Small Controlled Reception Pattern Antenna (S-CRPA) Design and Test Results

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BIOGRAPHY

Dr. Huan-Wan Tseng is an Antenna & RF Engineer at NAVSYS Corporation. He has a Ph.D. from Ohio State University, an ME from University of Florida, and a BS from Tatung Institute of Technology (Taipei, Taiwan), all in Electrical Engineering.

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ABSTRACT

NAVSYS has developed a miniaturized GPS antenna array technology that reduces the size of the antenna elements and the array dimensions. This is an enabling technology, which allows GPS controlled reception pattern antenna arrays (CRPAs) with anti-jamming capability to be installed on vehicles where their size has previously prohibited their use. This includes aircraft where size and weight constraints resulted in fixed reception pattern antenna (FRPA) installations instead of CRPAs and in munitions applications where space and surface area are at a premium.

This paper presents test results of the NAVSYS six inch four element L1 antenna in an anechoic chamber. Test results include antenna impedance, mutual coupling, antenna element pattern, group delay, and adaptive patterns.

INTRODUCTION

A key factor in the array performance is the number of antenna elements. The more elements available, the more precisely a null can be steered in the direction of a jammer, improving the overall SNR and also allowing flexibility in placing nulls on jammers. The maximum number of jammers, which can be nulled by a GPS array, is equal to one less than the number of antenna elements (N-1). The more elements in a beam forming or null forming array, the greater the degree of directionality in the array and the greater the gain in the direction of the desired signals.

To prevent spatial correlation, the antenna array elements in a conventional array must be placed half a wavelength apart. This changes the relative phase shift between elements as a function of the input signal elevation angle so that there is no phase shift (0^o) when the signal is perpendicular to the array and a half cycle phase shift between elements (180^o) when the signal is horizontal to the array.

It is possible to shrink the size of the individual antenna elements by designing small patch elements using a high dielectric substrate. This will allow more antenna elements to be clustered closer together in the same over-all array footprint. The major innovation presented in this research effort is the introduction of a shaped high-dielectric superstrate, which allows reduction in the mutual coupling between elements and the same half-cycle phase relationship to be maintained between antenna elements as in a full-size array. The combination of these effects enable the over-all size of a GPS antenna array to be shrunk while still providing equivalent A/J protection to a full-size conventional GPS CRPA. This will allow the existing 7-element CRPA array of 14-inch diameter to be reduced to less than 6 inches in diameter.

NAVSYS MINI-ARRAY

The miniature array is composed of a ground plane, a substrate with the antenna elements on its surface, and a superstrate on top of the elements. The dielectric constant of the substrate is increased so that the size of the antenna elements can be reduced. By controlling the design of the antenna elements, the efficiency is increased so that they have the same gain as a standard GPS antenna element. By adjusting the dielectric constant and shape of the superstrate, the mutual coupling between the antenna elements is minimized and the reduced antenna spacing is scaled so that it appears to be effectively $\lambda/2$ in its beamforming or null steering performance. However, the shape of the superstrate has an appreciable effect on the shape of the individual element patterns and must be taken into account.[1]

Figure 1 and Figure 2 show views of the 4-element, 6 inch version of the NAVSYS mini-array. This was tested by Lincoln Laboratory to measure its antenna characteristics. The results of this testing are described in the following sections of the paper.

[1] Dale Reynolds,et al, “Miniaturized GPS Antenna Array Technology and Predicted Anti-Jam Performance”, ION GPS ’99, 14-17 September 1999, Nashville, TN.

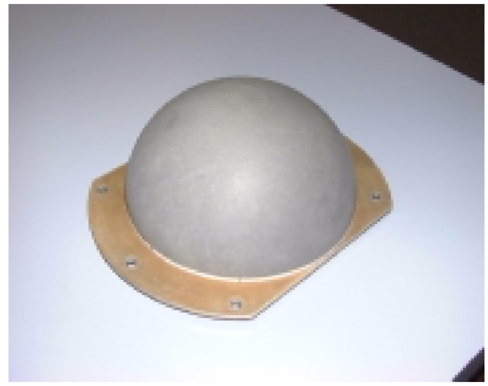

Figure 1 Six Inch Mini Array

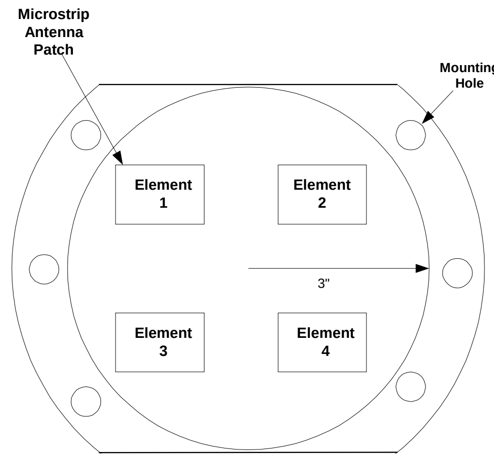

Figure 2 Top view of the 4-element mini-array configuration

ANTENNA RETURN LOSS

Figure 3 shows an example of the NAVSYS antenna return loss. The VSWR varied from 1.44 to 1.55 between elements.

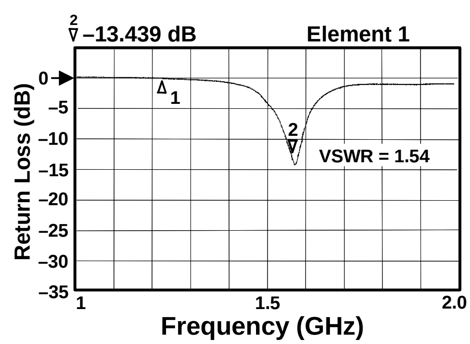

Figure 3 Measured Return Loss of Element 1

MUTUAL COUPLING

Figure 4 shows an example of the NAVSYS mutual coupling measurements. The mutual coupling at L1 varied from –12.684 to –23.934 dB between elements.

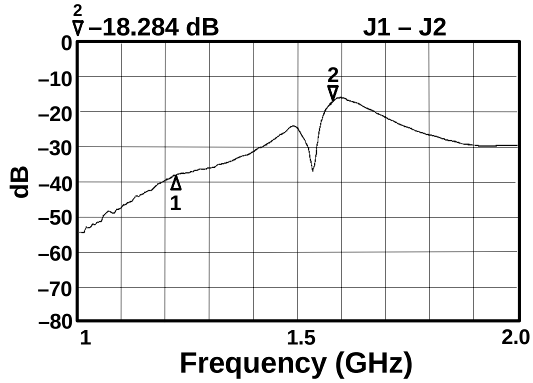

Figure 4 Mutual Coupling Between Element 1 and Element 2

ANTENNA GAIN AND PHASE

Figure 5 shows the gain and Figure 6 shows the phase of the NAVSYS antenna at the L1 frequency band using an 18 inch diameter ground plane.

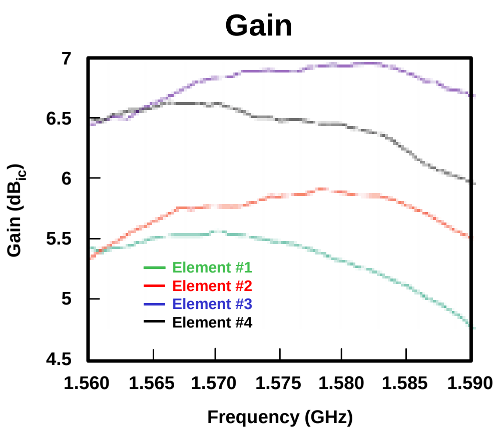

Figure 5 Gain Measurement at L1 (With 18” Diameter Ground Plane)

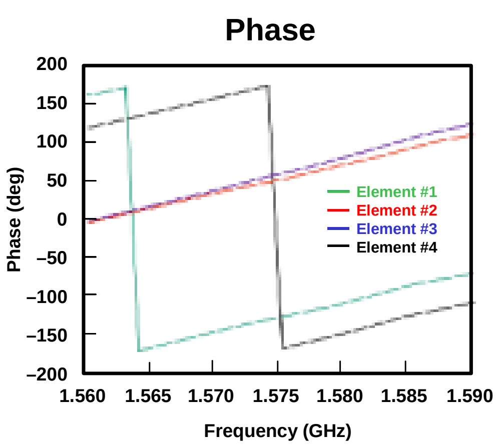

Figure 6 Phase Measurement at L1 (With 18” Diameter Ground Plane)

GROUP DELAY RESPONSE

The group delay response of the NAVSYS antenna over all angles at L1 is shown in Figure 7 and Figure 8.

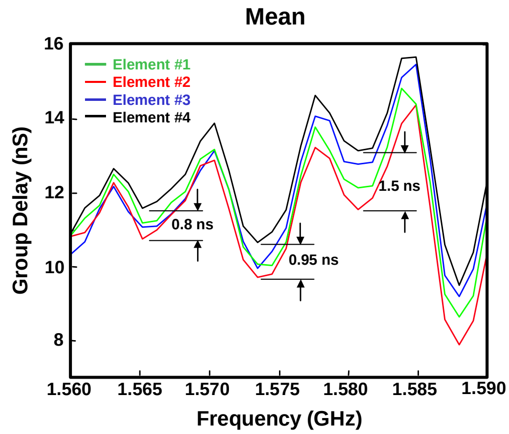

Figure 7 Group Delay Response at L1

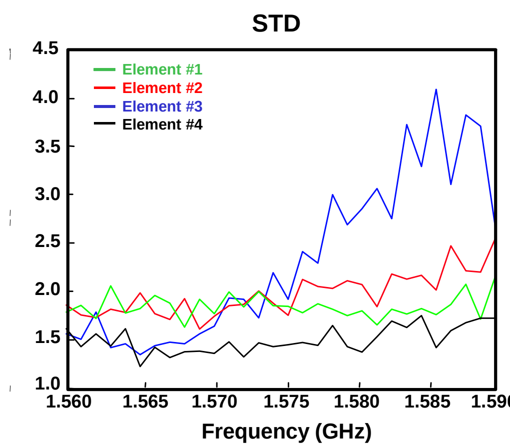

Figure 8 Standard Deviation of Group Delay Response at L1

ANTENNA ELEMENT PATTERNS

The NAVSYS antenna element patterns at L1 using an 18” diameter ground plane (AUT Receive) are shown in Figure 9 through Figure 12 for Right Hand Circular Polarization (RHCP). The element patterns are squinted due to the refracting effect of the hemispherical superstrate, the implications of which are addressed in the next section.

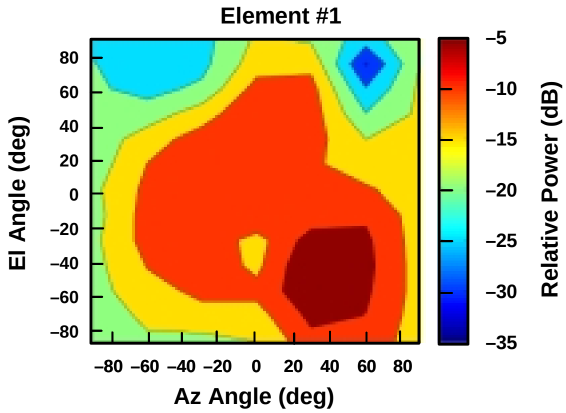

Figure 9 Element #1 Pattern (RHCP) at L1

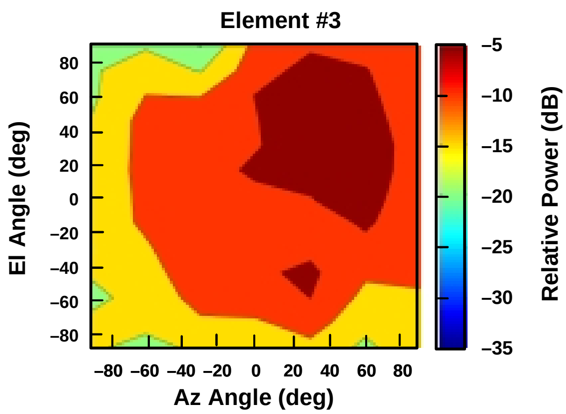

Figure 10 Element #3 Pattern (RHCP) at L1

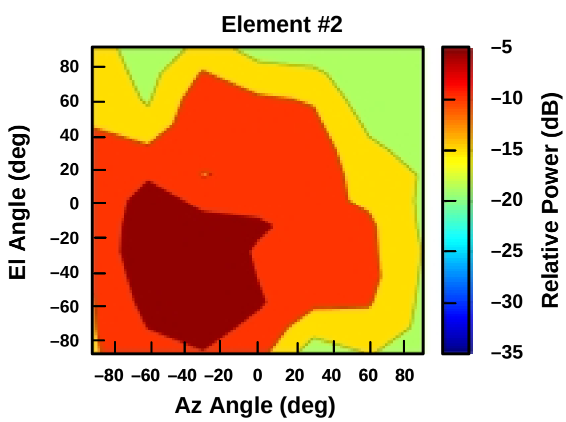

Figure 11 Element #2 Pattern (RHCP) at L1

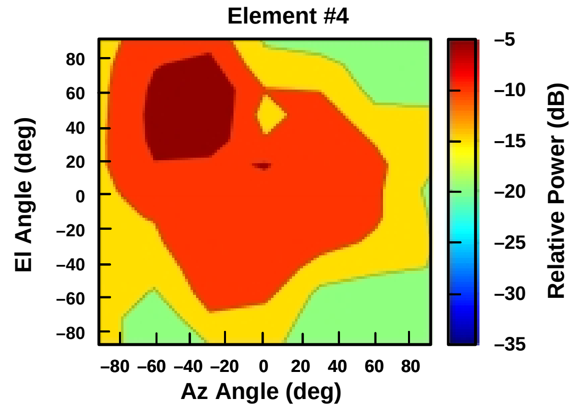

Figure 12 Element #4 Pattern (RHCP) at L1

AXIAL RATIO PERFORMANCE

Figure 13 shows the axial ratio of one of the antenna elements over the L1 band. The axial ratio performance of the array is poor indicating at most 3 dB of polarimetric loss (polarimetric mismatch between the array and the satellite signal). Since this array has been used successfully to receive GPS signals the 3 dB loss in SNR due to the polarimetric mismatch has been found to be of no consequence.

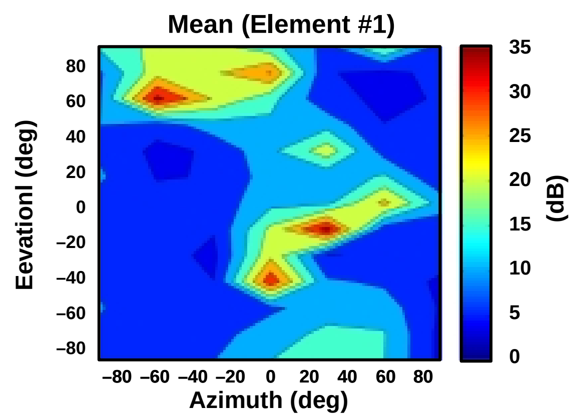

Figure 13 Element #1 Axial Ratio Over L1 Band

MEAN TIME RESPONSE

Figure 14 and Figure 15 shows the mean and standard deviation of time response of the NAVSYS Antenna over all angles at L1 for 24 MHz bandwidth using an 18” diameter ground plane. The time-response results suggest that the antenna is only mildly dispersive and should have a negligible distorting effect on GPS signals. The time domain channel match appears to be excellent.

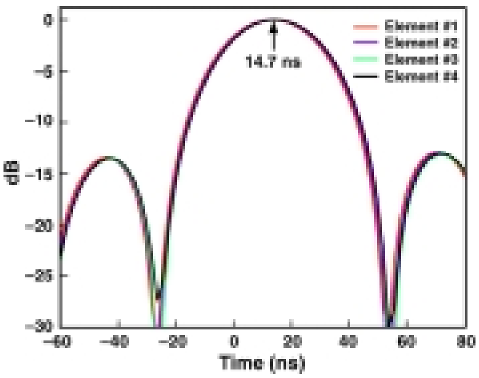

Figure 14 Mean Time-Responses for NAVSYS Antenna at L1 (24 MHz) Over all Angles

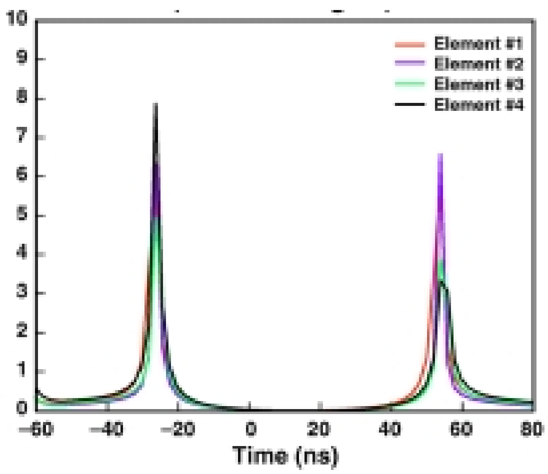

Figure 15 Standard Deviation of Time-Responses for NAVSYS Antenna at L1 (24 MHz) Over all Angles

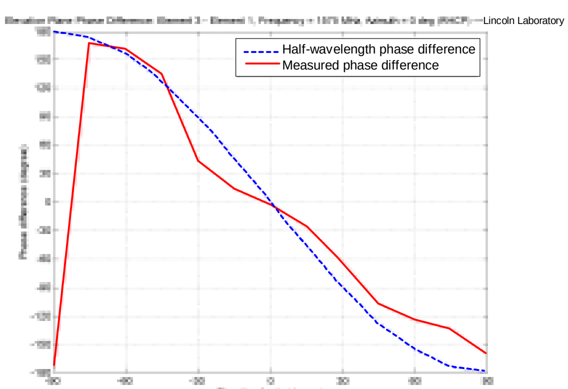

Figure 16 Half-wavelength and measured phase difference between antenna element 3 and 1.

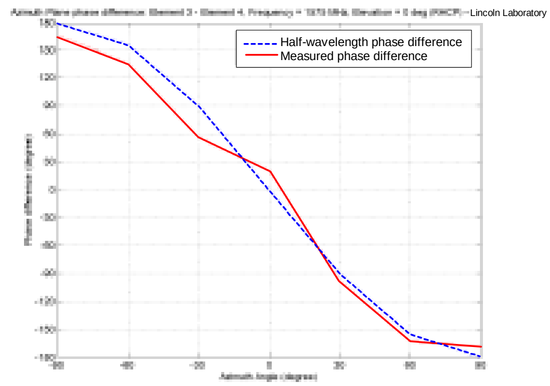

Figure 17 Half-wavelength and measured phase difference between antenna element 3 and 4.

Figure 16 and Figure 17 show the half-wavelength and measured phase difference between antenna elements of the mini-array. The measurements confirm that the mini-array indeed preserves the half-wavelength electric spacing between the antenna elements.

The miniature array was also tested using digital antenna electronics developed by NAVSYS to measure the phase relationship between the antenna elements. Based on our theoretical analysis, the observed phase angle between the antenna elements was expected to remain within 0.05 cycles of the phase angle observed in a full-size conventional array. Test data was collected using actual GPS satellite observations and also in an anechoic chamber. In Figure 18 and Figure 19 the observed phase difference between antenna elements is plotted against the incident angle of the received satellite signal. These figures also show the theoretical phase angle separation that would be expected for a full-size conventional array (0.5 cycles between elements or 0.5√2 cycles across the array diagonal), and for a reduced size conventional array with the same physical antenna separation as in the mini-array (0.22 cycles between elements and 0.32 cycles across the diagonal). The actual performance of the mini-array is clearly following the theoretical performance providing the same phase relationship as full-size conventional array in the reduced form-factor.

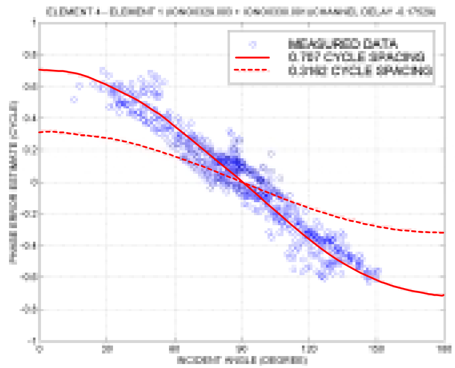

Figure 18 Mini-Array Phase Relationship between diagonal antenna elements using GPS satellite observations

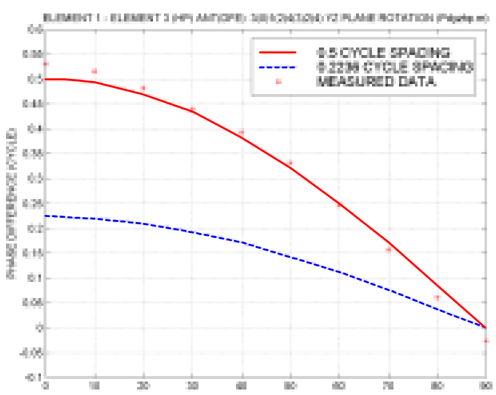

Figure 19 Mini-Array Phase Observations in anechoic chamber between adjacent antenna elements

Because the antenna would be out of frequency, no data is available to show the element pattern in the absence of the superstrate.

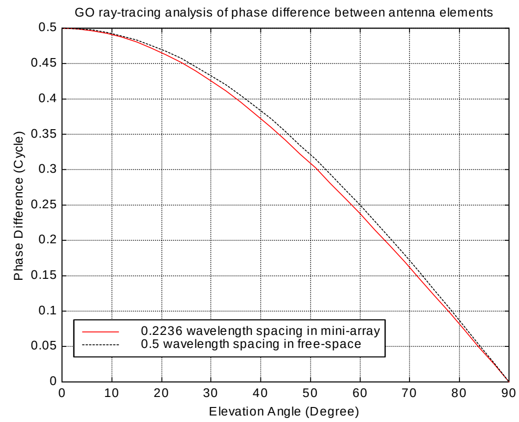

Figure 20 Comparison of the phase difference between antenna elements with a half-wavelength spacing in free-space and with 0.2236 free-space wavelength spacing in the mini-array by using GO ray-tracing method.

It is interesting to note that the measurements of the phase difference between antenna elements agree with our theoretical prediction by using geometric optics (GO) ray-tracing method. Figure 20 shows the comparison of the phase difference between antenna elements with a half-wavelength spacing in free-space and with 0.2236 free-space wavelength spacing in the mini-array by using GO ray-tracing method. The figure predicts that it is possible to preserve the half-wavelength electrical spacing by using a high dielectric lens with a small footprint. By comparing the theoretical prediction and the measurements, it is surprising to know that the GO ray-tracing method works even for such an electrically small antenna array structure.

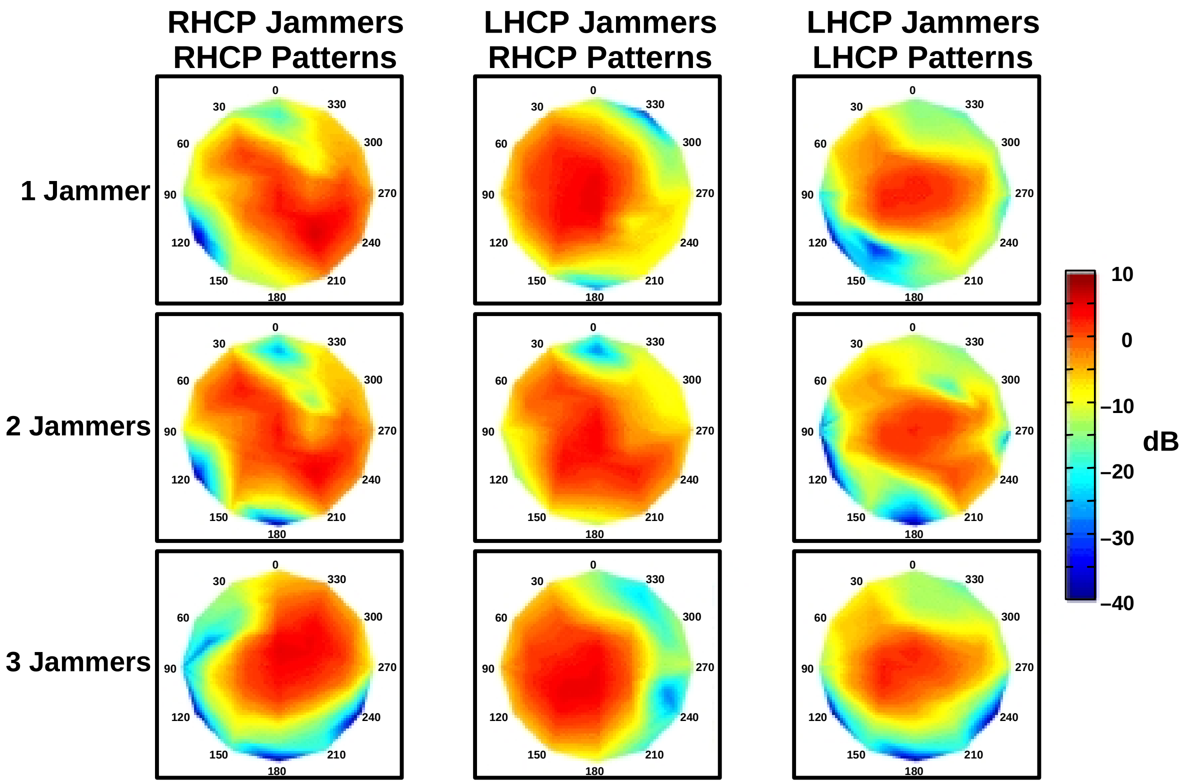

Figure 21 NAVSYS Adaptive Patterns L1 20 MHz Bandwidth Jammers

ADAPTIVE PATTERN

Figure 21 illustrates the adaptive patterns at L1 for 20 MHz bandwidth jammers using a steering vector which approximates the transpose of (1,1,1,1) and was obtained directly from the antenna measurements. For the NAVSYS antenna which has squinted beams, using (1,1,1,1)T instead of (1,0,0,0)T, which is used for the GAS-1 A/E processor, is preferable. NAVSYS does not have data available to show the comparison.

The test data evaluates the mini array's beam-steering and null-steering performance. These results include a matrix of RH/LH polarized jammers and patterns. The Mini-Array was able to null up to three jammers while still providing gain across much of the field of view on the GPS satellites tracked. The adaptive patterns were obtained by a covariance matrix inversion with jammer ERP of 50 dBW, a jammer-to-noise ratio of 47.6dB, and a signal-to-noise ratio of 0 dB where the antenna gain is 0 dBic. The adaptive performance is quite good even against cross-polarized jammers. The coverage is shown in the two RHCP patterns, and the nulls are shown in the RHCP jammer/pattern and the LHCP jammer/LHCP patterns.

MILITARY AND COMMERCIAL APLICATIONS

Many of the smaller munitions in operation or in development do not have a form factor that allows for a conventional CRPA to be installed. Because of size and weight constraints, some host aircraft within the Air Force and Navy have also elected to install FRPA antennas which cannot provide the A/J protection needed in many tactical environments. The GPS mini-array will enable A/J capability to be provided on many small munitions, aircraft and other host vehicles where the size and weight of the conventional CRPA array has previously been prohibitive. For example, current programs, such as the Joint Direct Attack Munition (JDAM), Joint Air-to-Surface Standoff Missile (JASSM), and the Joint Standoff Weapon (JSOW), will be able to benefit from the reduced size but full performance of the mini-array technology.

Commercial applications also exist for the Mini-Array. The digital beam-forming has been proven to give performance advantages for precision GPS applications[2]. The small size of the Mini-Array enables antenna arrays to be used for many precision GPS applications, including surveying, precision vehicle guidance and kinematic GPS applications

CONCLUSION

The benefits of the Mini-Array and digital beam-steering electronics are summarized below.

- Small antenna array footprint reduces installation costs
- Size and weight of antenna array are reduced
- Mini-array is compatible with existing GPS anti-jam electronics

ACKNOWLEDGEMENTS

MIT Lincoln Laboratory provided the data and generated the results within as part of a GPS JPO program to evaluate commercially available small GPS adaptive arrays.

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[2] A. Brown, R. Silva, E. Powers, "High-Gain Advanced GPS Receiver for Precision GPS Applications," Proceedings of GNSS 2000, Edinburgh, Scotland, May 2000.