Abstract: The continued convergence of radar, electronic warfare and communication applications require advances in broad band phased array antennas, including both performance improvements and development of manufacturing technology. Nurad and the University of Massachusetts collaborated to design and fabricate 3:1 and 9:1 bandwidth arrays. The first array designed and tested was a 3:1 band phased array. Using lessons learned from that antenna, a 9:1 band array antenna was designed. The results showed that acceptable electrical performance is readily available and that the manufacturing of the array was vastly more complex than originally expected. This presentation discusses the electromagnetic simulation results and compares them to the measured data, while focusing on manufacturing issues and advancements.

1 BACKGROUND

1.1 Design Baseline: University of Massachusetts Antenna
Several arrays with bandwidths up to 5:1 have been designed by the University of Massachusetts. The dual-polarized array in Figure 1 is a frequency-scaled prototype for an early design of the Square Kilometer Array radio telescope. Numerical simulations predicted this array to operate with VSWR<2 from 1-5 GHz and scanning to 45° in any plane. The 144-element array (8x9x2) in Figure 1 was extensively tested [1] and its performance was quite good, even in such a small array.
Figure 1. Dual-polarized Vivaldi array designed for Square Kilometer Array radio telescope. VSWR for broadside beam is computed from measured coupling coefficients in 8x9x2 array. The low-frequency performance is affected by truncation - the array is only 2 wavelengths square at 2 GHz.

Based on prior experience with single- and dual-polarized Vivaldi arrays and on the reported results of others, e.g., [2], the 9:1 bandwidth array was designed using the Vivaldi element. The Vivaldi element is very attractive for phased array applications because it can be fed directly from stripline or microstripline, the balun is an integral part of the antenna structure. The Vivaldi elements of the completed array operate over the same frequency range as the array in [2] but our elements are shorter than the design presented in [2], 45mm compared to approximately 62mm.

1.2 Notch & Horn Antennas

Single element notch and horn antennas have been used in a variety of military applications, most notably Electronic Counter Measure (ECM) systems that require moderate to wide bandwidth, wide angular coverage, specific polarization control, and high power handling capability. Several examples are shown in Figure 2.

Nurad offers high power horn antenna designs with characteristics such as broad frequency ranges to cover 3:1 bandwidths, lensed apertures to provide beamwidth and pattern control and unique machined/angled apertures to solve difficult installation problems. Also available are special horn designs with bandwidths up to 9:1. These offer the clear advantage of using one antenna to cover larger frequencies instead of having several antennas covering the same frequencies. Nurad currently offers existing horn antennas from 100 MHz to 96 GHz for various applications with linear, circular, dual linear, and simultaneous circular polarizations.
Nurad also offers extended bandwidth horns to meet special customer requirements. Phase and amplitude tracking characteristics can be incorporated and matched sets can be provided for specific applications.

Horn antenna’s featured rugged construction and a lightweight, moisture sealed design make them well suited for extreme conditions of airborne platforms. Typical applications include ECM and other direction finding systems for both airborne and shipboard systems.

A common feature of all of these single element antennas is radiation pattern coverage of a defined (and usually wide) angular sector. The purpose of the research reported here is to develop an array antenna with that covers the same angular sector with a narrow and electronically steerable beam.

2 DESIGN & MODELING

2.1 Design Goals (3:1)
Nurad has threshold and objective design goals for the antenna array. The threshold is a 3:1 band width array. This array was designed not to push state of the art, but to start the process of understanding the manufacturing processes involved as well as working through the design process using the CAD resources available and creating a stepping stone design to the objective 9:1 bandwidth array.
Table 1. 3:1 Array Threshold Design Goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>6-18 GHz</td>
</tr>
<tr>
<td>VSWR</td>
<td>2.5:1 max</td>
</tr>
<tr>
<td>Gain</td>
<td>(10 \log(N) + g_e)</td>
</tr>
<tr>
<td>Weight</td>
<td>Minimize</td>
</tr>
<tr>
<td>Size</td>
<td>16 x 8 elements (no depth requirement)</td>
</tr>
<tr>
<td>Power</td>
<td>5 W per element</td>
</tr>
<tr>
<td>Target Environment</td>
<td>Airborne Military</td>
</tr>
</tbody>
</table>

Table 2. 9:1 Array Objective Design Goals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2-18 GHz</td>
</tr>
<tr>
<td>VSWR</td>
<td>2.5:1 max</td>
</tr>
<tr>
<td>Gain</td>
<td>(10 \log(N) + g_e)</td>
</tr>
<tr>
<td>Weight</td>
<td>Minimize</td>
</tr>
<tr>
<td>Size</td>
<td>128 x 64 elements 2.2” thick</td>
</tr>
<tr>
<td>Power</td>
<td>5 W per element</td>
</tr>
<tr>
<td>Target Environment</td>
<td>Airborne Military</td>
</tr>
</tbody>
</table>

2.2 CAD Tool

The arrays were designed by using efficient computer simulations to estimate the performance of candidate element geometries. The candidate elements were modified based on design curves developed at the University of Massachusetts [3] [4] [5] until satisfactory performance was achieved. Each array design requires numerous computer simulations of the array performance to optimize the element geometry, so the infinite array approximation was used. This approximation greatly reduces computation time but fails to capture truncation effects. Nevertheless, infinite array approximations have previously been shown to yield reasonably good predictions of performance for elements that are located at least two wavelengths from the array edge.

Several commercial and proprietary electromagnetic simulators can be used for the infinite array analysis. The finite-difference, time-domain (FDTD) solver for periodic boundary conditions, PB-FDTD [6], is particularly well-suited for wide-band array design. This simulator combines the efficiencies of the FDTD algorithm and unit cell modeling, and it provides a rigorous solution for beam steering in the principal planes. The input impedance of a coarse-resolution model for the 9:1 dual-polarized array can be analyzed over the frequency range of interest at a single scan angle in about 30 minutes on a typical desktop computer. Once a reasonably good design is achieved, a fine-resolution model can be evaluated to verify and tune the performance.
2.3 Egg Crate

The chosen design is an “egg crate” design where the boards cross at the edge of each element. A conceptual sketch is shown in Figure 3. This differs from the cross design in that the phase center of the orthogonal elements are offset from one another; however, the fabrication methods are simplified considerably over the cross design. In addition, this type of design builds on the legacy of other University of Massachusetts antenna designs so the particular characteristics are well understood.

![Figure 3. Egg Crate Design](image)

2.4 Notches

The elements were designed in rows and columns for ease of assembly and positional accuracy. Since these boards would interfere with each other as they cross, notches were cut into the boards as shown in Figure 44.
2.5 Notch Element Cross Section (3:1 & 9:1)

The 3:1 notch element has a cross section as shown in Figure 5. The stripline-fed Vivaldi antenna element design is reasonably standard for the required 3:1 bandwidth. The element spacing in the array was chosen to be 0.45 wavelengths at the highest frequency of operation, 18 GHz [7]. Vivaldi antenna arrays exhibit several impedance anomalies when the element spacing exceeds 0.5 wavelengths, and scan performance usually degrades for element spacing greater than 0.45 wavelengths. The desired scan range of the array was 60°.

Arlon AD-250, $\varepsilon_r=2.5$, was initially selected for the substrate material because it is relatively low cost and has low loss. This was later changed due to manufacturing problems that are described below. The element design utilized a stripline assembly to minimize radiated effects from the transmission line and was fabricated by using two 0.020” boards, total thickness = 1mm. Element depth was not critical and was adjusted for good electrical performance. The stripline design has plated through holes or vias to keep the outer circuit layers at the same potential and suppress parallel-plate and waveguide modes in the dielectric region. Figure 5 is a diagram of the final element showing the feed line placement and approximate location of the vias. The image is not to scale, but is representative of the final configuration.
2.6 Predicted Results

Initial modeling of the array showed good performance over the design band. The method used for evaluation was active array impedance and VSWR plots. VSWR of the array at broadside angle is less than 1.5 over most of the design band. At 45° incidence angle, both E and H-plane VSWR is also excellent and no anomalous behavior is observed. Figure 6 shows the VSWR plots for broadside and 45° beam pointing angles. Note that all of the simulation results are based on an infinite array simulation so truncation effects are not included in the VSWR simulations. Since the simulation was of an infinite array, no pattern performance was predicted.
Figure 6. Predicted Infinite Array Results
2.7 Active VSWR Finite Array (3:1)

Active VSWR predictions for a finite array were not run. This is due to computational limitations. The very small feed lines of the array would require very small meshing to accurately simulate combined with the electrically large array, ~7.2 lambda at 18 GHz, would create a long simulation time. The intent of the array was to demonstrate capability and was intended as a sub-array into a larger array. Therefore, Nurad felt that little was to be gained by simulating the finite array active VSWR.

2.8 Active VSWR Infinite Array (9:1)

The 3:1 array was relatively easy to design, and its fabrication and testing provided valuable lessons that were incorporated into that design of an array covering 2-18 GHz. The electrical design of this array was more challenging than the previous array because of the bandwidth requirement. The antenna element resembles the one for the 3:1 design, except it is much longer to operate at the lower frequencies, Figure 7.

![Figure 7. Sketch of 9:1 bandwidth array element. This sketch is approximately to scale. Actual feed line was fabricated with radius bend instead of square corner](image)

This element was designed by using full-wave, infinite-array simulations. The predicted VSWR of the element in a large (infinite) array is shown in Figure 8. The predicted VSWR for broadside angle is mostly below 1.5 and the VSWR at 45° scan is below 2:1 except for a small excursion near 5 GHz.
The element is fed by stripline comprised of two 0.010” Duroid 5880, $\varepsilon_r=2.2$, substrates, total element thickness is 0.5 mm. Element spacing is 7.5 mm, the same as the 3:1 array. Vias spaced approximately 2mm outline the element similar to Figure 5.
3 FABRICATION & MEASUREMENTS

3.1 Cross Section Views, Material & Technology
A view of the CAD design is shown in Figure 9. The boards were notched to allow the orthogonal array apertures to be at the same plane. The design requires the elements to be soldered at the board joints. Due to the frequency range and the resultant spacing of the elements, soldering of the individual elements would be extremely difficult and time consuming. Nurad used edge plating of the slots to allow better soldering between the two circuit boards at the adjacent elements. As it turned out, the contact provided by the edge plating was sufficient to eliminate the need for soldering along the joint. This is only applicable for the lab unit, and would require some type of mechanical attachment on a flight unit.

![Figure 9. CAD Model of Element](image)

3.2 Connectors
Because the array was to be extensively tested – impedance, coupling, radiation patterns – each element of the array was connectorized. Due to the large number of radiating elements and subsequent number of connectors, simple press-on connections were highly desirable. Simple connection to the circuit board was also required. Based on element size and the space available, SMPM connectors were the best choice. There are many different SMPM connector styles that could have been used for this application; however, the primary drivers were ease of installation and connector location tolerance. Radial misalignment due to tolerance buildup of up to 16 connectors was a concern; therefore a mechanism for alignment of the connectors to the board was important. The selected connector is shown in Figure 10. This type of connector was chosen due to the captive center conductor as well as the connector body protrusion through the board which allows the connector location to be controlled by the circuit board fabrication.
3.3 8 x 16 Array
A photo of the competed 3:1 array is shown in Figure 21. The radiating direction is up in the picture, with the connectors placed on the bottom. The array was fabricated using two layers of 0.020” thick material laminated together.

3.4 Assembly Scheme
Notches allowing the orthogonal boards to nest together were cut into each stick. These notch lengths are arbitrary and worked out best from a mechanical layout perspective to be different lengths. For the 3:1 band array, 16 of the short boards and 8 of the long boards would be required to fully populate the array. Figure 32 shows an example of each of the board types. Note that each edge of the notches was plated allowing contact with the orthogonal board.
3.5 Test Set-up

The initial concept for testing of both the 3:1 array and the 9:1 array was the same. Testing of the array involved fabrication of several fixed phase power divider assemblies. Five discrete power dividers were designed and built for the 3:1 array to provide beam positioning angles of 0°, 15°, 30°, 45°, and 60°, see Figure 43. These power dividers all had a uniform amplitude distribution. To reduce cost, only the 0° and 45° power divider boards were designed and built for the 9:1 array. The idea behind the testing was to measure the radiation patterns in the direction of the power divider array with all surrounding elements terminated in 50 ohm loads. For the 3:1 array (256) connectors, this was done by connectorizing all antenna elements and placing 50 ohm loads on the unused connectors. Both planes could then be measured using the same power divider and rotating it 90 degrees and connecting the center elements to the antennas and terminating the unused elements. The 9:1 array posed a problem. The array size of 128 by 64 elements meant that there would be 16,384 connectors to apply to the array. The number of connectors and associated 50 ohm terminations made the attempt cost prohibitive. Another way needed to be found. Since only the center row and column of the array would be measured for pattern data, only those elements needed connectors. The remaining elements were permanently terminated in matched loads comprised of two 100 ohm surface mount resistors in parallel. Standard pick and place equipment could be used to locate the resistors on the boards.
However, this presented another issue. Due to the width of the finished circuit board (~2.125"), standard pick and place equipment was unable to handle the boards. Since the substrate material is expensive, we did not want to fabricate the boards oversize and then cut to the final width. Nurad overcame this design issue by cutting the boards in half along the length and placing the boards back to back. This required the boards to be joined along the length (64 joints), but allowed automated equipment to apply the approximately 32,000 resistors.

3.6 3:1 Array Test Results

Testing of the 3:1 array was to include radiation patterns of a single row, or column, and active VSWR of a single row or column. There were many issues with trying to measure the VSWR of the array. First was that the SMPM connectors do not have a calibration kit for the Agilent network analyzers. This meant that the SMA to SMPM adapter would not be calibrated out of the measurement. For individual element VSWR’s, this was not a problem as the measurement would be representative of the element performance. In order to try and calculate the active VSWR of the array however, the phase between the adjacent elements needed to be known precisely. Several concepts for the measurement technique were considered. None were actually developed though due to the possibility of error in the calibration standards as well as the cost and time needed for development. The concept used was to measure the data for each element and then mathematically generate the active VSWR. Upon taking these measurements and running the calculations, it was determined that the accuracy of the measurements was not adequate to determine the correct value for the active VSWR of the array. Much of the error resulted from the connector mating variability, especially in phase. However, the information provided did show that the modeled data provided a good indication of the performance of the fabricated array.

Pattern measurements for the 3:1 array were run using the fixed phase shifter feed boards. The measurements showed good pattern shape. Patterns for the zero degree phase card and the 45 degree phase card are shown in Figure 54 and Figure 65. Three frequencies,
6, 11 and 18 GHz are overlaid on each pattern. The gain of the patterns is not compensated for the loss of the power divider network. Based on the measurements of the power divider, the power lost in the divider assembly is 5.9 dB at 6 GHz, 12.6 dB at 11 GHz and 16.4 dB at 18 GHz. These values track within the measurement error of the theoretical loss of the divider. Therefore, to determine the gain of the array, without the power divider, the peak gain of the assembly should be added to the loss of the power divider.

Figure 54. 0° Card Patterns
3.7 Fabrication of the 9:1 Array
The 9:1 array was intended to be built upon the success of the 3:1 array. The manufacturing processes and materials were initially intended to be the same for both. However, as the 3:1 array was being designed and built it was realized that a variety of issues would make it difficult to build them the same. Due to the increased frequency band, the antenna boards needed to be thinner than on the 3:1 array. A positive of using the thinner board was a reduction in the material cost for the antenna array; however, the
thinner boards caused several issues. Two 0.010” thick boards are sandwiched together to make the final antenna board. The connector mounts on the top surface of one of the boards, which is halfway through the laminated assembly. The method of fabrication requires the pocket to be machined after lamination. The pocket is only 0.010” deep and the copper cannot be milled off of the board, making depth control critical. Unfortunately, the board flexes due to the thickness causing the pocket milling to be very difficult. In addition, the thin boards change dimensionally due to the heating and cooling required during processing. This caused other issues with the placement of the plated through holes. This dimensional change is random in nature and even changes in different areas of the same board. This challenge was overcome by the incorporation of targets etched onto the board during fabrication. These targets were then used to scale the locations for the plated through holes rather than using the CAD file to determine the locations. The end result is that each board is very slightly different from all others due to the unique shrinkage of the material used for fabrication. However, while the resolution to the problem is a great engineering solution, the customized nature of each board has a considerable cost impact.

Nurad worked all of the issues out for the fabrication of the 9:1 antenna array. The manufacturing process was proven by fabrication of one of each of the different board types required for fabrication. However, due to the cost of fabrication and the large number of boards required for the 9:1 array the development effort was placed on hold.

4 CONCLUSION

Two different broadband phased array antennas were designed and built. The 3:1 array was characterized as both individual radiating elements as well as patterns using fixed power divider assemblies. The 9:1 array CAD design was straightforward and based on the successful measurement to prediction correlation of the 3:1 array provides confidence the measurement of the larger antenna would also be successful. A number of challenges were identified and overcome in the design, layout, material selection and fabrication of the antenna array.

References


