

# Assembling, Calibrating and Testing a Phased Array in Two Separate Halves

Benjamin L. Caplan, 978.440.1833, Benjamin\_L\_Caplan@raytheon.com

Joseph K. Mulcahey, 978.440.3291, Joseph\_K\_Mulcahey@raytheon.com

Jeffrey C. Upton, 978.440.1930, Jeffrey\_C\_Upton@raytheon.com

Kevin R. O'Donnell, 978.440.1228, Kevin\_R\_ODonnell@raytheon.com

Raytheon Company, Integrated Defense Systems, 528 Boston Post Rd., Sudbury, MA 01776  
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**Abstract**—A phased array was recently assembled, calibrated and tested in two separate halves due to test facility limitations. This unique method has many advantages for future phased array production as it allows arrays of any size to be calibrated and tested to a very high accuracy, which results in decreased sidelobe level, beam pointing error, and increased directivity. This technique takes a major step toward removing limitations on the size of phased arrays that can be characterized in a Near-Field Range (NFR).

Many issues needed to be considered since full array performance had to be characterized before the two halves were married together. The major topics that this paper explores are a pattern summation algorithm, whether or not dummy elements are necessary during testing, and both electrical and mechanical misalignment of the two halves.

## 1. INTRODUCTION

For many reasons, including ease of hardware integration and the need for accurate calibrations and pattern characterization, it was important to test a recent phased array in a planar NFR [1]. Reduced calibration and testing errors lead to decreased sidelobe levels, beam pointing error, and increased directivity; some of the most important parameters of a phased array [2]. To better accommodate NFR limitations, the array was built in two separate halves so that each half could be integrated, calibrated and tested individually. Full array performance was characterized before the two halves were married together and as a result many concerns needed to be addressed. This paper will explore considerations unique to this approach. A pattern summation algorithm including all possible half-to-half differences is presented first. Next, the idea of using passive, dummy elements to maintain the proper mutual coupling environment for all active elements during NFR testing is investigated. Finally, electrical misalignment errors in the form of amplitude and phase biases are considered, as are mechanical misalignment errors in the form of one half tilting with respect to the other. All data shown herein is simulated.

## 2. PATTERN SUMMATION

A simple method was developed to combine the measured far-field antenna patterns from the two array halves into a single composite pattern. This composite pattern was shown to closely resemble the pattern that would have been measured if the entire array had been available at once. The algorithm and its verification are presented here.

Let  $E_1(u,v)$  be the complex far-field electric field intensity pattern of array half one,  $E_2(u,v)$  be the far-field pattern of array half two, and  $E_c(u,v)$  be the composite pattern. In order to add the patterns of the two array halves, several offsets must be applied. The XYZ phase center translations of each half must be accounted for, as well as roll, pitch and yaw rotations. An amplitude and phase bias must also be accounted for, as the pattern measurements may be performed months apart and the measurement system may have changed. Without loss of generality, relative corrections may be applied to one array half only to simplify the equations. The pattern summation formula is

$$E_c(u,v) = E'_1(u,v)e^{jk\vec{r}_1 \cdot (\hat{r} - \hat{r}_0)}a_1e^{j\phi_1} + E'_2(u,v)e^{jk\vec{r}_2 \cdot (\hat{r} - \hat{r}_0)}a_2e^{j\phi_2} \quad (1)$$

where  $k = 2\pi/\lambda$  is the free-space wave number. The rotation of the starting field  $E_i$  for array half  $i$  is indicated by  $E'_i$ . The phase center position vector of the  $i$ th half relative to the center of the coordinate system is given by

$$\vec{r}_i = \hat{x}x_i + \hat{y}y_i + \hat{z}z_i \quad (2)$$

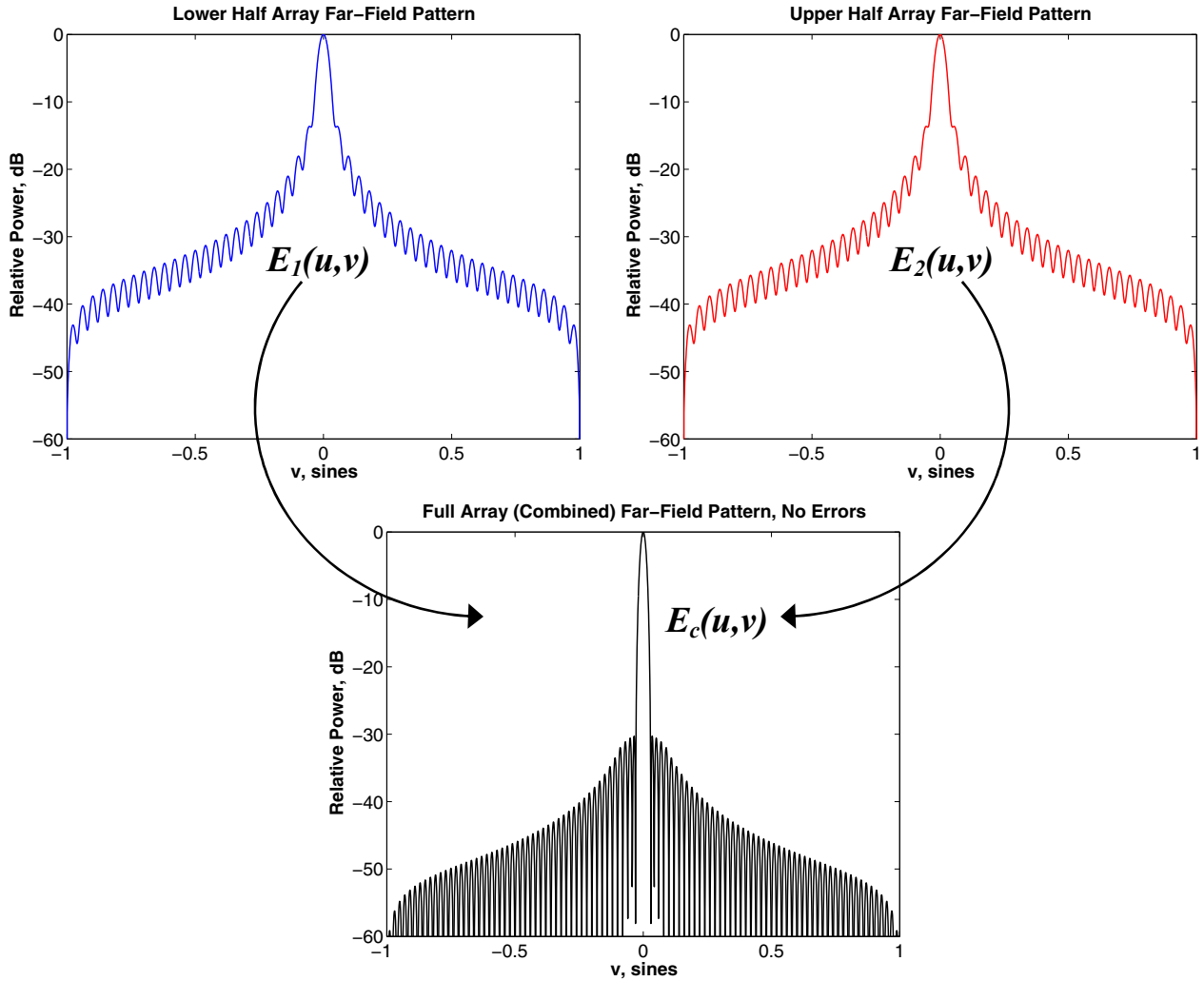
Unit vectors in the direction of any point in space  $(u,v)$  and the beam peak  $(u_0,v_0)$  are given by

$$\hat{r} = \hat{x}u + \hat{y}v + \hat{z}\sqrt{1-u^2-v^2} \quad (3)$$

$$\hat{r}_0 = \hat{x}u_0 + \hat{y}v_0 + \hat{z}\sqrt{1-u_0^2-v_0^2} \quad (4)$$

And finally, the complex bias for each half is

$$bias = a_ie^{j\phi_i} \quad (5)$$



**Figure 1** – Lower and Upper Half Array Patterns Ideally Combined

To illustrate this pattern summation concept, suppose there is a 100 element by 100 element array with a lattice spacing of  $\lambda/2$  in each direction. Also assume that the element pattern power decreases at a nominal  $\cos^{1.3}(\theta)$  and that there is a 30dB,  $\bar{n} = 5$  Taylor taper applied at the aperture in each direction. Figure 1 shows patterns of the lower half of the array, the upper half of the array, and the full array assuming there are no offsets between the two halves. Notice that even though the half array patterns look nothing like a 30dB Taylor taper, when combined together they do.

The accuracy of this algorithm was verified in two separate activities. First, by building a small portion of the full array, called a pilot array, with approximately 1% of the elements in the full array. In the NFR, three scans were run on the pilot array: all elements active, only the elements in one half of the array active, and only the elements in the other half active. The results were very encouraging, as combining the two half array patterns using Eq. (1) produced a pattern that was nearly identical to the measured full pilot array pattern. When the first of the two array halves was tested in the NFR, a similar procedure was done and the results showed

that the combining algorithm worked just as well on the larger scale. These results give high confidence in the accuracy of the algorithm, though in neither case was there rotational misalignment as there may be when the halves are joined together; this effect is addressed in the mechanical misalignment section.

### 3. DUMMY BOUNDARY ELEMENTS

One idea that was researched and ultimately determined to be unnecessary was adding passive, “dummy” loaded elements to the bottom of the upper array half and the top of the lower array half for NFR testing. The purpose of adding these extra elements would be to have all elements, especially those near the divide of the two halves, experience the same mutual coupling environment during NFR testing as they would when the two halves are combined. To determine the necessity of these “dummy” elements, a 12 element by 12 element Mutual Coupling Array (MCA) was built. This MCA is a smaller array with the same elements and lattice as the real array, but no active RF hardware or beamforming behind the elements. It was used to measure embedded element patterns [3] in the same

coupling environment found in the real array before that array was assembled. Embedded element patterns of edge elements were found to be similar to those in the center except for a slight asymmetry. After array simulations, it was concluded that “dummy” elements would have an insignificant effect and therefore were not necessary.

As an example, consider the same theoretical 100 element by 100 element array. The asymmetrical pattern of an edge element, without dummy elements, is shown in Figure 2 compared to the pattern of a centrally located element. Both patterns are theoretical, but the amount of deformation is representative of MCA measurements. A full array simulation was performed with asymmetrical element patterns for elements on the top row of the lower half array and bottom row of the upper half array. The pattern for edge elements in the upper half is a mirror image about  $v = 0$  of that for edge elements in the lower half. Full array pattern results are also shown in Figure 2. The difference from the ideal array pattern is negligible, which is why dummy boundary elements were unnecessary for NFR testing.

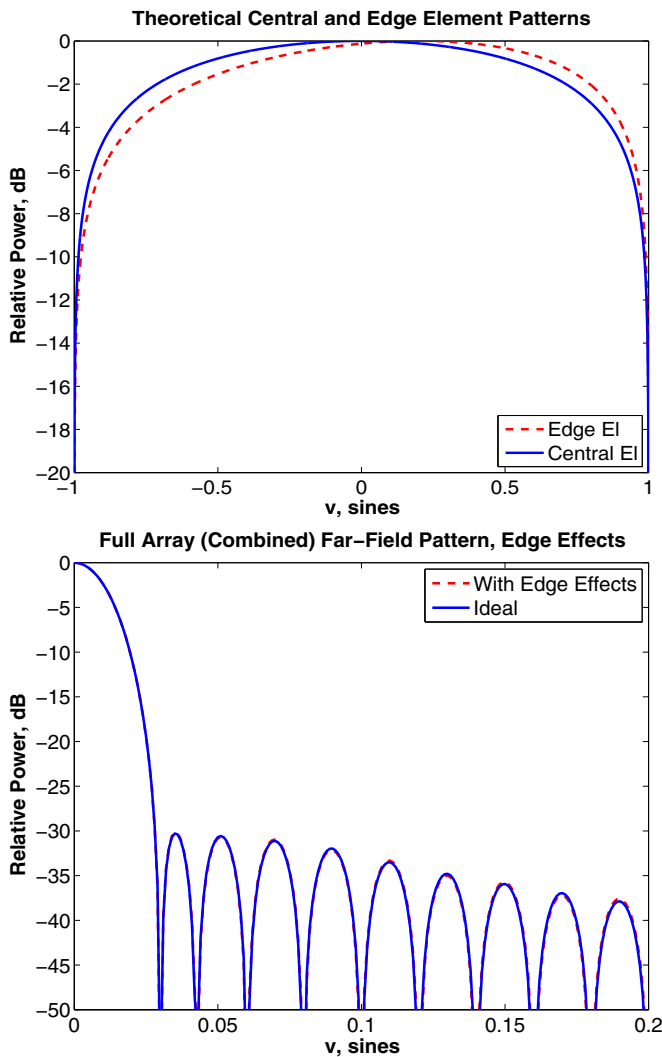


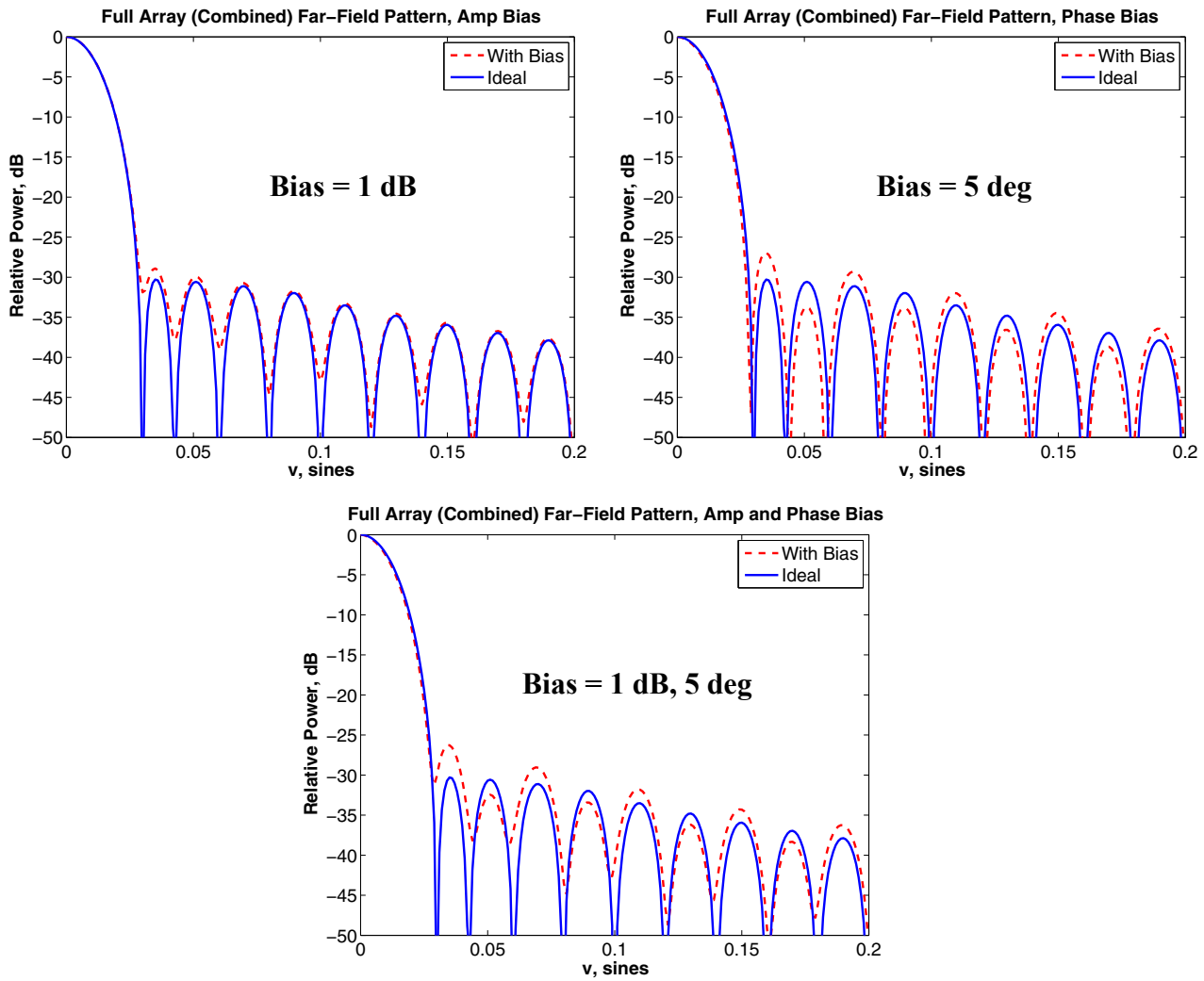
Figure 2 – Edge Element Effects

#### 4. ELECTRICAL MISALIGNMENT OF HALVES

Electrical alignment of the two array halves is an important activity to ensure high quality full array performance. Amplitude or phase offsets between the two halves will result in performance degradation such as quantization lobes, decreased directivity and increased sidelobe levels [4]. This electrical offset between halves is captured in the bias term, given by Eq. (5). The NFR data has everything necessary to calculate the amplitude offset. Measured pattern directivity plus noise power determine the gain of each array half; the difference between half gains is the real number  $a_n$ . The phase offset term is much harder to obtain from NFR measurements due to the fact that all data is relative to a reference signal, but it can be found from full array measurements.

Once the halves are joined together, any amplitude and phase difference can be measured, and subsequently minimized, by use of a single Near-Field Horn (NFH) in front of the array. The NFH is named as such because it is in the near-field of the entire array, yet it must be in the far-field of any individual element. Amplitude and phase will be measured one element at a time through all elements in both halves. The NFH alignment procedure will determine an amplitude and phase bias for each of the explicitly calibrated modes, add the phase delta to the calibration constants, and repeat the measurement to insure compliance with the array similarity error budget, with iterations as necessary. The method for determining the offsets will be to discard elements failing diagnostics, remove the expected  $e^{-jkr}$  phase runout for each element measurement for each mode, best-fit a plane to the top and bottom phase fronts separately for each mode, and determine the bias of one plane relative to the other. Because only two numbers, amplitude and phase bias, are derived from a large number of measurements, there is the benefit of averaging to reduce the effect of measurement noise and other random errors. Note that an amplitude offset can be detected with this procedure, but should be inconsequential if noise alignment of each half was done in the NFR. If there is still an amplitude offset, an attenuator can be added at the back of one half. Should other channels exist, to maintain fidelity of the NFR array characterization the same NFH procedure should be used separately for each channel to time/phase align one half to the other using manually adjusted line stretchers.

To illustrate the effect that these electrical misalignment errors could potentially have, again consider the same theoretical 100 by 100 element phased array with the 30dB Taylor taper. Figure 3 shows bias effects in three parts: Amplitude only (upper left), phase only (upper right), and phase and amplitude (bottom). The phase bias has a much more pronounced effect on the combined pattern, raising and dropping the levels of each successive sidelobe. This is consistent with the half-array quantization interval. Exaggerated biases of 1 dB and 5 deg were used; the



**Figure 3 – Amplitude and Phase Bias Effect**

electrical alignment procedure should be able to make the errors much smaller than this.

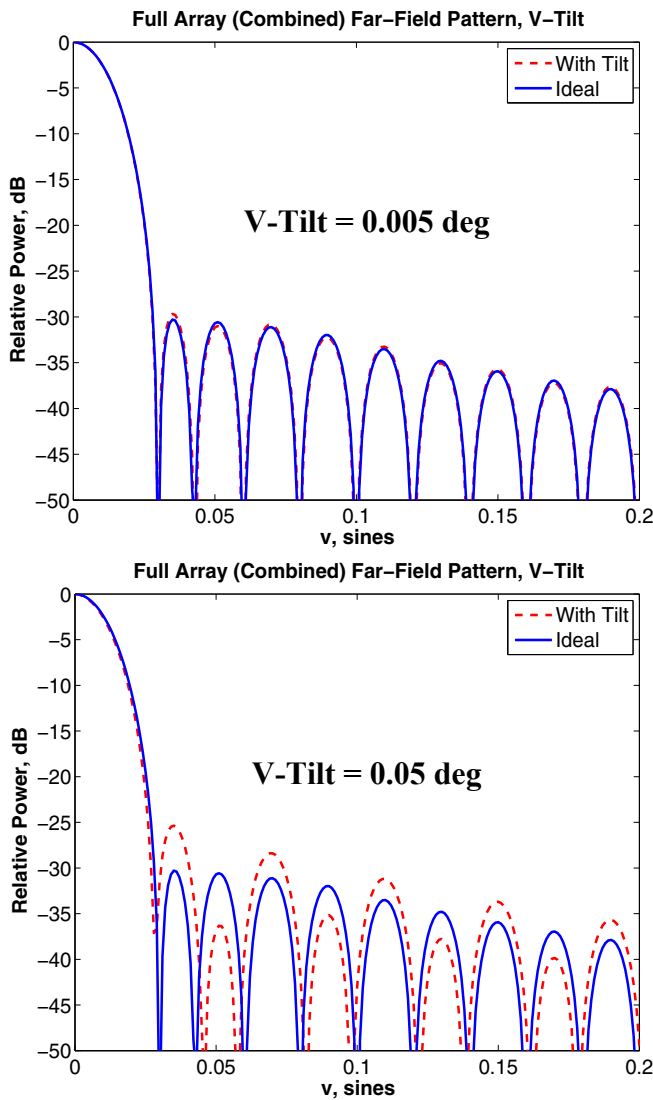
## 5. MECHANICAL MISALIGNMENT OF HALVES

When the two array halves were calibrated and tested in the NFR, each was co-planar to the scan plane of the near-field probe to within a small error. After the halves are joined together, although small, there may be roll, pitch, and yaw rotational offsets between the two halves. Keeping these offsets small is important in order to minimize degradation of array performance. There will also be small x-, y-, and z-axis offsets, but, through simulation, these were found to have a much less significant effect on the full array pattern. Also, any z-axis offset will appear as a phase bias between halves and be cancelled out at boresite when the phase bias is removed. As mentioned earlier, the rotation of the starting field  $E_i$  for array half  $i$  in Eq. (1) is indicated by  $E_i'$ .

The same procedure used to remove electrical misalignment errors can also be used to remove

mechanical misalignment errors. These rotational errors will manifest themselves as U-plane and V-plane tilts between halves and can be calculated and removed in a way similar to removing a phase bias in the previous section. Using measurements from the horn in front of the array, a best-fit plane is fit to the top and bottom phase fronts separately for each mode. Any tilt between halves can then be removed in the calibration. Again, because measurements are made on many elements, there is the benefit of averaging to significantly reduce the effect of measurement noise and other random errors.

Using the same theoretical 100 by 100 element array, a V-tilt offset was added between halves. Figure 4 shows the effects of V-tilt offsets of 0.005 degrees and an exaggerated 0.05 degrees. The 0.005 degree tilt has little effect on the combined pattern, but the 0.05 degree tilt has a much more pronounced effect. Again, due to the half-array quantization interval, each successive sidelobe is raised and then dropped. The mechanical alignment procedure should be able to align each half to within closer than the lowest case tilt shown here, 0.005 degrees.



**Figure 4 – V-Tilt Mechanical Misalignment Effects**

## 6. CONCLUSIONS

Due to test facility limitations, a phased array was recently assembled, calibrated and tested in two separate halves. There were many unique issues that needed to be considered as all full array performance had to be characterized before the two halves were married together. A pattern summation algorithm, including any potential half-to-half differences, was developed and shown to correlate very well with measured results. Dummy boundary elements were considered and ultimately deemed unnecessary because of their negligible effect on full array pattern results. Electrical and mechanical misalignment errors were also considered and some, most notably phase offset and tilt, showed the potential for pattern performance degradation. To minimize these effects when the halves are joined together, a single horn will measure all elements and allow for the removal of any biases between halves.

## REFERENCES

- [1] A. D. Yaghjian, "An overview of near-field antenna measurements," *IEEE Trans. Antennas Propagat.*, Vol. AP-34, No. 1, pp. 30-45, Jan. 1986.
- [2] Hsiao, J. K., "Design of error tolerance of a phased array," *Elect. Letters*, Vol. 21, No. 19, pp. 834-836, September 12, 1985.
- [3] Aumann, H.M.; Fenn, A.J.; Willwerth, F.G.; "Phased array antenna calibration and pattern prediction using mutual coupling measurements," *IEEE Trans. Antennas Propagat.*, Vol. AP-37, No. 7, pp. 844-850, Jul 1989
- [4] Mailloux, R. J., "Array grating lobes due to periodic phase, amplitude and time delay quantization," *IEEE Trans. Antennas Propagat.*, Vol. AP-32, No. 12, pp. 1364-1368, Dec 1984.