GPS Multipath Mitigation Using a Three Dimensional Phased Array

Alison K. Brown and Ben Mathews, *NAVSYS Corporation*

BIOGRAPHY

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. She was a member of the GPS-3 Independent Review Team and the Interagency GPS Executive Board Independent Advisory Team, and is an Editor of GPS World Magazine. She is an ION Fellow and an Honorary Fellow of Sidney Sussex College, Cambridge.

Ben Mathews is the manager of the Digital Signal Processing, Modeling, and Simulation Section at NAVSYS Corporation. His work includes the design and development of NAVSYS advanced GPS systems including digital beam-steering, GPS jammer geolocation systems, and bistatic spatial signal processing. He holds a MSEE from Virginia Tech.

ABSTRACT

Digital beam steering with a phased array has previously been demonstrated to improve the Signal/Multipath (S/M) level for precision applications by providing gain in the direction of the GPS satellites. A disadvantage of using horizontal planar antenna arrays is that the beam pattern is symmetric in the Up/Down directions. This means that only the phased array ground plane affects the antenna array Up/Down ratio, which defines the relative gain between the satellite and a horizontally reflected multipath signal. By including both horizontal and vertical antenna element separation in an array design, multipath can be rejected, improving both the Up/Down gain ratio (for horizontal multipath sources) and also rejecting multipath from other directions.

In this paper the relative advantages of some alternative 3-D antenna array designs are shown, compared with conventional planar or vertical arrays. Simulation results are shown of the alternative antenna array properties and a 3-D antenna array that has been built and tested using our in-house digital beam-steering GPS receiver is presented.

INTRODUCTION

The development of advanced digital beam-forming GPS receivers now allows optimized spatial processing algorithms to be applied for GPS anti-jam protection. This same technology can also be extended to improve multipath rejection for high performance applications, such as for the Shipboard Relative GPS Joint Precision Approach and Landing system (SRGPS JPALS)[1].

Figure 1 CRPA and High-gain Advanced GSP Receiver (HAGR) Gain Stage on the Carrier Flight Deck

Under contract to NAVAIR, NAVSYS has developed an advanced digital beam-forming receiver, the HAGR-A, that uses a software GPS receiver architecture to apply adaptive digital spatial processing for anti-jam and multipath mitigation. This approach allows for high anti-jam protection and also allows for embedding integrity monitoring features within the GPS receiver to detect RFI, multipath, and antenna electronics failures. The HAGR-A has previously been tested using a conventional Controlled Reception Pattern Antenna (CRPA)[2] installed on an aircraft carrier (Figure 1). This test showed that the carrier environment experienced significantly higher multipath than a fixed installation. The test results also showed that beam steering removed significant portions of the multipath error at all elevations.

The test data also showed that multipath error mitigation at lower elevations was not as effective as that at higher elevations. This is due to the Up/Down symmetry in the beam-steering array pattern when using a conventional planar phased array such as the 7-element CRPA. For low elevation satellites, in particular, this limits the ability to reject multipath. In this paper, we describe how the digital spatial processing can be extended to allow beam-forming using three-dimensional (3-D) antenna arrays and present simulation results that demonstrate the advantages of some alternative 3-D antenna arrays in improving the Up/Down ratio for rejection of low elevation satellite multipath.

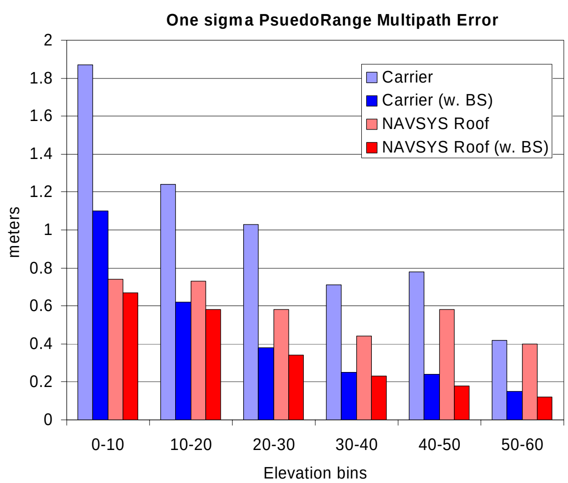

Figure 2 Pseudorange Multipath Error as a Function of Elevation[2]

HIGH-GAIN ADVANCED GPS RECEIVER (HAGR)

NAVSYS' High-gain Advanced GPS Receiver (HAGR)[3] is a software reprogrammable, digital beam-forming GPS receiver. The HAGR components are illustrated in Figure 3. With the HAGR digital beam-forming implementation, each RF input from an antenna element is converted to a digital signal using a Digital Antenna Element (DAE) card (Figure 5). The HAGR can be configured to operate with up to sixteen antenna elements (L1 and L2), which can be installed in any user-specified antenna array pattern. A 16-element Compact PCI form factor HAGR configuration is shown in Figure 6 and an 8-element L1/L2 1 ½ ATR form factor configuration is shown in Figure 7.

Each DAE card 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 where the spatial processing is performed under software control to generate the beam-forming solution for each satellite tracked (Figure 4). 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. For development purposes, we have also designed the capability to download the antenna array weights directly into the HAGR through a real-time MATLAB®/Simulink® interface.

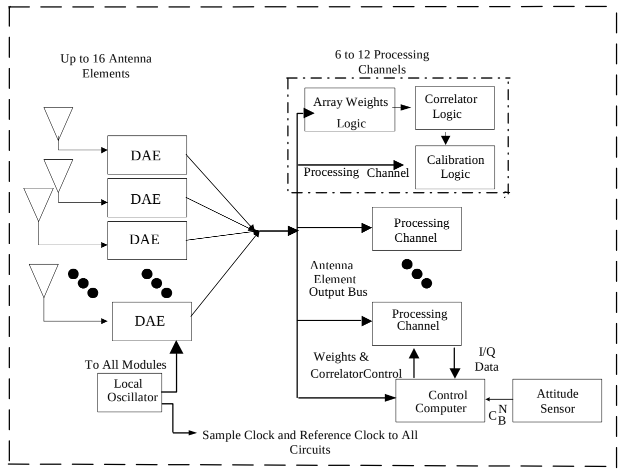

Figure 3 HAGR Spatial Signal Processing

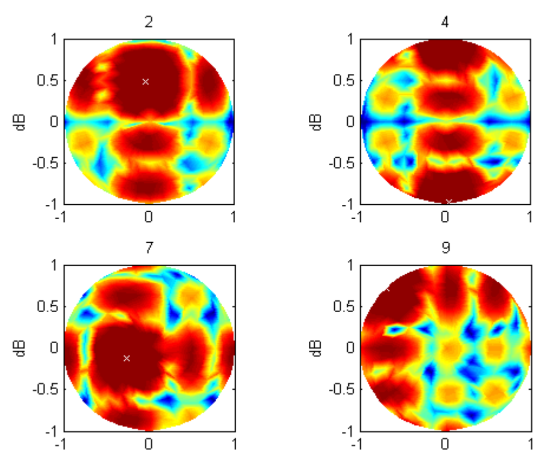

Figure 4 L1 Beam-Steering Antenna Patterns for Four GPS Satellites

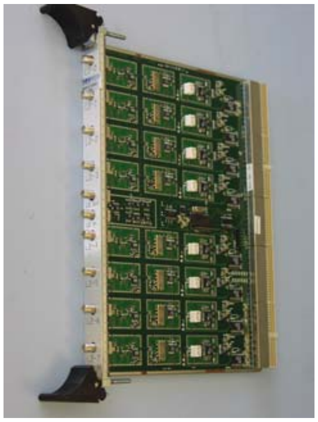

Figure 5 Digital Antenna Element card

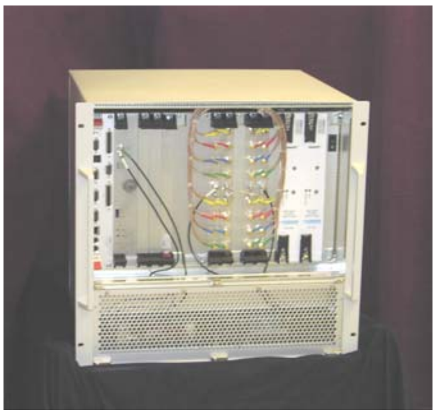

Figure 6 CPCI Form Factor HAGR receiver

Figure 7 HAGR-A 1 ½ ATR Form Factor receiver

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.

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

$$s_i(0,t)\sqrt{G_{\alpha_{ik}}}e^{j\theta_{ik}} = s_i(0,t)e_{sik}$$

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

$\underline{x}_k$ is the position of the kth antenna element

$\sqrt{G_{\alpha_{ij}}}$ is the antenna element gain in the direction of 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. With conventional beam-steering, the weights are applied to maximize the Signal/Noise of the GPS satellite signals assuming that the noise is Gaussian and that there is no interference present.

Beam-steering weights: $\underline{w}_{BS} = \underline{e}_s$

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.

$$R = E[\underline{y}(t)\underline{y}(t)']$$

Beam-forming weights:

$$\underline{w}_{BF} = R^{-1}C^H(CR^{-1}C^H)^{-1}\underline{e}_s$$

The constraint matrix C is selected so that the satellite signal power of the beam-formed solution is unchanged.

$$C\underline{w} = 1$$

The software design of the HAGR allows for advanced spatial processing to be applied to further improve multipath rejection by using three-dimensional antenna arrays. In the following section, the design of an adaptive beam-forming algorithm designed to maximize the Up/Down gain ratio towards the GPS satellite signals is described. This has the advantage of maximizing the rejection of multipath signals reflected from horizontal surfaces near the antenna array.

MULTIPATH BEAM-FORMING TO MAXIMIZE UP/DOWN RATIO

The design of the multipath beam-forming algorithm was selected to optimize the weights for a situation where multipath arrives from the same azimuth as the direct signal, but with negative elevation, at a power level 3dB down from the direct signal. The method used is a constrained optimization approach[4]. The first step in this algorithm is to create a "model" interference-only spatial correlation matrix of the multipath signal.

$$R_{ss} = A_m^2 S \cdot S^H + R / r_{SF} \approx A_m^2 S \cdot S + \sigma_n^2 I$$

S Steering matrix

A_m Amplitude of multipath signal ($\sqrt{\frac{1}{2}}$ in this case)

r_{SF} Scale factor to compute from R matrix

σ_n^2 Variance of white noise on each of the antennas

The steering matrix has dimensions of *KxN*, where *K* is the number of elements (7 in this case) and *N* is the number of interfering signals (1 in this case). The elements of the steering matrix are computed as follows, with subscript $_{ij}$ indicates for ith antenna and jth multipath signal:

$$S_{ij} = \sqrt{G_{\alpha_{ij}}} e^{j\theta_{ij}}$$

The second step is to perform the constrained optimization. This optimization minimizes the total power in the beam-formed signal in the direction of the steering matrix, subject to a gain requirement towards the desired signal:

$$\min_{\tilde{w}} \underline{w}^H R_{ss} \underline{w} \quad \text{subject to: } C\underline{w} = 1$$

Multipath Beam-forming Weights:

$$\underline{w}_{MBF} = R_{ss}^{-1}C^H\left(CR_{ss}^{-1}C^H\right)^{-1}\underline{e}_s$$

The relative amplitude of the multipath signal and the noise variance control the focus of the algorithm. A large noise variance (σ_n^2) shifts the focus toward creating weights with equal magnitudes, since this will provide most gain over noise. A small noise variance will move focus to placing lower gain in the direction of the multipath signal.

ANTENNA ARRAYS SIMULATED

Simulations were run to evaluate the relative performance benefits of the arrays shown in Figure 8 to Figure 12 and described below. Each of these antenna arrays were assumed to have 7 antenna elements, although the HAGR beam forming can operate with larger arrays. This allowed a comparison of the multipath rejection properties of the arrays where the only difference between the arrays was the geometry of the individual elements.

<u>Flat Antenna Array</u>

The flat antenna array modeled the performance expected using a conventional CRPA array. This has the antenna elements laid out in the symmetrical planar format shown in Figure 8. No improvement of the Up/Down ratio is possible using this array since the beam patterns are symmetric about the horizontal direction.

<u>Curved Antenna Array</u>

A curved version of the CRPA was modeled to evaluate the effect of adding some vertical dimension to the array, as shown in Figure 9.

<u>Stack Antenna Array</u>

A vertical array can be built using stacked dipoles. The simulation evaluated the effectiveness of the vertical array shown in Figure 10 for multipath rejection.

<u>Curved (B) Antenna Array</u>

Figure 11 shows an antenna array with a higher vertical profile. This also includes two rings of antenna elements which further breaks up the beam-forming symmetry allowing for better multipath rejection under some conditions.

Cross Antenna Array

Figure 12 shows an antenna that is laid out with a vertical dipole array (3 elements) surrounded by 4 elements in a horizontal plane. This "cross" configuration combines some of the advantages of a horizontal and a vertical antenna array.

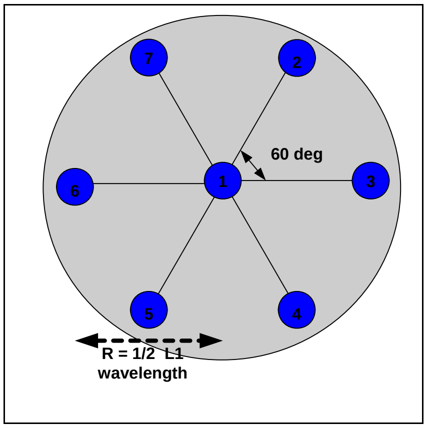

Figure 8 Flat 7-Element Antenna Array

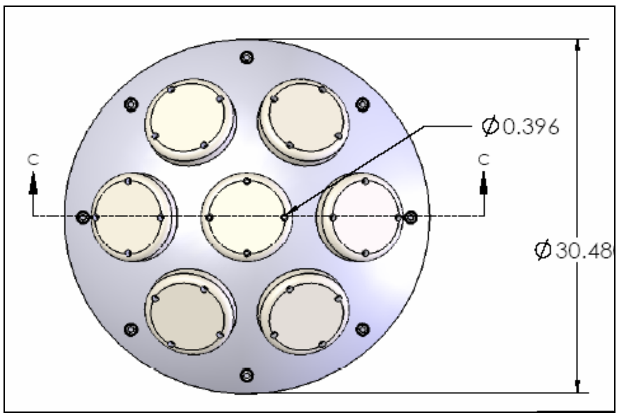

Figure 9 Curved 7-Element 3-D Antenna Array

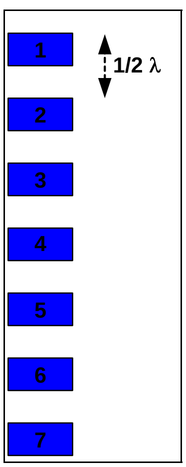

Figure 10 Stack 7-Element Antenna Array

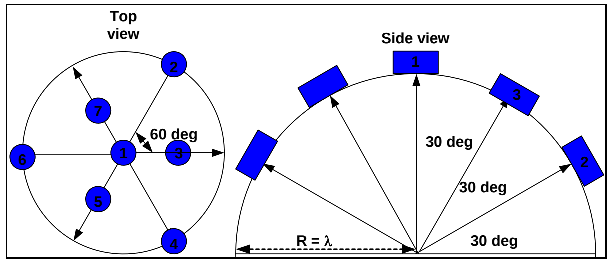

Figure 11 Curved (B) 7-Element 3-D Antenna Array

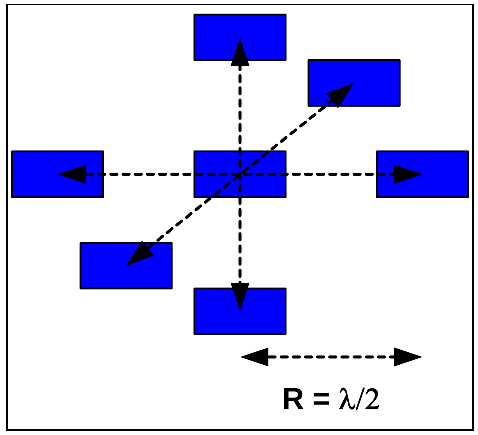

Figure 12 Cross 3-D 7-Element Antenna Array

SIMULATION RESULTS

The simulation was run to evaluate the performance of each of the different antenna array configurations. The following performance parameters were considered.

Gain: This defines the amount of gain that the beam-forming algorithm placed in the direction of the GPS satellites. This quantifies the C/N0 and J/S improvement that would be experienced from beam-steering.

Up/Down ratio: This defines the relative gain in the direction of the GPS satellite (up) relative to a multipath signal reflected from a horizontal surface (down).

The simulations were run first assuming straight beam-steering. These results show only the relative benefits of the antenna array pattern itself. Figure 13 and Figure 14 show the comparative performance of the different antenna arrays. The stack (vertical) antenna array showed the best performance in terms of the multipath rejection. This was expected as it has the most significant spatial discrimination in the vertical dimension. However, this array would also have the poorest performance if multipath was received from a vertical surface. The Curve (B) antenna had the lowest gain as the antenna ground plane and layout blocks some of the elements from viewing some of the satellites.

The simulations were then repeated using digital multipath nulling to improve the Up/Down ratio. The depth of the null in the direction of the multipath signal (down) is adjustable. Reducing the optimization parameter σ_n^2 will place more emphasis on nulling the multipath signal. This will increase the up/down ratio, but decreases gain towards the desired signal. Figure 15 and Figure 16 show the simulation results with an optimization parameter σ_n^2=1 and Figure 17 and Figure 18 show the simulation results with an optimization parameter σ_n^2=0.1.

With optimization parameter σ_n^2=1, the Up/Down ratio at 10 degrees elevation is improved from 3 dB to 5 dB for the Curve (B) antenna pattern with no noticeable change to the Gain towards the satellites. With optimization parameter σ_n^2=0.1, the Up/Down ratio is further improved to 10 dB although at low elevations the Gain towards the satellites is also affected.

Based only on the Up/Down ratio as figure of merit, the conclusion is that the vertical array performs best. However, with a vertical array, the symmetry in horizontal plane is now traded for a line-symmetry around the vertical antenna. The beam pattern is cone shaped. In the presence of vertical reflecting surfaces, its performance will degrade. Post processing cannot break this symmetry. The flat array is the obvious loser. Between the 3-D arrays, the cross performs better than the large curved array, both for gain and Up/Down ratio, although it may be a lot more difficult to build. The small curved array is still too close to a horizontal plane to effectively break the up down symmetry. All 3-D arrays would allow additional nulls placed after data collection to break vertical symmetry or deeper nulls if the multipath turns out stronger than expected.

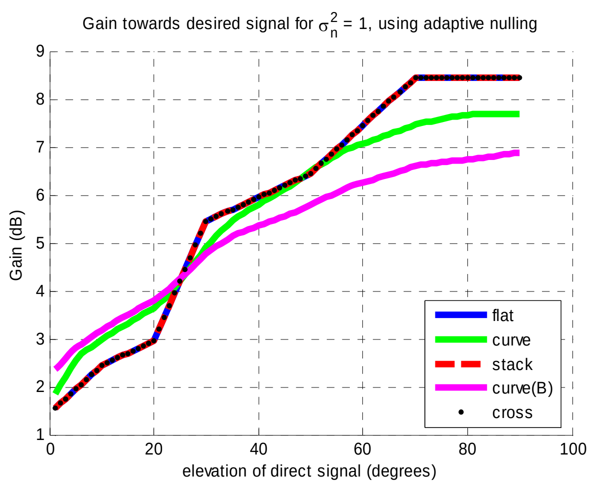

Figure 13 Gain Results without multipath reduction

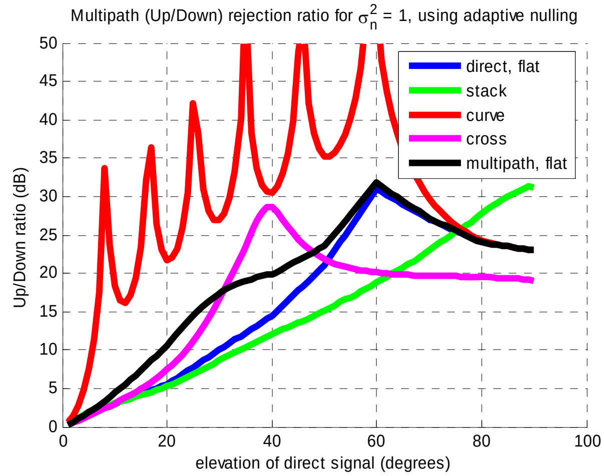

Figure 14 Up/Down Ratio Results without multipath reduction

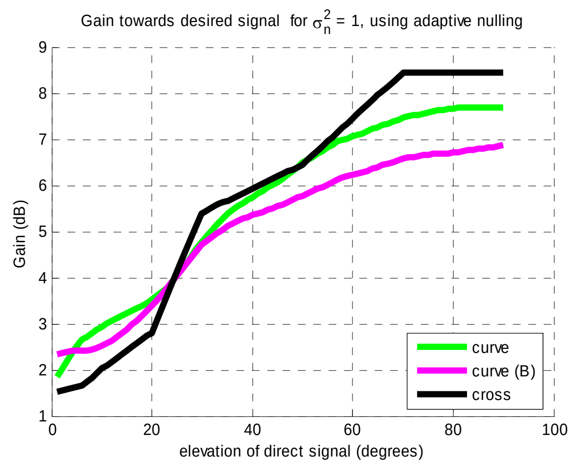

Figure 15 Gain Results with multipath reduction, σ_n^2 =1

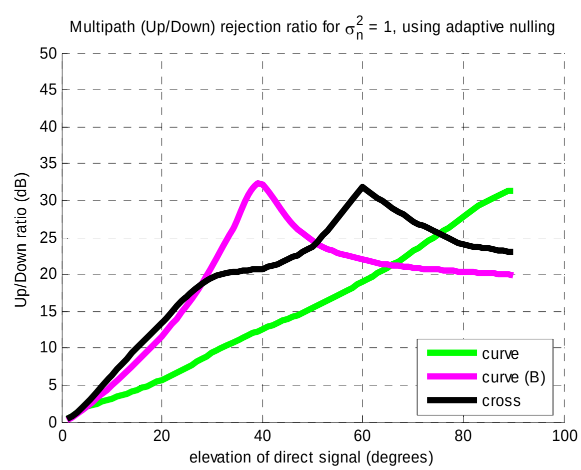

Figure 16 Up/Down Ratio Results with multipath reduction, σ_n^2 =1

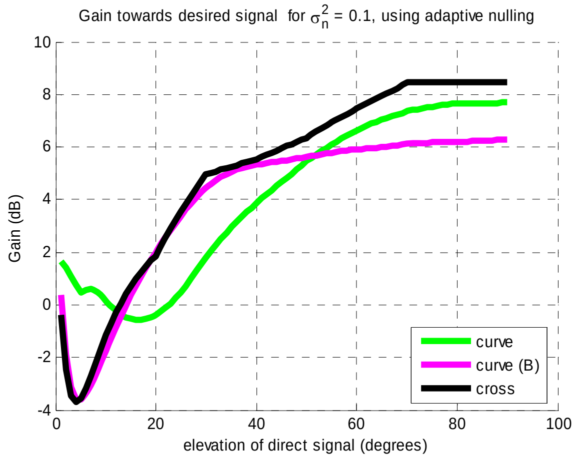

Figure 17 Gain Results with multipath reduction, σ_n^2 =0.1

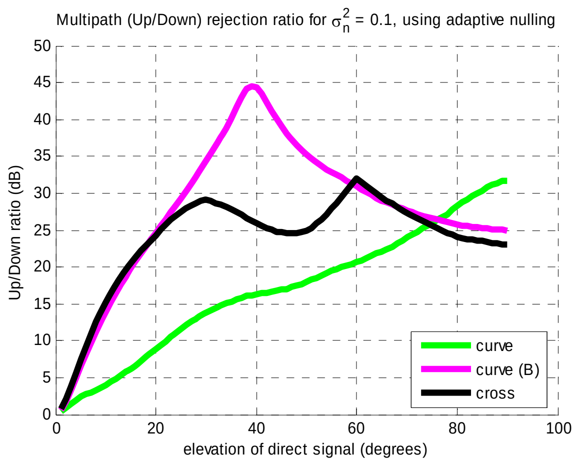

Figure 18 Up/Down Ratio Results with multipath reduction, σ_n^2 = 0.1

CONCLUSION

Based on the simulation results, the 3-D antenna array shown in Figure 11 had the best multipath rejection performance in both the horizontal and vertical dimensions. A prototype of this antenna array was built for field testing to evaluate its performance under representative conditions (see Figure 19).

Before any antenna array can be used for beam-steering, the relative phase offsets between the antenna elements must be calibrated so that they can be applied in the beam-forming weights[2]. The calibration process is more complex for a 3-D antenna array than for a 2-D antenna array as the antenna phase centers are a function of both the position of each element on the antenna array and also the azimuth and elevation of the satellite. Under contract to NAVAIR, NAVSYS isadding the capability to the HAGR-A shown in Figure 7 to allow it to perform built-in, real-time calibration of the antenna phase offsets for both 2-D and 3-D antenna arrays. The NAVSYS 3-D antenna was used to collect multipath test data on the USS Eisenhower in early summer of 2005. Test data was collected using NAVSYS' Digital Storage Receiver which allows the array data to be played back post-test into the HAGR for data analysis and comparison using different beam-forming algorithms. Data was also collected for comparison with a conventional CRPA antenna array. The test results from these field trials are currently being evaluated.

Further improvements in the multipath rejection performance can also be achieved by adding additional antenna elements. As an example, a potential 19-element array design is shown in Figure 20 that could be assembled in the same form factor as the 3-D array shown in Figure 19.

Figure 19 NAVSYS Prototype 3-D 7-Element Antenna Array

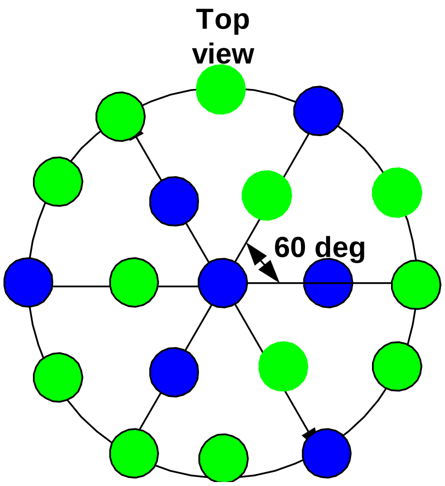

Figure 20 Conceptual 19-element 3-D Array

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D HAGR is being performed under SBIR Contract N68335-04-C-0053.

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