back into the digital spatial processing logic of NAVSYS' HAGR, as shown in Figure 4[3].

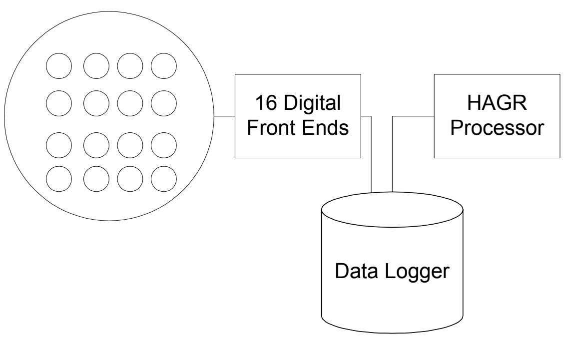

Figure 3 16 Element Digital Storage Receiver

The algorithms implemented in the HAGR for the spatial processing and analysis are based on software and firmware which allows the HAGR to be reprogrammed for different modes of operation. The normal mode is to apply digital weights to maximize the received signal strength through digital beam-forming. With a 16-element phased array this applies over 10 dB of gain in the direction of the GPS satellite signals (see Figure 7 and Figure 8). The HAGR digital spatial algorithms can also be programmed to apply both digital beam-forming and null-forming for GPS anti-jam applications.

In this paper, the test results were created by configuring the HAGR to generate spatial GPS data sets which were used to characterize the multipath spatial environment. The approach used is described in the following sections.

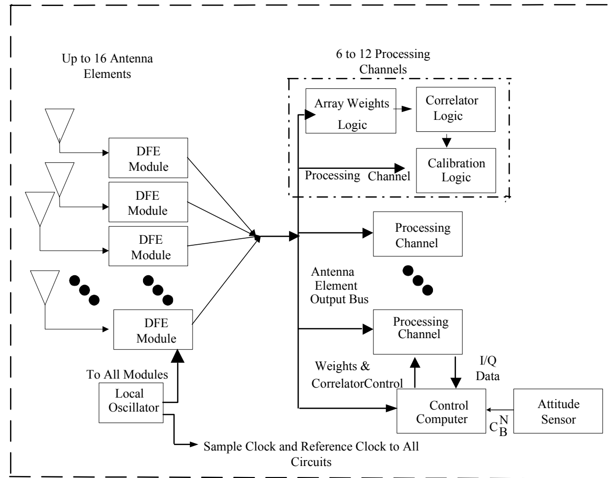

Figure 4 HAGR System Block Diagram

Figure 5 Sixteen Element HAGR Antenna Array

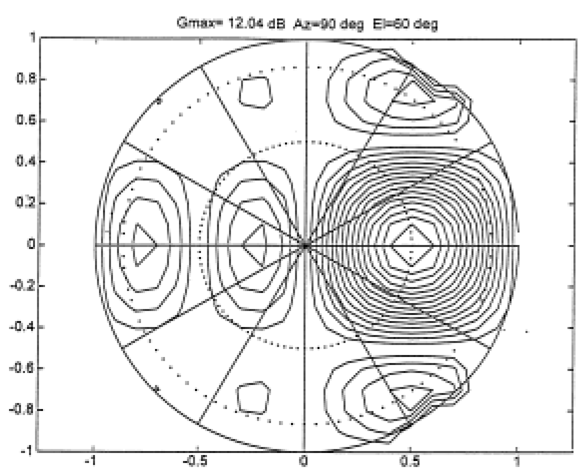

Figure 6 16-Element Digital Beam Forming Gain Pattern

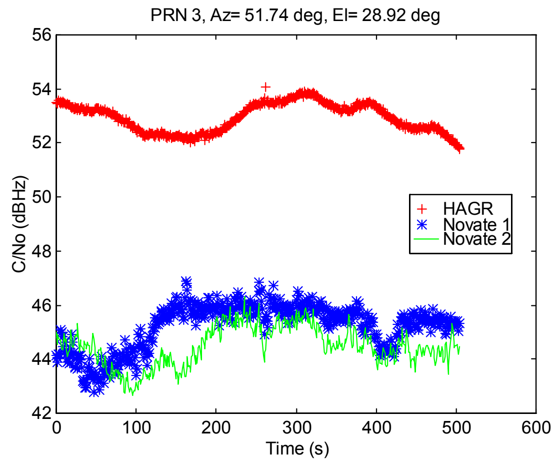

Figure 7 HAGR Digital Beam-steering Gain - SV 3

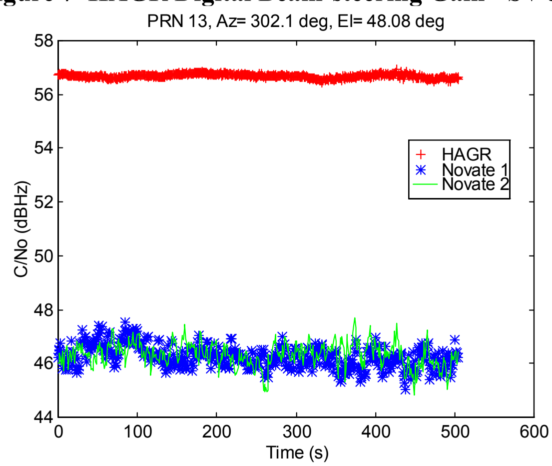

Figure 8 HAGR Digital Beam-Steering Gain - SV 13

MULTIPATH POWER DETECTION ALGORITHM

The raw digital signal recorded by the DSR from each element in the GPS antenna array can be described by the following equation.

$$y_k(t) = \sum_{i=1}^{Ns} s_i(x_k, t) + n_k(t) + \sum_{j=1}^{N_M} s_{Mj}(x_k, t)$$

$$\underline{y}(t) = \sum_{i=1}^{Ns} s_i(0, t)\underline{e}_{si} + \underline{n}(t) + \sum_{j=1}^{N_M} s_{Mj}(0, t)\underline{e}_{Mj}$$

where $s_i(x_k,t)$ is the ith GPS satellite signal received at the kth antenna element

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

$s_{Mj}(x_k,t)$ is the jth multipath signal received at the kth antenna element.

The GPS signals arriving at each element of the array can be calculated from the nominal signal, arriving at the array center ($s_i(0,t)$) factored by the spatial vector, $\underline{e}_s$, which s calculated from the line-of-sight to the satellite ($\underline{1}_i$) and the vector of array element offsets from the center of the array ($\underline{L}$).

$$\underline{e}_s = \exp\{-\frac{2\pi}{\lambda}\underline{1}_i^T \underline{L})$$

The HAGR spatial processing is used to create a correlated signal output (IQ_{ik}) for each satellite in view (i) and for each antenna element (k). The vector of IQ values includes the spatial components of both the direct signal, and the correlated multipath signal, assuming that the additive multipath delay (τ_M) is small compared with the code chip.

$$\underline{IQ}_i(t) = \left(\sum_{k=1}^{Ns} s_k(0,t)\underline{e}_{si} + \underline{n}(t) + \sum_{j=1}^{N_M} s_{Mj}(0,t)\underline{e}_{Mj} \right) \hat{C}_i(t) e^{-\hat{\theta}_i(t)}$$

$$= A_i e^{\theta_{si}(t)} \underline{e}_{si} + \underline{\tilde{n}}(t) + \sum_{j=1}^{N_M} A_{Mj} e^{\theta_{Mj}(t)} \underline{e}_{Mj}$$

One method of estimating the spatial direction from the IQ data is to compute the power as a function of the particular spatial direction.

$$P(\underline{\hat{e}}_s) = \left| \underline{IQ}\, \underline{\hat{e}}_s{}' \right| \approx \left| A_i e^{\theta_{si}(t)} + \sum_{j=1}^{N_M} A_{Mj} e^{\theta_{Mj}(t)} \underline{e}_{Mj} \underline{\hat{e}}_s{}' \right|$$

This provides a measure of the signal and multipath power from each spatial direction.

SIMULATED RESULTS

To demonstrate the ability of the power detection algorithm to detect the spatial direction of the multipath signals, a simulation was first used to test the algorithm performance. A simulated signal was generated which included a wavefront arriving at the array from the direct satellite source and also wavefronts arriving from two multipath sources. The direct and multipath sources each had the following azimuth and elevation angle values.

SV:	297.1	32.4 (deg)
Mpath1	209.2	18.5 (deg)
Mpath2	43.6	22.1 (deg)

The resulting power detection plot from the simulated data is shown in Figure 9. The white 'x' marks show the predicted locations for the power peaks of each of these signals. Based on this simulation analysis, the spatial processing was able to accurately detect the directions of each of the three signal sources.

For low elevation satellites, the horizontal antenna array pattern is unable to distinguish the absolute azimuth and an image of the satellite appears in the opposite direction (see Figure 10). This effect must be taken into account when analyzing the power spatial distribution for multipath signals.

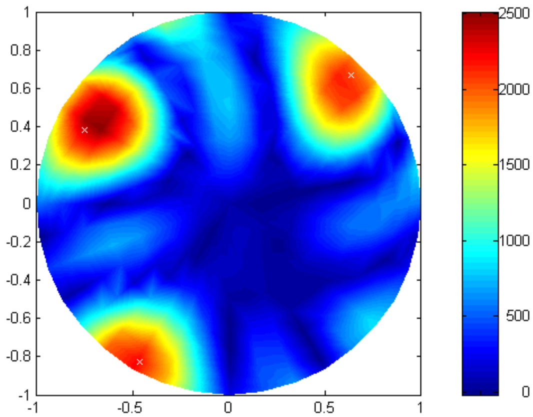

Figure 9 Simulated Direct and Multipath Signals

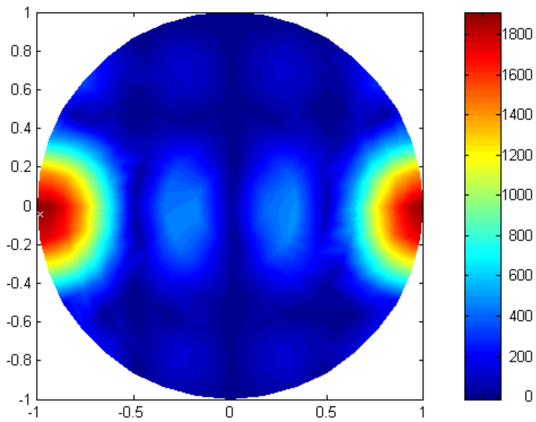

Figure 10 Low Elevation Satellite Signal (el=10.4 deg)

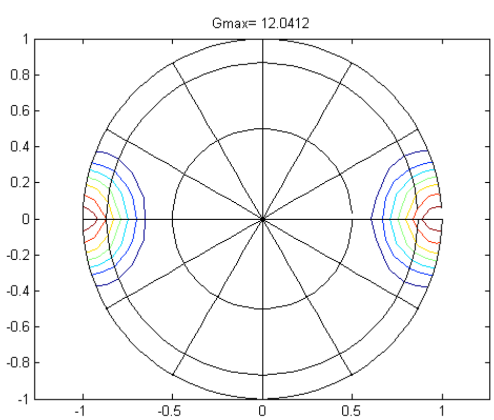

Figure 11 Low Elevation Array Gain Pattern (el=10.4 deg)

FIELD TEST RESULTS

The multipath characterization was tested by recording data from a 16-element antenna array using our HAGR electronics and broad-band DSR data logger (see Figure 3).

The 16-element antenna array was installed in our parking lot, near the NAVSYS building (Figure 14). The array was first positioned horizontally and data was processed to characterize the local multipath. Figure 12 is a skyplot of the satellite positions during the horizontal array test. In Figure 17 through Figure 31 the results of this analysis are shown. These show some detected multipath for some of the satellites in the North West where the NAVSYS building was located and also some ground reflections. The maximum multipath levels are generally 6 dB below the direct signals (the plots show the detected signal relative magnitude).

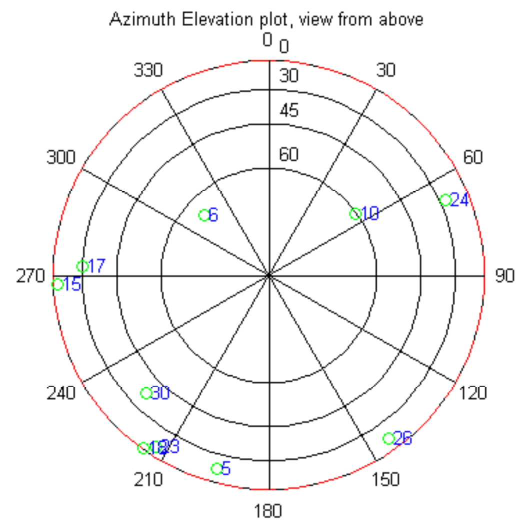

Figure 12 Skyplot during Horizontal Array Tests

The phased array was then tilted to characterize the multipath environment better from ground reflected signals. The building was again to the North-West of the array and during this test a vehicle was also located to the South East of the array (see Figure 16).

Table 1 Tilted Array SV Az/El (Nav & Body frame)

Svid	Az (N)	El (N)	Az (B)	El (B)
3	297.10	32.43	317.75	18.09
6	172.77	8.87	190.94	24.70
9	107.91	23.35	117.11	34.86
14	209.25	18.54	231.78	27.04
15	45.05	79.48	15.64	67.59
17	97.44	62.90	77.07	68.17
18	346.40	71.38	356.21	54.66
26	43.65	22.14	54.41	15.94

The array was tilted away from the building, pointing towards the South where there were no obstructions (see Figure 15). Figure 13 is a skyplot of the satellite positions during the tilted array test. The direction of the peak detected signal power for each of the satellites in the antenna (body) axes (az_B,el_B) was used to solve for the pitch, roll and heading of the antenna array, based on the following relationship and the knowledge of the satellite azimuth and elevation in the navigation frame (az_N,el_N) (see Table 1).

$1_N(az_N, el_N) = C_B^N(pitch, roll, heading) 1_B(az_B, el_B)$ Based on this equation, the array had the following attitude. [pitch, roll, heading] =[16.65 3.53 -15.75] degrees

The multipath characterization plots were then generated for each satellite. These are shown in Figure 24 through Figure 31. For each case, the direct satellite signal direction (in body frame) is shown by the mark, 'x'. The direction of a satellite reflected signal off the ground is marked by a 'o'.

These plots were repeated for each time point at a 10 Hz rate over a 20 second period to create a time varying sequence of the multipath detected spatial characteristics. From the plots, it could be seen that the detected multipath and satellite directions were consistent from time interval to time interval.

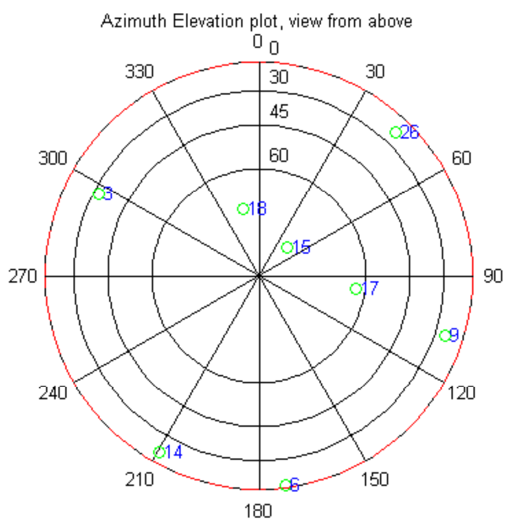

Figure 13 Satellite Skyplot during Tilted Array Field Test

The signal returns from the North-West direction were attributed to multipath signals from the building. In the South-East directions, the multipath source that was present there was the automobile shown in Figure 16. Some reflected ground multipath is apparent on the high elevation satellites that correspond with the 'o' markers (SV 15, 17 and 18). .

Figure 14 Array Test Set up next to NAVSYS Building

Figure 15 Tilted Array South Field of View

Figure 16 Tilted Array Test Configuration

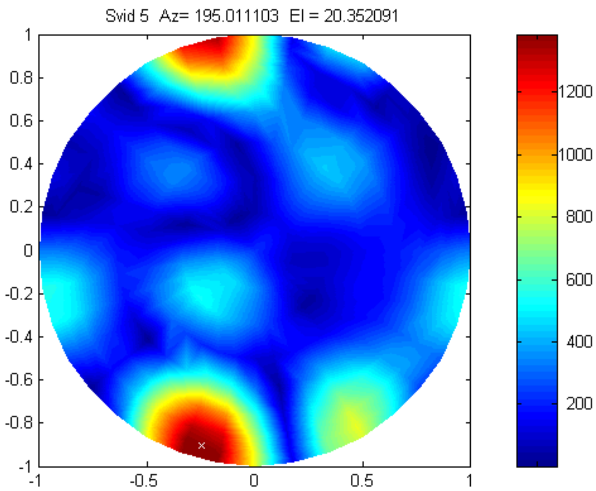

Figure 17 Horizontal Array Data - SV5

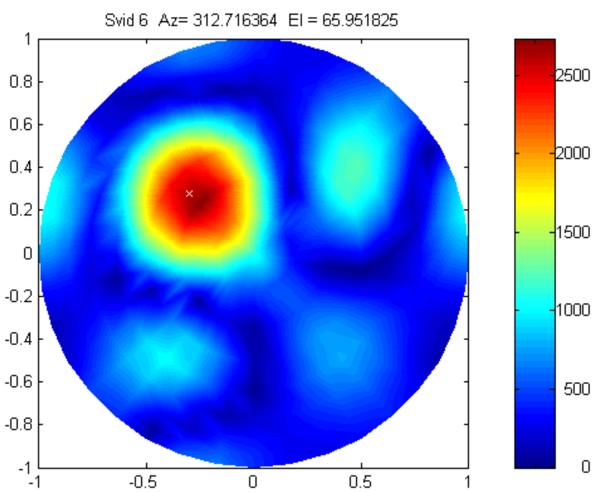

Figure 18 Horizontal Array Data – SV 6

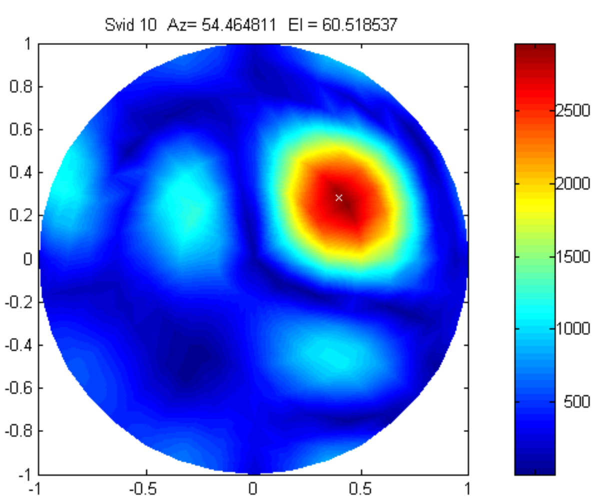

Figure 19 Horizontal Array Data – SV 10

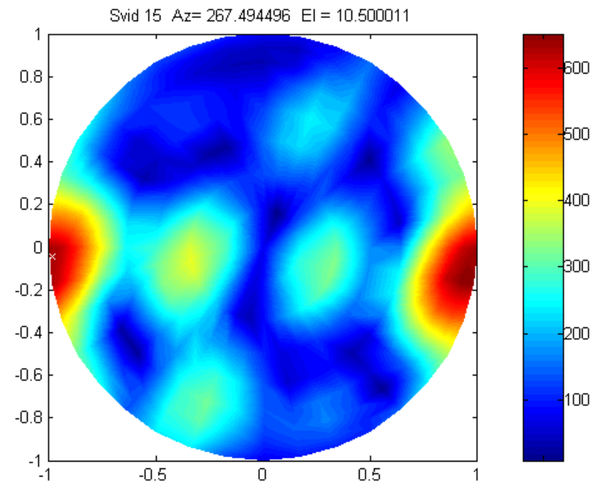

Figure 20 Horizontal Array Data – SV 15

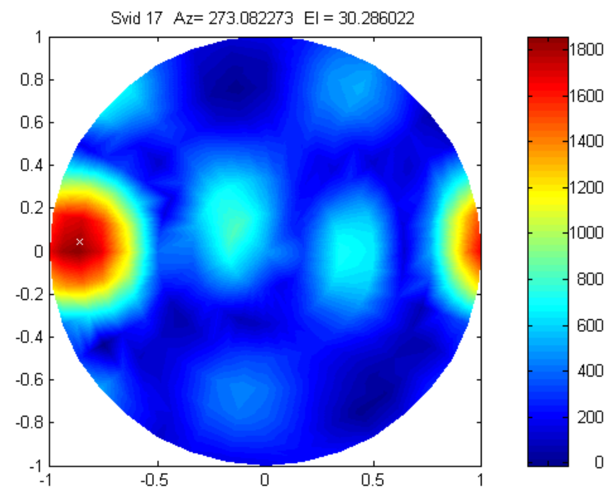

Figure 21 Horizontal Array Data – SV 17

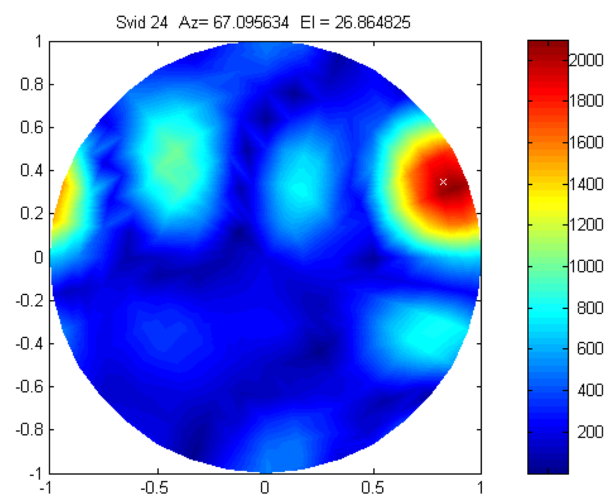

Figure 22 Horizontal Array Data – SV 24

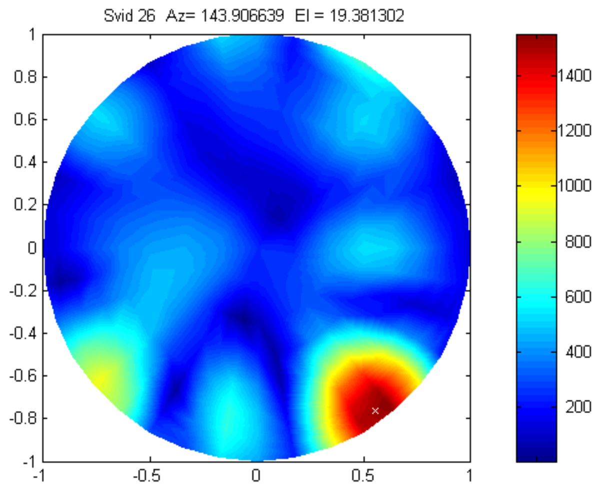

Figure 23 Horizontal Array Data – SV 26

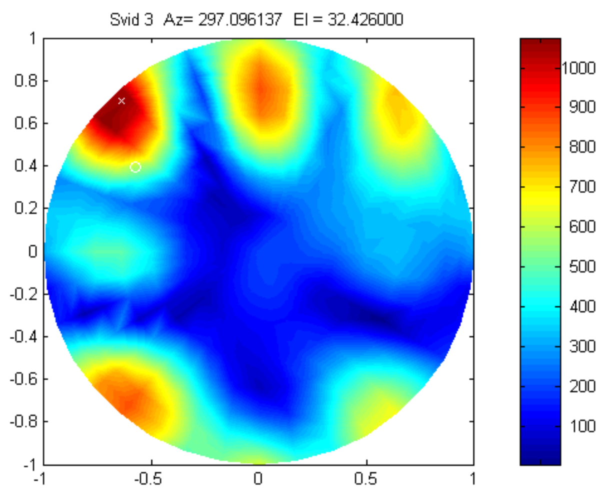

Figure 24 Tilted Array Data - SV 3

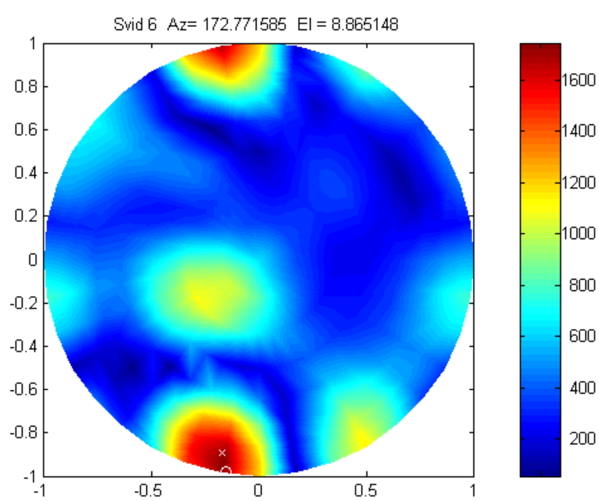

Figure 25 Tilted Array Data - SV 6

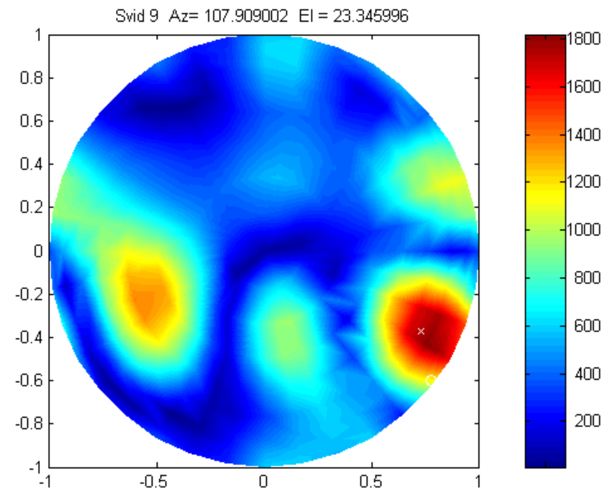

Figure 26 Tilted Array Data - SV 9

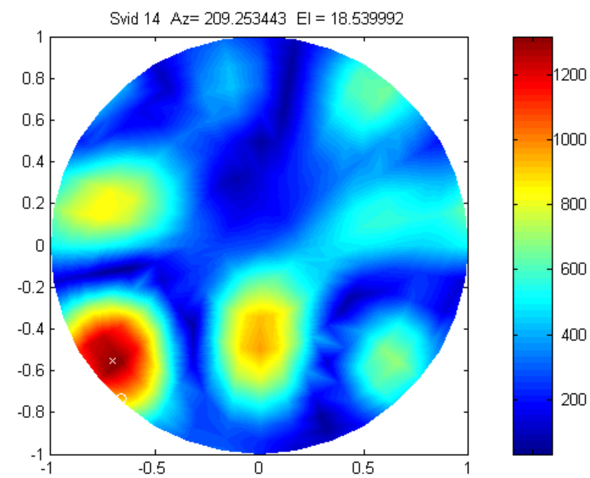

Figure 27 Tilted Array Data - SV 14

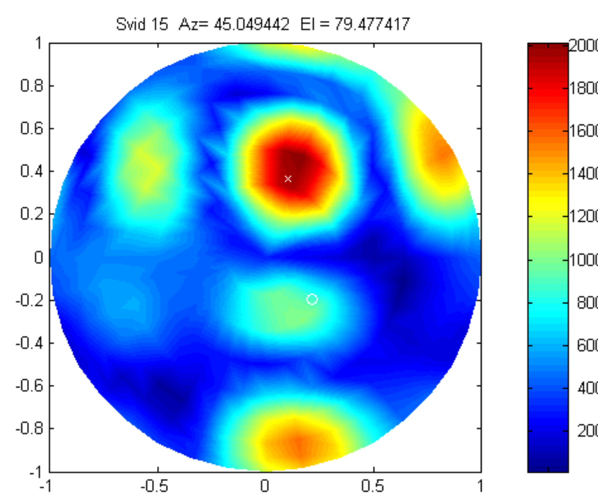

Figure 28 Tilted Array Data - SV 15

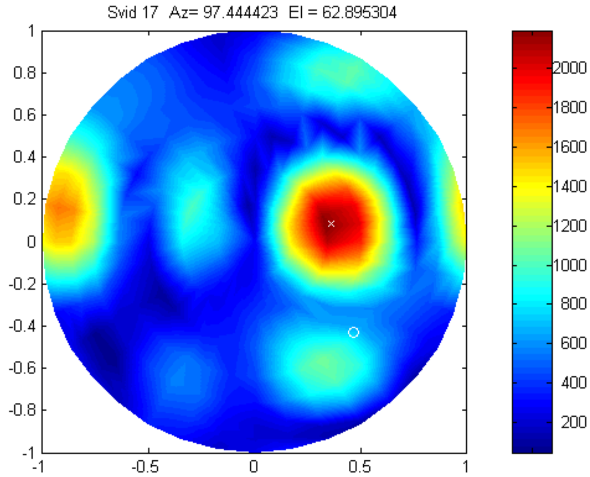

Figure 29 Tilted Array Data - SV 17

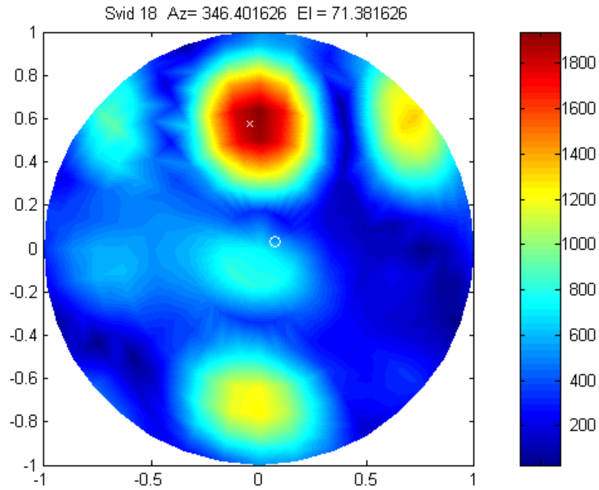

Figure 30 Tilted Array Data - SV 18

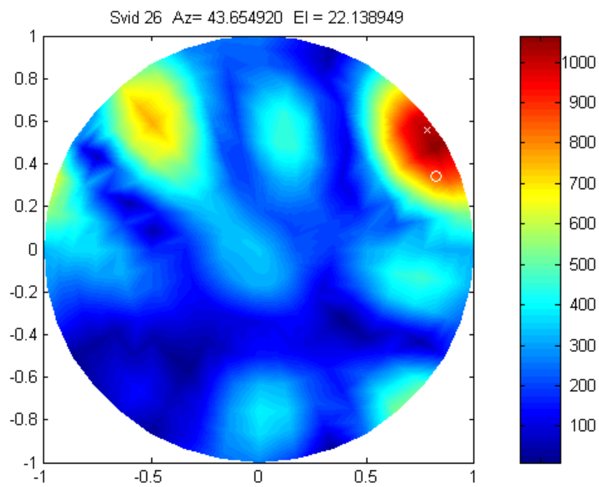

Figure 31 Tilted Array Data - SV 26

CONCLUSION

The multi-element digital storage capability enabled by NAVSYS' Digital Storage Receiver (DSR) technology provides a powerful tool for characterizing the multipath environment. In this paper, algorithms for detecting the presence and direction of multipath are described that were implemented using NAVSYS HAGR digital spatial processing GPS receiver. Test results showing the algorithm performance using simulated data sets and actual field test data are also presented. This test capability has application for characterizing multipath environments to optimize reference receiver site selection, and to qualitatively measure the magnitude of the multipath errors that can be introduced in the code and carrier phase which is important for safety critical GPS applications. The dynamic estimation capability of the multipath sources can also be used to detect and remove the effects of the multipath signal errors[4], which is of benefit for precision timing or positioning applications, such as surveying or precision approach and landing.

REFERENCES

[1] M. May, A. Brown, B. Tanju, "Applications of Digital Storage Receivers for Enhanced Signal Processing", Proceedings of ION GPS '99, Sept 1999, Nashville, TN

[2] A. Brown, N. Gerein, "Advanced GPS Hybrid Simulator Architecture", Proceedings of the 57th ION Annual Meeting, June, 2001, Albuquerque, NM

[3] A. Brown, R. Silva, G. Zhang, "Test Results of a High Gain Advanced GPS Receiver," ION 55th Annual Meeting, Cambridge, Massachusetts, June 1999

[4] A. Brown, "Multipath Rejection Through Spatial Processing", Proceedings of ION GPS 2000, Salt Lake City, Utah, September, 2000