Design, Simulation, and Testing of a Miniaturized GPS Dual-Frequency (L1/L2) Antenna Array

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BIOGRAPHY

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Dean Nathans is the Head of the GPS and Navigation Systems Product Development Team Branch at SPAWAR Systems Center. He holds a BSEE from Rutgers College of Engineering and an MEE from Villanova University. Mr. Nathans' responsibilities include Navy Navigation Warfare programs in support of the Navy's Navigation Systems Program Office at SPAWAR, as well as the Office of Naval Research and the GPS Joint Program Office. Mr. Nathans has been employed by the Navy in the Communications and Navigation Technology areas as an engineer, project manager, and supervisor for twenty three years.

Dr. Edmond Wong is a scientist involved with navigation Systems at SPAWAR Systems Center. He has a PhD in Acoustic Engineering from Penn State University. His experience is in the area of signal processing, array beam forming, GPS AJ antennas and GPS direction finding.

ABSTRACT

NAVSYS Corporation has developed a 7-element GPS L1/L2 Small Controlled Reception Pattern Antenna (S-CRPA) packaged in a 7-inch form factor. In order to further reduce the footprint of the antenna array such that

the GPS technology can be more widely adopted, NAVSYS Corporation teamed up with SPAWAR Systems Center, Naval Research Laboratory, and EDO Corporation under ONR sponsorship to design and develop a 7-element dual-frequency L1/L2 S-CRPA in a 5.3-inch form factor.

This paper will report the design and simulation of the 5.3-inch 7-element L1/L2 S-CRPA and present measurements of the antenna array prototype. Simulation and test results will be summarized including the input impedance of antenna elements, the mutual coupling between antenna elements, the radiation pattern of the antenna elements, and the antenna array performance when integrated with antenna electronics and used for GPS navigation.

INTRODUCTION

This paper presents the design, simulation, and testing of a 5.3" 7-element GPS dual-frequency (L1/L2) S-CRPA based on the miniature antenna array (Mini-Array) technology developed at NAVSYS. The purposes of the Mini-Array technology are to reduce the footprint of the antenna array and at the same time to preserve the half-wavelength phase difference (e.g. at L1 frequency) between the antenna elements.[1-5] In NAVSYS's current implementation of the GPS dual-frequency (L1/L2) S-CRPA, a solid high dielectric hemispherical lens is used above the seven antenna elements to bend the incoming wave to provide the half-wavelength phase difference between the antenna elements. Each microstrip dual-frequency antenna element consists of stacked patches. This S-CRPA reported here has been designed to fit within a 5.3" diameter footprint. The diameter of this new 5.3" S-CRPA is only 38% of the existing 7-element GPS Antenna System (GAS), in use by the Department of Defense, which has a 14.1" diameter. In terms of footprint area, this new S-CRPA occupies only 14% of that of the traditional 7-element GAS. Because the size of the antenna elements needs to be very small in order to fit into the S-CRPA footprint, it becomes more difficult and not very efficient to develop these antenna elements by cut-and-try method, and a detail and accurate computer simulation is needed prior to prototyping to reduce the time and cost of the development.

The design and simulation reported here represent the progressive efforts involved in the development and improvement of this new S-CRPA. In the development, a single probe-feed antenna element was first designed by NAVSYS and simulated by the Naval Research Laboratory (NRL). This single-probe antenna element design was initiated because of the potential benefits of simpler construction and lower cost as compared with a dual probe-feed design. One antenna element prototype was fabricated and measured to verify the accuracy of the simulation. Based on the simulation results, the problems of the new S-CRPA with single probe-feed design were identified and necessary modifications were determined. It was found that the single probe-feed design could not meet all the specifications of the S-CRPA, and it was necessary to adopt a dual probe-feed design. Based on their experience in designing and manufacturing conventional CRPA, EDO Corporation took the challenge of improving the antenna element design using a dual probe-feed structure. One 5.3" 7-element GPS L1/L2 S-CRPA prototype was successfully designed, simulated, built, and tested by EDO Corporation based on NAVSYS' Mini-Array technology. The preliminary test results reported in this paper demonstrate very good performance from this new 5.3" S-CRPA.

DESIGN OF 5.3" 7-ELEMENT GPS (L1/L2) S-CRPA

Figure 1 shows the configuration of the 5.3" 7-element GPS dual-frequency (L1/L2) S-CRPA. The array consists of one center reference antenna element and six peripheral antenna elements located on the corners of a hexagon. This configuration is similar to that of the existing 14.1" diameter CRPA. A solid high dielectric hemisphere is used as a lens to cover the seven antenna elements. Each dual-frequency antenna element consists of stacked microstrip patches on top of high dielectric substrates. The probe-feed structure is adopted in the design to satisfy the mechanical and physical requirements. Two kinds of antenna elements were developed in sequence. The first one was with a single probe-feed for the sake of simplicity, easy construction, and low cost.

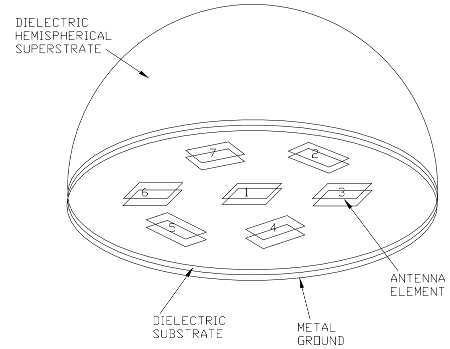

Figure 1 Configuration of 5.3" 7-element GPS dual-frequency (L1/L2) S-CRPA

The simulation method and simulation results of this single probe-feed design are described in the next sections. Some of the simulation results were compared with the prototype measurements to validate the accuracy of the simulation.

SIMULATION METHOD AND SIMULATION RESULTS OF THE SINGLE PROBE-FEED DESIGN

NRL uses the finite difference time domain (FDTD) method to simulate the single-probe feed antenna element and the antenna array. The FDTD is based on Cartesian coordinates and rectangular grids with grid size of 0.635 × 0.635 × 0.381 mm. Liao's second order boundary conditions.[6] are used to truncate the computation space about 16 cells from the edges of the structure. Simulations are run for 8000 time steps with a time increment of 0.97 psec. The active port is a one-cell voltage gap excited by a modulated Gaussian wave with a 50-Ohm load, and the passive ports are terminated by one-cell 50-Ohm loads. The computer system used for the simulation is a Linux cluster of 14 nodes with a total memory of 10.7 Gbytes. Figure 2 and Figure 3 show the simulated input impedance and VSWR of the antenna element versus the prototype measurement results. The measurements were conducted with an HP-8753C network analyzer at NAVSYS. The simulated input impedances and VSWRs for the single probe-feed antenna element design were sufficiently close to the measured impedances and VSWRs in Figures 2 and 3, that we judged that the FDTD simulation for other antenna characteristics could be used to infer the performance of the entire antenna array. Figure 4 shows the simulated mutual coupling between antenna element 1 (the center element) and the six peripheral elements. The mutual coupling is always below –17 dB in both the L1 and L2 bands. Figure 5 shows the simulated mutual coupling between antenna element 2 and the other six antenna elements. There is a stronger mutual coupling (approximately –13 dB) between element 2 and 5. Figure 6 and Figure 7 show the simulation results of the two orthogonal radiated field components of the antenna element versus the elevation angle and the frequency. The radiated fields are highly linearly polarized as seen in these simulated results. Figure 8 and Figure 9 show the simulated right-hand circular polarization (RHCP) antenna element radiation pattern at 1575 MHz and at 1227 MHz, respectively. These two figures reveal that the radiation pattern of the antenna element with single probe-feed is not very uniform.

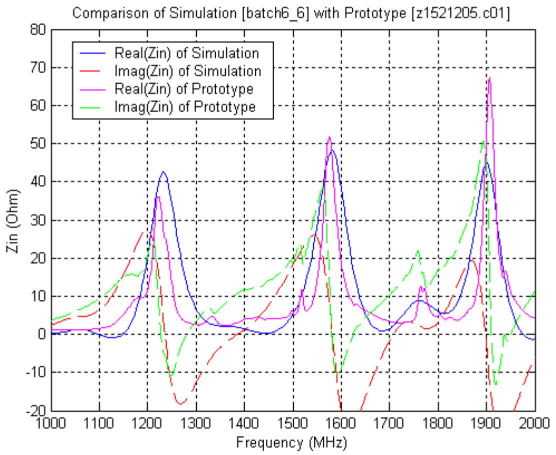

Figure 2 Comparison of simulated and prototype measurement of input impedance of antenna element (single probe-feed design)

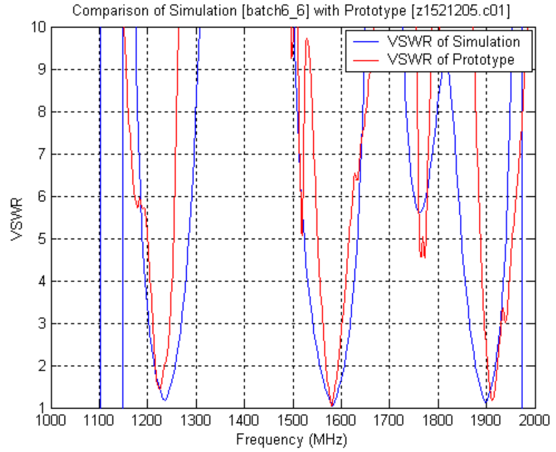

Figure 3 Comparison of simulated and prototype measurement of VSWR of antenna element (single probe-feed design)

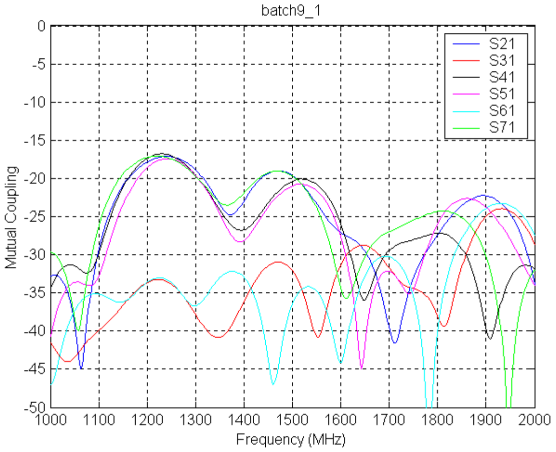

Figure 4 Simulated mutual coupling between the center element (element 1) and the peripheral elements (element 2 to 7) (single probe-feed design)

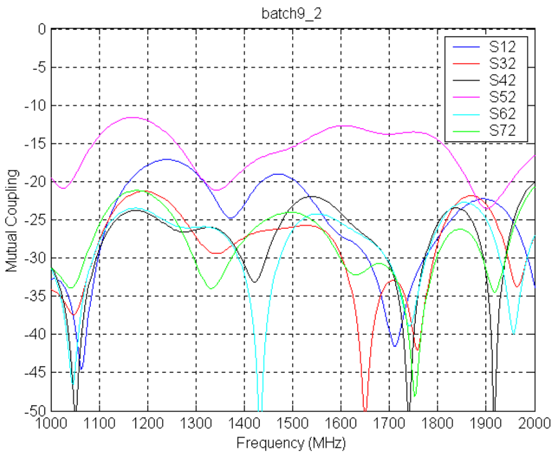

Figure 5 Simulated mutual coupling between antenna element 2 and the other antenna elements (single probe-feed design)

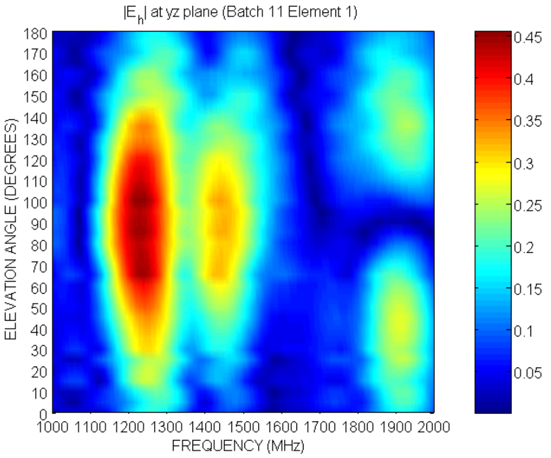

Figure 6 Simulation of one of the two orthogonal radiation field components versus frequency and elevation angle (single probe-feed design)

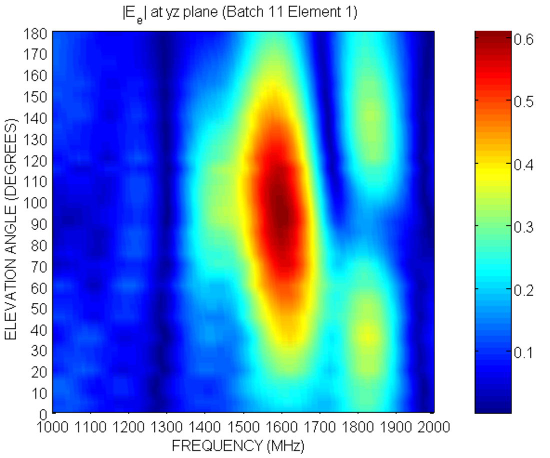

Figure 7 Simulation of the other orthogonal radiation field components versus elevation angle and frequency (single probe-feed design)

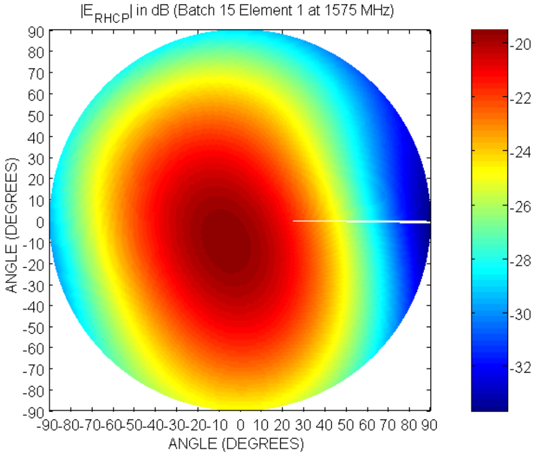

Figure 8 Simulated RHCP radiation pattern of the center antenna element at 1575 MHz (single probe-feed design)

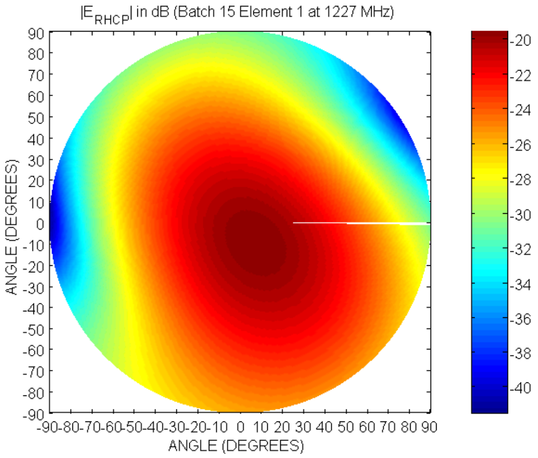

Figure 9 Simulated RHCP radiation pattern of the center antenna element at 1227 MHz (single probe-feed design)

CONCLUSIONS FROM THE SIMULATIONS OF THE SINGLE PROBE-FEED ANTENNA ELEMENT DESIGN

Based on NRL's simulation results, several problems were identified with the single probe-feed antenna element design:

1. The antenna impedance bandwidth is narrow, and it is very difficult to tune the antenna element.
2. The mutual coupling between diagonal antenna elements is relatively high, and it needs to be reduced.
3. The radiation field from the antenna element is linearly polarized. The S-CRPA requires a right-hand circularly polarized antenna element.
4. The radiation pattern is not very uniform.

The main lesson we learned from the simulations of the single probe-feed antenna element design is that it cannot provide enough degrees of freedom to address and satisfy the many S-CRPA requirements. For example, on the one hand if the probe-feed is located at specific location to satisfy the resonant frequency and impedance bandwidth requirement then it cannot satisfy the axial ratio or radiation pattern requirement because it is not at a symmetric location, and on the other hand if the probe-feed is located at a symmetric location then it cannot satisfy the impedance bandwidth requirement. In essence, theoretically it might be possible to use a single probe-feed to satisfy all the requirements, but in practice it is very difficult. In order to overcome the difficulties of the single probe-feed design, a dual probe-feed antenna element design is needed. The dual probe-feeds can provide more degrees of freedom to address each individual requirement. For example, the positions of the two probe-feeds can be properly located to satisfy the resonant frequency and impedance bandwidth requirements, and the signals from the two probe-feeds can be combined correctly to satisfy the axial ratio requirement. Even though the dual probe-feed antenna element is much more involved as compared with the single probe-feed antenna element, the complexity is justified based on the stringent S-CRPA requirements.

MINIATURIZED ANTENNA ARRAY WITH DUAL PROBE-FEED ANTENNA ELEMENTS

EDO Corporation took the challenge to improve the antenna elements with a dual probe-feed design. The antenna element for the new S-CRPA was designed by NAVSYS Corporation and simulated by NRL. The antenna element prototypes were fabricated and measured at EDO Corporation to validate the simulation results. The simulation results are very close to the measurements. Only the measurement results are presented in this paper. The antenna element measurements include the VSWR, mutual coupling, axial ratio, and the radiation pattern. Figure 10 shows the picture of the new 5.3" 7-element GPS dual-frequency (L1/L2) S-CRPA with dual probe-feed antenna element design.

Figure 10 Picture of the new 5.3" 7-element GPS dual-frequency (L1/L2) S-CRPA

VSWR Measurements of Antenna Elements

Figure 11 through Figure 14 show typical VSWR measurements of the antenna elements in the L1 and L2 bands. As shown in these figures, the impedance bandwidth in both frequency bands is more than 200 MHz (VSWR < 2.0:1.0). The VSWR measurements were conducted at EDO Corporation with a network analyzer.

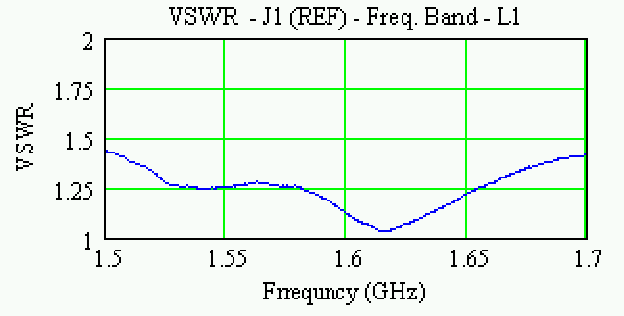

Figure 11 Measured VSWR of element 1 in L1 band (dual probe-feed design)

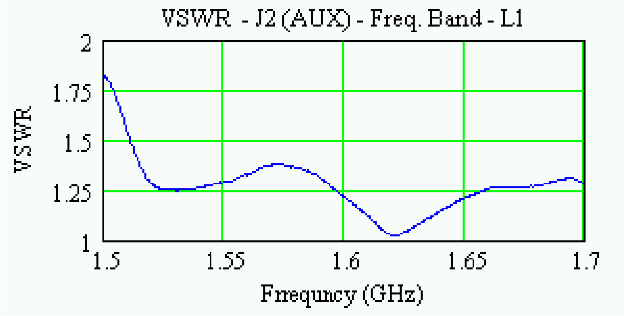

Figure 12 Measured VSWR of element 2 in L1 band (dual probe-feed design)

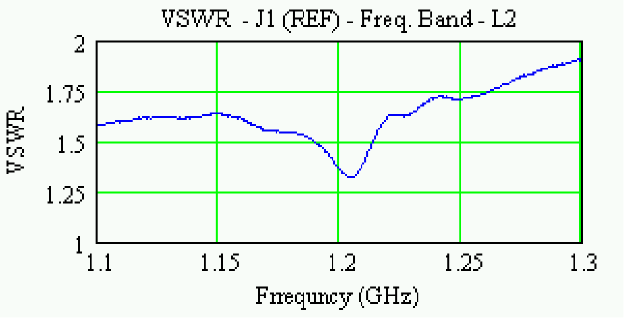

Figure 13 Measured VSWR of element 1 in L2 band (dual probe-feed design)

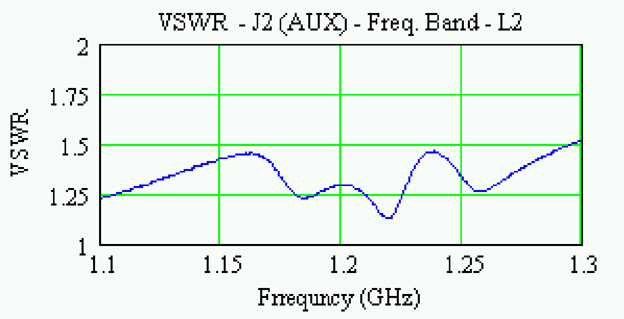

Figure 14 Measured VSWR of element 2 in L2 band (dual probe-feed design)

Mutual Coupling

Figure 15 through Figure 18 show typical mutual coupling between the antenna elements in the two frequency bands. In general, the mutual coupling is always below –15 dB even though the antenna elements are closely located next to each other. The mutual coupling measurements were conducted at EDO Corporation with a network analyzer.

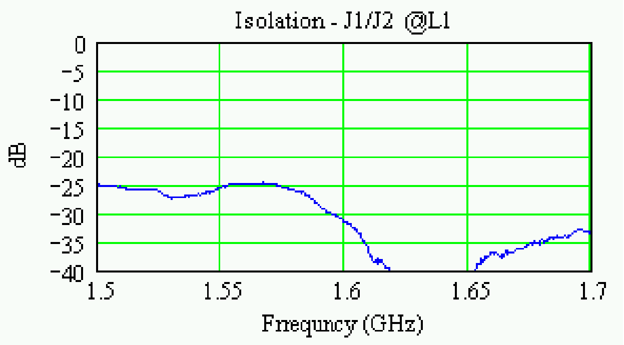

Figure 15 Measured mutual coupling between element 1 and 2 in the L1 band (dual probe-feed design)

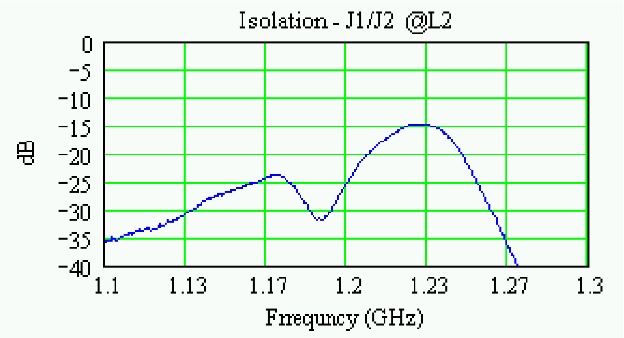

Figure 16 Measured mutual coupling between element 1 and 2 in the L2 band (dual probe-feed design)

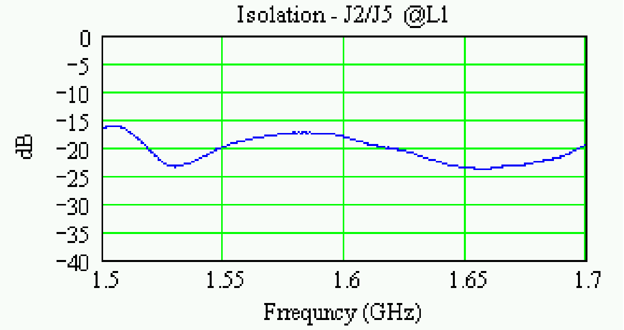

Figure 17 Measured mutual coupling between element 2 and 5 in the L1 band (dual probe-feed design)

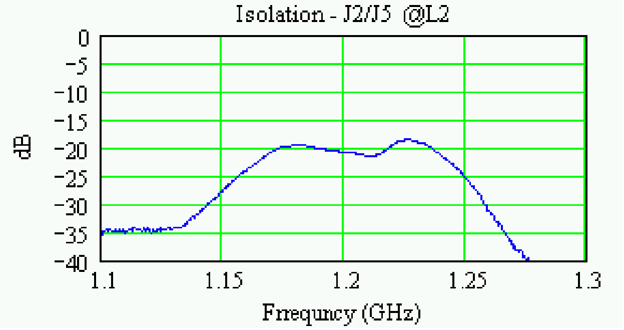

Figure 18 Measured mutual coupling between element 2 and 5 in the L2 band (dual probe-feed design)

Axial Ratio

Table 1 shows the measured axial ratio of element 1 at broadside. The measurement indicates that the radiation field from the antenna element is right-hand circularly poloarized. The axial ratio measurements were conducted in an anechoic chamber at EDO Corporation.

Freq. (GHz)	J1
1.212	1.4
1.215	1.4
1.217	1.4
1.222	1.2
1.227	1.1
1.232	1.0
1.237	0.8
1.239	0.8
1.242	0.8
1.560	0.7
1.563	0.7
1.565	1.7
1.570	0.9
1.575	1.0
1.580	1.1
1.585	1.2
1.587	1.2
1.590	1.3

Table 1 Measured axial ratio (in dB) of element 1 at broadside (dual probe-feed design)

Radiation Pattern

Figure 19 and Figure 20 show the RHCP antenna radiation pattern of element 1 in the L1 and L2 band, respectively. The radiation patterns are very broad and uniform. The radiation pattern measurements were conducted in an anechoic chamber at EDO Corporation.

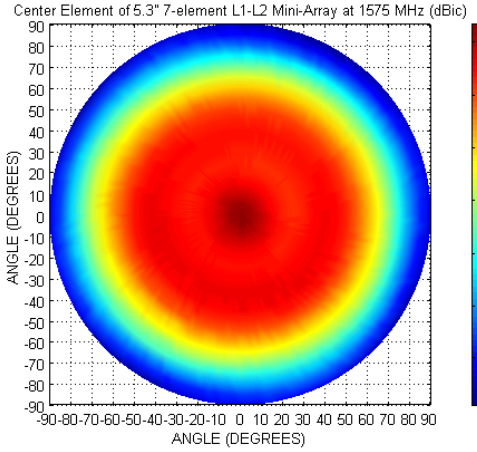

Figure 19 Measured RHCP radiation pattern of element 1 at 1575 MHz (dual probe-feed design)

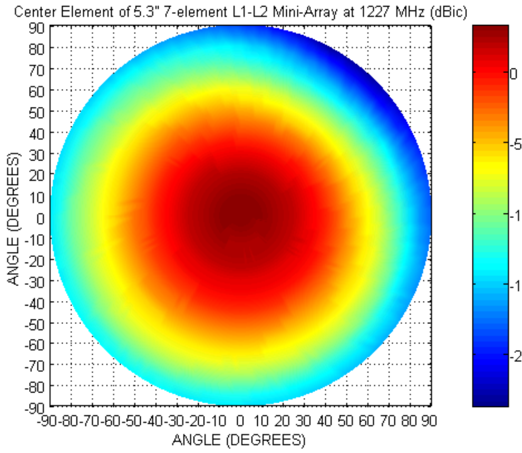

Figure 20 Measured RHCP radiation pattern of element 1 at 1227 MHz (dual probe-feed design)

S-CRPA GPS SATELLITE TRACKING TESTS

Some of the preliminary results of GPS satellite tracking tests with the new 5.3" 7-element GPS dual-frequency (L1/L2) S-CRPA prototype are shown here. This prototype was manufactured by EDO Corporation. The GPS receiver used in the test was a High Gain Advanced GPS Receiver (HAGR) developed by NAVSYS Corporation. The HAGR consists of a digital front end module, a digital beam-steering module, and a correlation acceleration module, and it is operated under a powerful and user friendly modular software control, which enables it for mutiple high performance GPS navigation and tracking applications. Before the tracking test, the S-CRPA and the HAGR system were calibrated to remove the delay differences between the seven RF channels. All the seven antenna elements were used in the tracking test. Figure 21 through Figure 26 show the measured C/N_0 performance of the S-CRPA when tracking the GPS satellites in the L1 band with C/A codes. In these figures, the top plot indicates the C/N_0 values of tracked GPS satellites, the middle plot indicates the elevation angle of the tracked satellites, and the bottom plot indicates the azimuth angle of the tracked satellites. These six figures show respectively the tracking performance of six correlation channels with combined beam-steered signals from the seven S-CRPA antenna elements by the digital beam-steering module. The measurements were conducted at NAVSYS on July 15, 2002, for a period of approximately 14 hours. In general the C/N_0 of the S-CRPA is in the 48 to 53 dB-Hz range as compared to 40 to 45 dB-Hz of a single antenna element. These results demonstrate the very good performance of this new 5.3" S-CRPA.

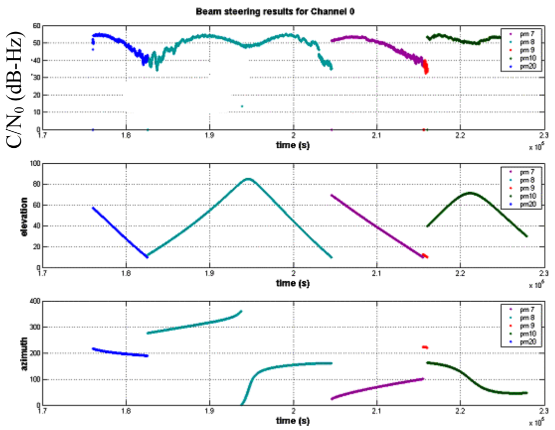

Figure 21 Measured C/N$_0$ of PRN 7, 8, 9, 10, and 20 with the 5.3" 7-element L1/L2 S-CRPA

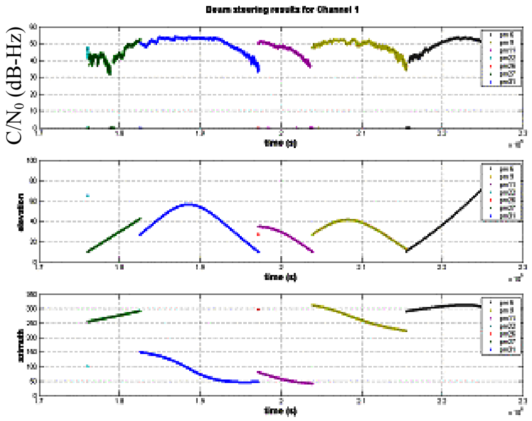

Figure 22 Measured C/N$_0$ of PRN 6, 9, 11, 22, 26, 27, and 31 with the 5.3" 7-element L1/L2 S-CRPA

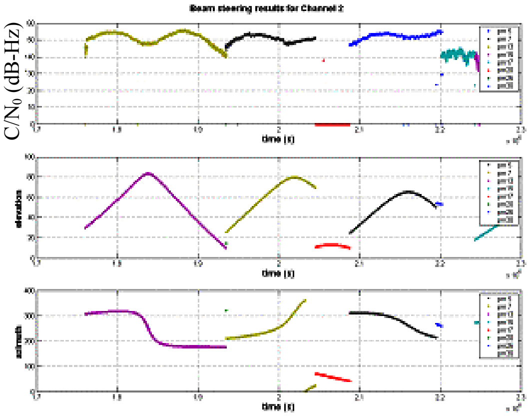

Figure 23 Measured C/N$_0$ of PRN 5, 7, 13, 15, 17, 20, 26, and 30 with the 5.3" 7-element L1/L2 S-CRPA

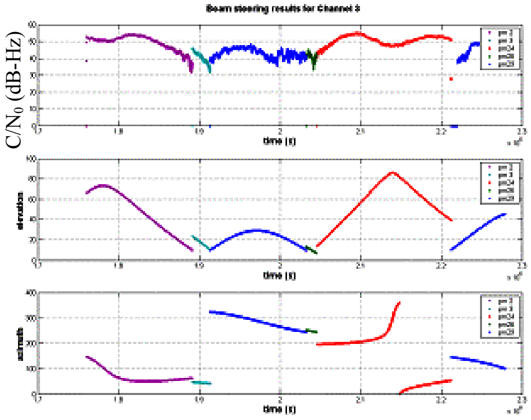

Figure 24 Measured C/N$_0$ of PRN 2, 3, 24, 26, and 29 with the 5.3" 7-element L1/L2 S-CRPA

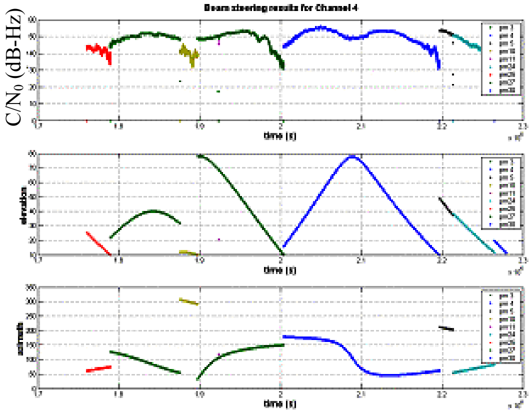

Figure 25 Measured C/N$_0$ of PRN 3, 4, 5, 10, 11, 24, 25, 27, and 30 with the 5.3" 7-element L1/L2 S-CRPA

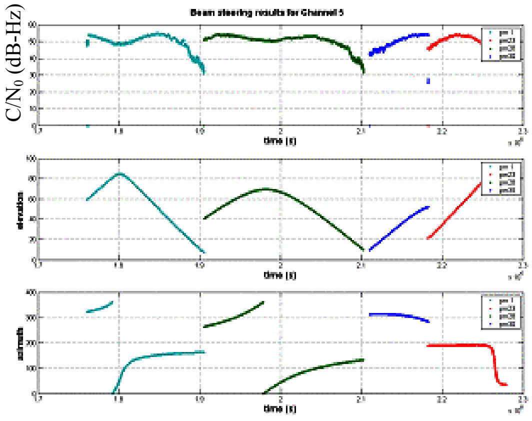

Figure 26 Measured C/N$_0$ of PRN 1, 23, 28, and 30 with the 5.3" 7-element L1/L2 S-CRPA

CONCLUSION

This paper presented the design, simulation, and testing of a new 5.3" 7-element dual-frequency GPS (L1/L2) S-CRPA, and very promising results have been shown. This new miniaturized antenna array is especially suitable for the following applications:

(a) The available space for antenna is limited.
(b) There is a need for beam forming to increase the antenna gain.
(c) There is a need for null-steering for anti-jam.

Because of the small size and weight, this new S-CRPA can make the GPS technology more widely adopted. The simulations have dramatically reduced the development time and cost of this new S-CRPA.

The SPAWAR Systems Center, San Diego, will be performing more testing of the 5.3" 7-element L1/L2 S-CRPA with the dual probe-feed design at the Naval Air Station, Patuxent River, MD, anechoic chamber to further validate the simulation results, and obtain additional radiation pattern and nulling data. Nulling testing will be included with the GAS-1 Antenna Electronics from Raytheon Systems Limited. The measurement results will be the subject of a future paper.

ACKNOWLEDGMENTS

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