**Naval Research Laboratory**

**Washington, DC 20375-5320**

**NRL/MR/5320--00-8439**

# Measurement Results of an Affordable Hybrid Phased Array Using a Radant Lens

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May 15, 2000

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY (*Leave Blank*) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | May 15, 2000 | |

4. TITLE AND SUBTITLE

Measurement Results of an Affordable Hybrid Phased Array Using a Radant Lens

5. FUNDING NUMBERS

PE–62232N

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/PU/5320--00-8439

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*Sachs Freeman Associates, Largo, MD 20774
**Radant Technologies, Inc., Stow, MA 01775

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

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14. SUBJECT TERMS

| | |
|---|---|
| Phased array | Diode lens |
| Antennas | Electronic steering arrays |
| Affordable phased arrays | |

15. NUMBER OF PAGES

33

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | SAR |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

# MEASUREMENT RESULTS OF AN AFFORDABLE HYBRID PHASED ARRAY USING A RADANT LENS

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**Abstract: An affordable phased array for a ship self-defense experimental engagement radar is described. The array uses a hybrid approach by combining a slotted waveguide array with phase shifters at each column to provide scanning in the azimuth plane and a Radant lens placed in front of the slotted array to provide independent scanning in the elevation plane. The approach avoids using a phase shifter or a T/R module behind each radiating element and simplifies beam steering using row-column controls which reduce the phased array cost. The production cost of the proposed array is estimated to be less than one-third the cost of a similar sized array using a phase shifter or T/R module behind each radiating element. Recently, a 4'×8' Radant lens was procured from Radant Technologies, Inc. and placed in front of the existing (modified AN/TPQ-36) phased array. This paper reports on the results of this hybrid array.**

## 1. Introduction

The Phased Array is one of the most versatile type of antenna used in radars aboard Naval ships. Each radiating element of a phased array is normally associated with a phase shifter or a T/R module where the element phase can be varied through 360°. The radiating elements are spaced nominally at a $\lambda/2$ spacing to avoid grating lobes. A typical phased array, with a 1° pencil beam, needs an aperture of at least $50\lambda\times50\lambda$ requiring some 10,000 radiating elements and phase shifters. The complexity of the corresponding feed network can increase rapidly with the size of the phased array. The phase shifters (or T/R modules) and control circuitry along with the feed network account for the major hardware cost in a phased array antenna. A few years ago a study was made by NRL on ways to obtain two-dimensional scanning at low-cost. In that study, a hybrid approach of combining a slotted waveguide array with a Radant lens was identified as a low-cost approach to a phased array which can meet the requirements of Ship Self-Defense [1]. Since then, a slotted waveguide array was assembled which was a modified version of a production series (AN/TPQ-36) built by Hughes Aircraft Company. The modified version used high-power phase shifters and a

Manuscript approved February 17, 2000.

monopulse feed network, and can phase scan in the azimuth plane.

In 1995 a contract was awarded to procure a Radant lens from Radant Technologies Inc. The lens was delivered to NRL in June 1998. NRL added the lens to the front of the waveguide slotted array (modified AN/TPQ-36) to obtain scanning in the vertical plane. This paper presents the experimental results of this affordable hybrid phased array. The Radant Lens program was sponsored by ONR 311.

## 2. Modified AN/TPQ-36 Radar Antenna

The AN/TPQ-36 antenna consists of a stack of vertical slotted waveguide arrays each with a phase shifter to provide azimuth scanning. A TPQ-36 antenna was modified at NRL by procuring high-power phase shifters and a high-power monopulse feed network. A TPQ-36 array face was procured from Hughes Aircraft (now Raytheon), high-power phase shifters were procured from Raytheon and a high-power monopulse feed network was procured from Westinghouse (now Nrothrop Grumman). Figure 1 is the modified AN/TPQ-36 antenna. NRL performed the integration and testing of the antenna. The resulting antenna has performed extremely well, as expected, to scan the beam in the azimuth plane. The details are documented in an NRL report [2].

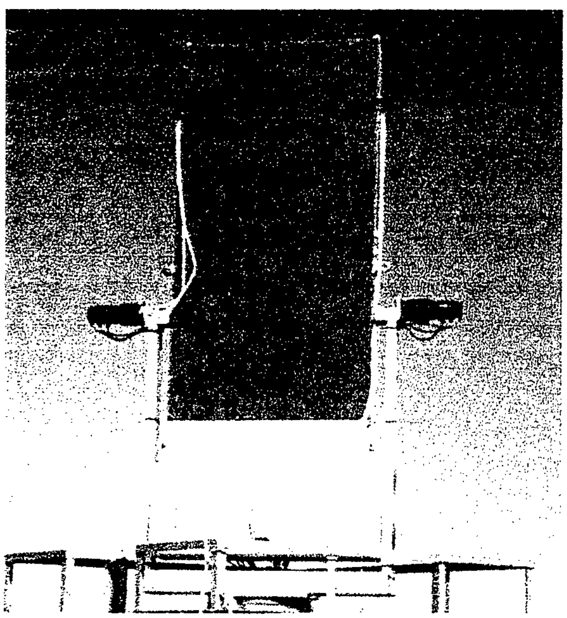

Figure 1. Modified TPQ-36 Antenna

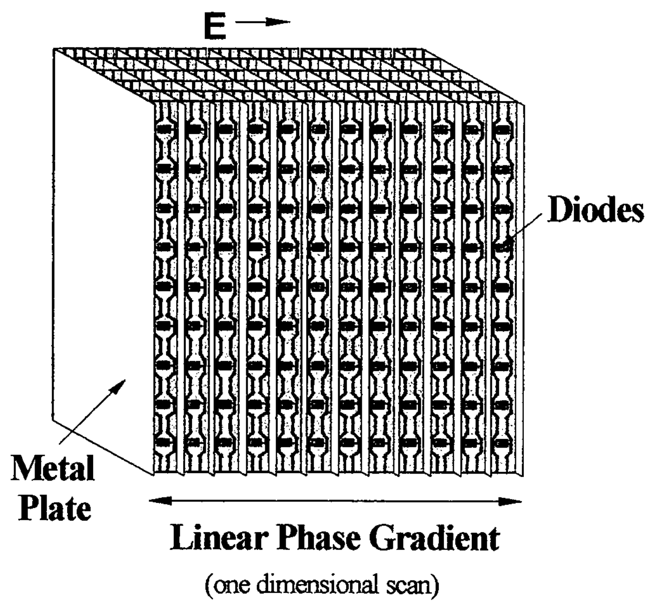


Figure 2. Radant lens concept

## 3. Radant Lens

As stated earlier, the modified AN/TPQ-36 antenna can be used to scan the beam only in the azimuth plane. To scan the beam in elevation, a Radant lens has been procured from Radant Technologies, Inc. The Radant lens is a novel antenna, with a low-cost means of obtaining two-dimensional scanning by simply retrofitting it to the front of an existing one-dimensional scanning array, like the waveguide slotted array.

The Radant lens reduces many of the fabrication problems that increase the cost and the transmission loss associated with the conventional implementation of a passive phased array - namely the discrete element and its phase shifter. The Radant lens eliminates all packaging, connectors, and transmission lines associated with the discrete phase shifters. It also reduces greatly the number of control circuits, drivers and connecting leads.

The basic principle on which the Radant lens operates has been demonstrated earlier by Radant Technologies, Inc. [3] under a contract to Rome Laboratory. The Radant lens concept is illustrated in Fig. 2. The lens is constructed from a set of parallel conducting plates. In between each set of plates is a series of dielectric support layers on which are two strips of metal cross connected by a set of diodes as shown in Fig. 3. The amount of metalization controls the amount of phase shift per dielectric layer. The operating principle of the Radant lens is that the phase shift through the lens changes when the diodes in one layer are turned on or off. The total phase shift results from selectively switching between the two diode states on each layer using a digital bias control circuit. In between the two parallel plates are 13 dielectric layers with diodes, which are used in combination to create a 4-bit bulk (i.e., column or row) phase shifter. The top view of one column of the lens is shown in Fig. 4. To construct a 4-bit phase shifter, three different types of dielectric layers, each with a different amount of metalization, is used to produce either a 11.25, 22.5, and a 45 degree phase shift. For example, to create a 112.5 degree phased shift, the 22.5 degree bit and 90 degree bit must be turned on. This is accomplished by turning on all the diodes on the first and second layers, activating the 22.5 degree bit, and also turning on all the diodes on the sixth, seventh, and eighth layers, activating the 90 degree bit. The set of thirteen layers was used to improve matching and minimize the resulting return loss.

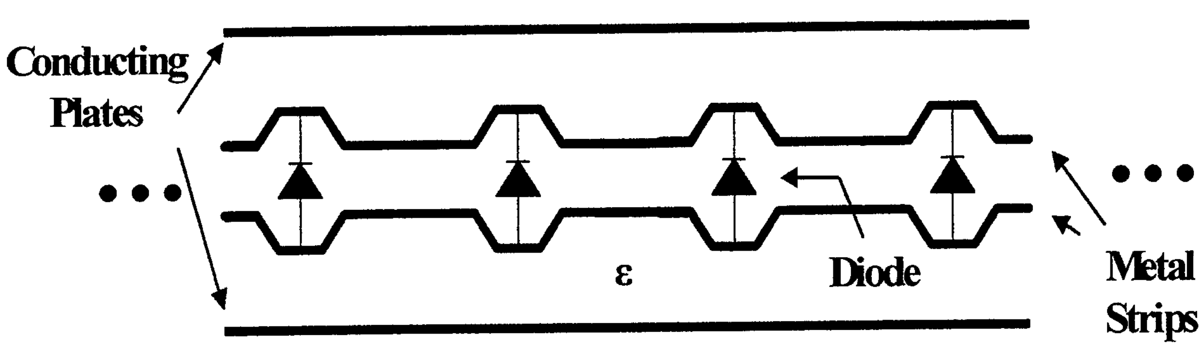


Figure 3. Dielectric support layer with diodes and metal strips between two conducting plates

The simplest Radant lens configuration is an E-plane scanning lens in which beam scanning results from a linear phase gradient along the E-plane dimension. One Radant lens provides one-dimensional electronic beam scanning. By restricting the scan action of a lens to a single plane, a great simplification in the bias circuitry is achieved since the individual diodes need not be

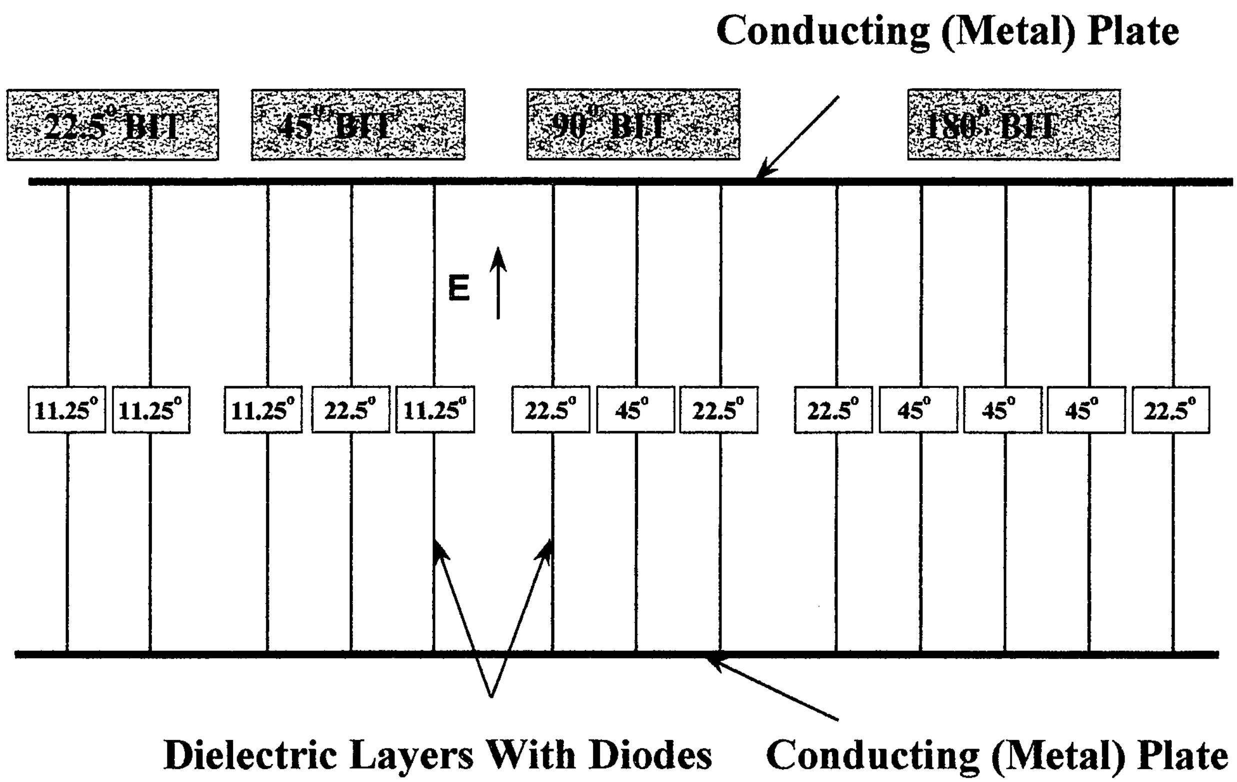


Figure 4. Top view of one column of the Radant Lens, illustrating 13 layers for a 4-Bit Phase Shifter.

addressed independently. This reduces the complexity of the driver and facilitates its location exterior to the lens. Two-dimensional scanning can be achieved by cascading two Radant lenses or using one Radant lens in a hybrid configuration [4,5,6]. As stated before only the hybrid configuration is discussed in this paper. However, it may be of interest to note that the Radant lens technology is also being advanced in France by Thompson-CSF. They are using this technology in producing the RBE-2 radar for the French Rafale Fighter Aircraft. They are using a dual lens system with a polarization rotator in the middle to scan the beam in azimuth and elevation [7].

In 1995, a contract was awarded to procure a Radant lens in order to add it to the front of the slotted waveguide array to achieve two-dimensional scanning. A photo of the Radant lens in the final stage of construction is shown in Fig. 5.

Figure 6 shows the hybrid phased array configuration using a slotted waveguide array and a Radant lens in front of it. The slotted waveguide array with associated phase shifters is used to scan the beam in azimuth plane and the Radant lens is used to scan the beam in the elevation plane.

The procurement cost of a single developmental Radant lens is about \$3M. However, the production cost is estimated to be about \$1M. Combining the Radant lens with the previously procured slotted waveguide array and a transmitter will result in a production cost of the hybrid phased array of about \$3M. On the other hand, a phased array of the same size requires 12,000

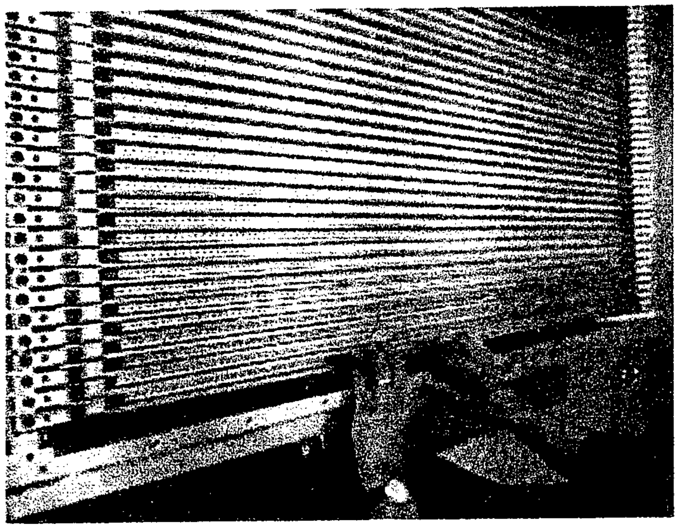

Figure 5. The Radant lens in final stage of construction.

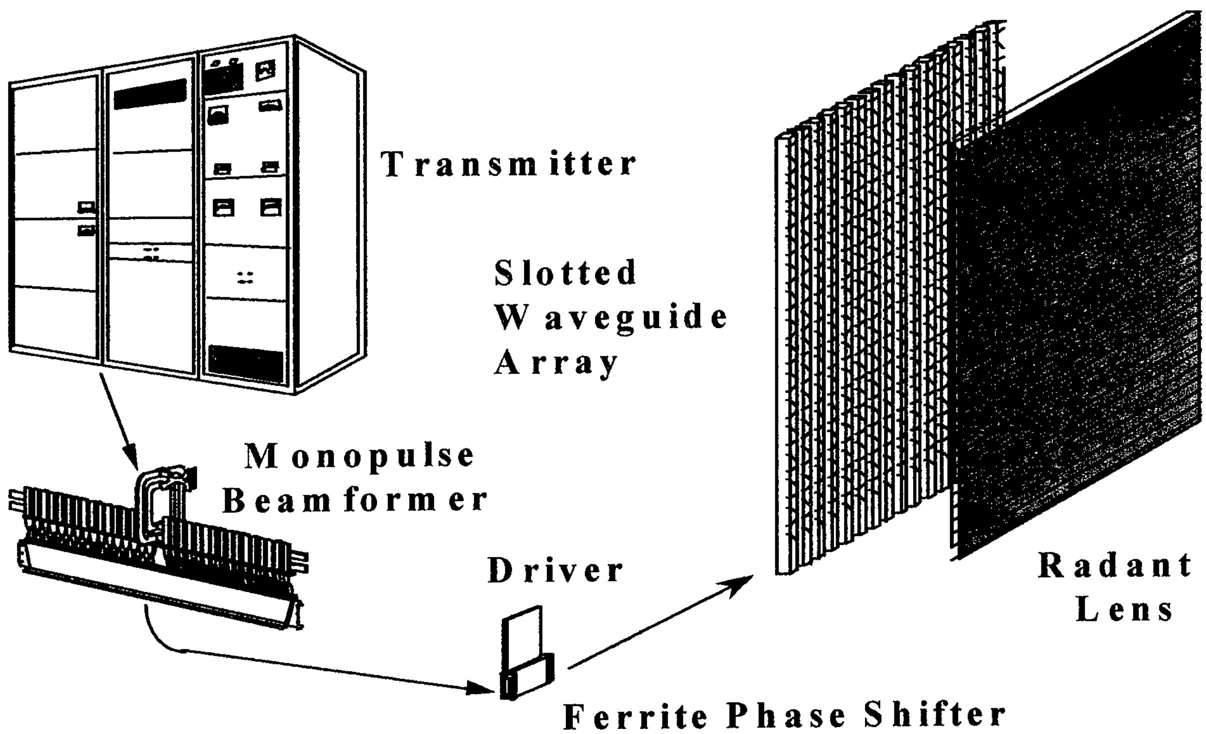


Figure 6. Radant lens with slotted waveguide array system.

phase sifters and drivers (or T/R modules). With an optimistic assumption of $500 per phase shifter and driver (or $1000 per T/R module), the total cost of a 12,000 element phased array will range from $8M to $14M. Therefore, a hybrid array with a Radant lens costs much less than a regular phased array and, hence, is an affordable phased array.

## 4. Theoretical Predictions

As stated before, each dielectric layer is made up of a dielectric substrate with two metalized strips interconnected by PIN switching diodes. The phase shift is accomplished by selectively

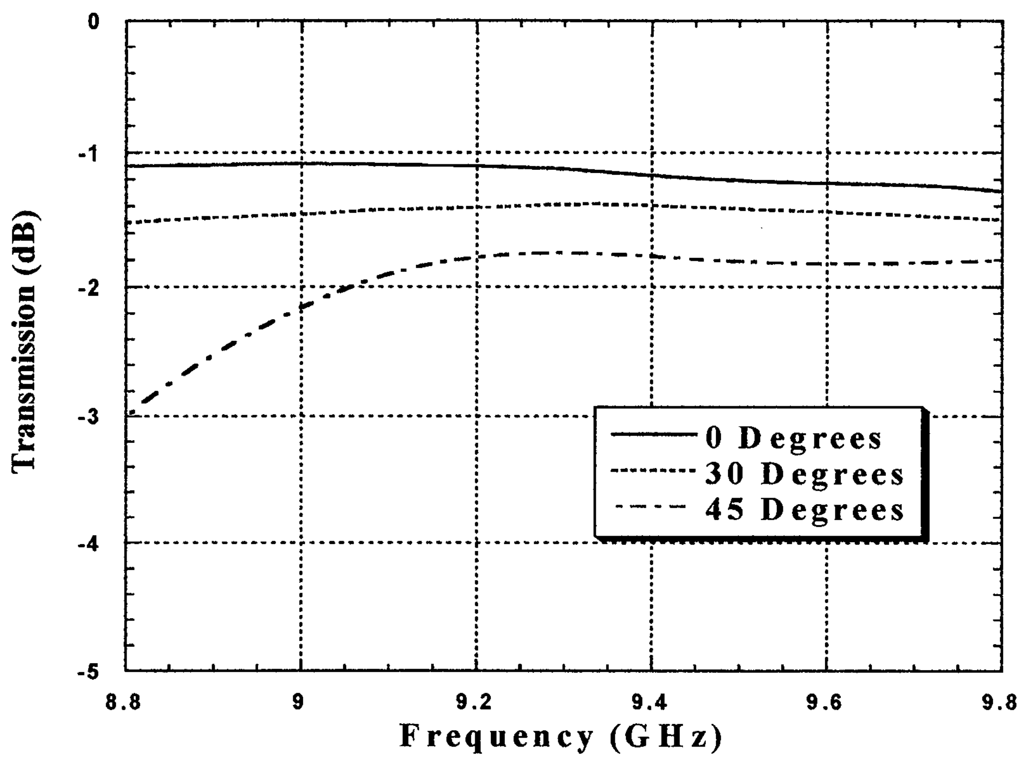


Figure 7a. Plot of model predicted full lens transmission response.

setting forward or reverse biasing groups of diodes mounted on the dielectric layers. The amount of phase shift introduced by each layer depends on the amount of metalization and the property of the diodes. The equivalent circuit model employs lumped elements (inductors, capacitors and resistors) to represent the metalization, the diodes, etc. The Radant Lens operation is modeled using these lumped element values [8]. Three different layers, which gave 45°, 22.5°, and 11.25° phase shift, were designed and built. These three types of layers were used to create a model for the entire lens as illustrated by 13 layers in Fig. 4 for one column of the lens. The theoretically predicted transmission response for the full 13 layer lens is shown in Fig. 7a. The average normal incidence (0°) transmission is about -1.2 dB, with an absolute value of -1.1 dB at band center. To confirm the theoretical predictions, a group of five (5) early production phase shift modules (13 layers) were RF tested. These measured results are shown in Fig 7b. The normal incidence measurements indicated an average insertion loss of -1.2 dB. Within the uncertainty of measurement errors, these measurements agreed well with the theoretical predictions.

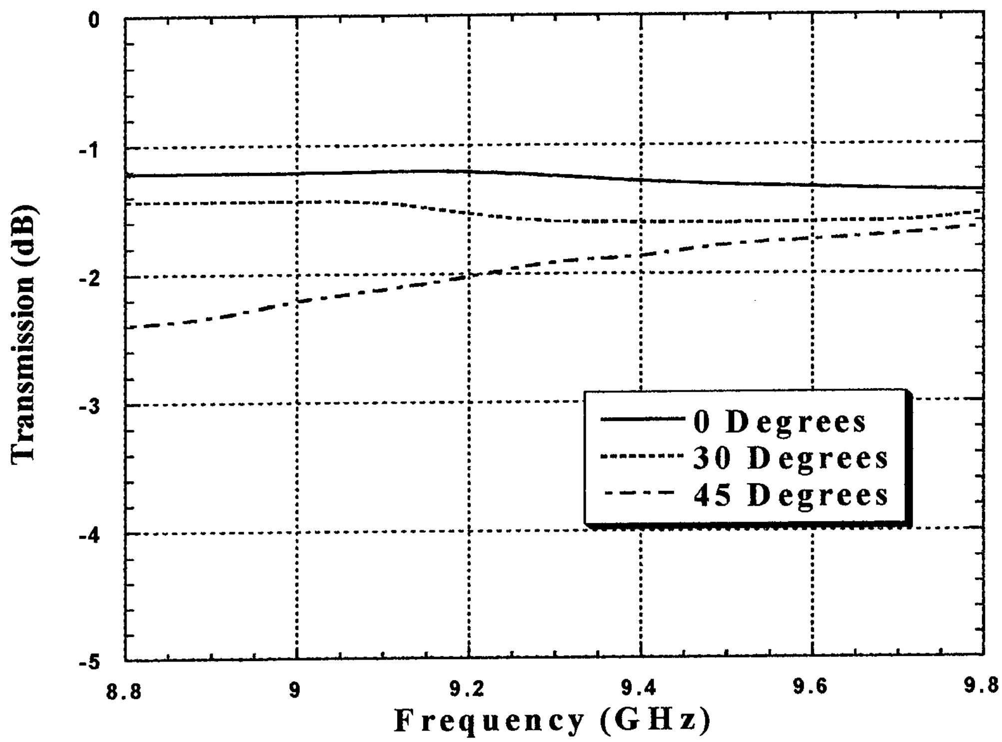


Figure 7b. Plot of transmission measurements taken on five (5) early production modules.

**5. Beam Steering Hardware and Software**

The Radant lens is composed of 136 row elements. Each row element is driven by an individual driver board which controls the bias of the 4 sets of diode layers, representing 180°, 90°, 45°, and 22.5° of phase shift, as mentioned earlier. Each of these driver boards provides an addressable double-buffered digital phase control. Phase settings are loaded into first stage registers sequentially by a beam-steering control computer. The operational registers of all driver boards are then loaded simultaneously from their first stage registers by a global NEWBEAM trigger. These 136 driver boards are housed in 4 external card cages.

Rather than controlling these 136 driver boards from a single beam-steering control computer, control is distributed to a separate controller located in each card cage. These 4 beam-steering controllers are custom designed boards based on Transputer microprocessors. The Transputer is a RISC (Reduced Instruction Set Computer) microprocessor with 4 built-in serial links

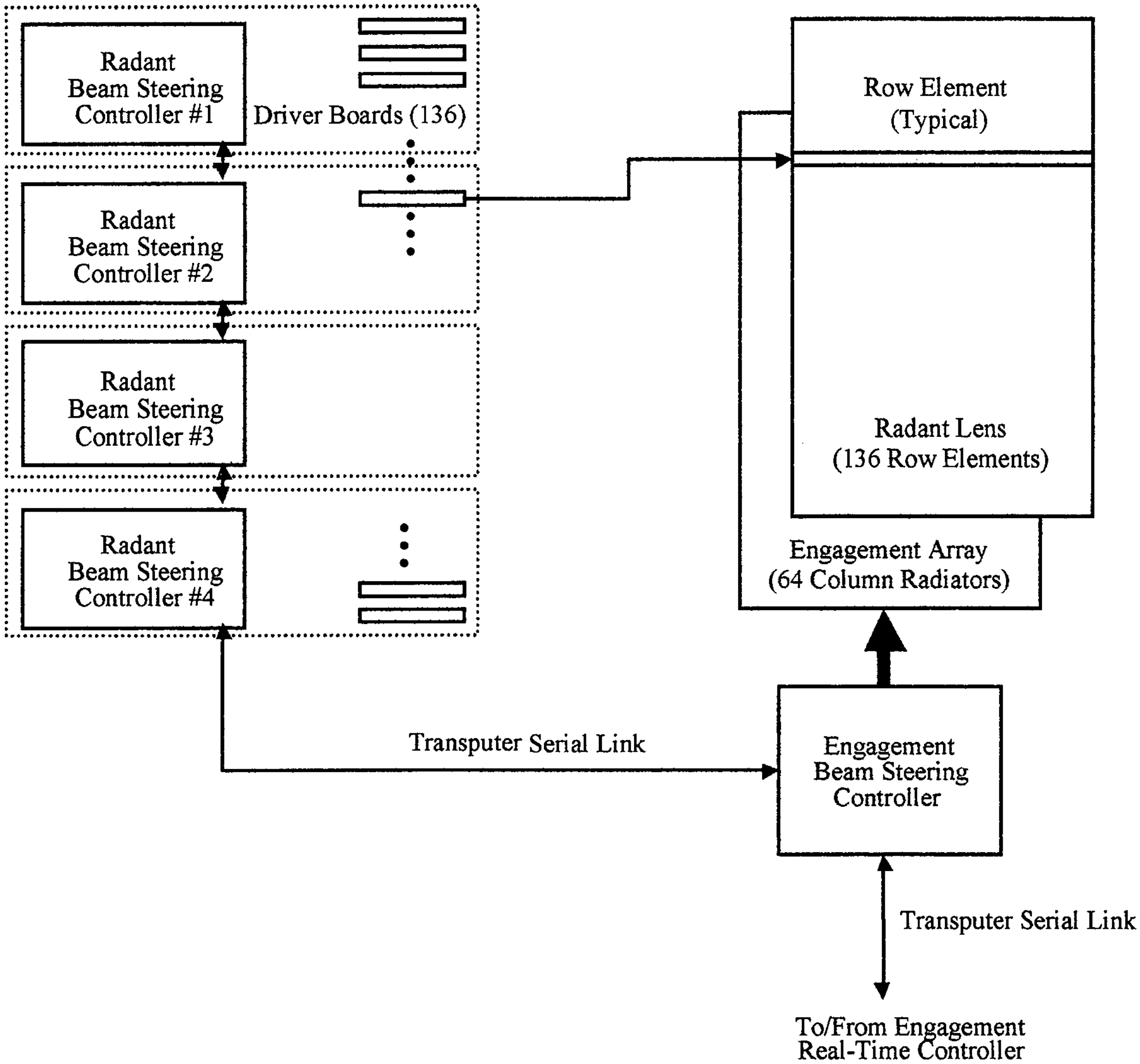


Figure 8. Radant/Engagement Antenna Controllers

for inter-processor communication. These four controllers are daisy-chained through these links and connected to the existing Engagement beam-steering controller, which is also based on the Transputer [2]. These 5 controllers receive commands from the Engagement RTC (Real-Time Controller) over these links, indicating the desired pointing angle and RF frequency of the next dwell which begins at the next NEWBEAM trigger. These components are interconnected as shown in Figure 8.

Steering the beam of the hybrid antenna is done by forming horizontal and vertical phase gradients across the aperture. The horizontal gradient is realized by controlling the relative phase to each column of the slotted waveguide radiating element of the Engagement phased array antenna. The vertical gradient is realized by controlling the relative phase shift through each row element of the Radant lens. These phase gradients indicate the phase differential between adjacent elements and are given by:

$$\Delta\varphi_x = 2\pi(d_x/\lambda)\, \mathit{cos}\, \mathrm{El}\ \ \mathit{sin}\, \mathrm{Az}$$
$$\Delta\varphi_y = 2\pi(d_y/\lambda)\, \mathit{sin}\, \mathrm{El}$$

where

$d_x = 0.665\text{in}$ (Horizontal spacing between elements)
$d_y = 0.705\text{in}$ (Vertical spacing between elements)

assuming Az and El are relative to the antenna's boresight. Translation into this coordinate system is the responsibility of the Engagement RTC Real-Time Controller.

The Engagement array beam-steering software required very little modification to operate in this hybrid arrangement. The horizontal phase gradient calculation had to be changed to the above equation to account for 2D operation. Modification was needed to forward the beam-steering commands to the Radant beam-steering controllers.

Each Radant beam-steering controller is responsible for the control of 34 lens row elements. Each controller will first calculate the desired phase gradient from the given Elevation angle and Frequency. This phase gradient must then be modified to compensate for the squint produced by the slotted waveguide radiators of the Engagement antenna. Once this gradient is known, the phase setting at each row element is given by:

$$\varphi_{yi} = i\ \Delta\varphi_y$$

where

i is the index number of a given row element starting at the top of the lens.

Ideally, a 4-bit digital phase setting could be obtained by simply dividing $\varphi_{yi}$ by 22.5° and rounding the result. However, the nominal phase shift values of the diode layers sets vary with frequency and the H-plane incident angle. For example the 180° bit layer set may actually produce a 190° phase shift for a certain frequency and H-plane incident angle. Radant technologies measured how the individual layers sets varied with frequency and incident angle and produced an algorithm to determine the best digital phase settings [9]. This method first involves approximating the actual value of each layer set for the given frequency and H-plane incident angle (Azimuth) through a double 2nd order interpolation. The next step is to determine the combined phase shift for each of the 16 possible diode states. Finally, for each element (i) the diode state which has a combined phase state closest to $\varphi_{yi}$ is chosen.

## 6. Experimental Setup

The Radar Division Compact Range Facility is located at the Naval Research Laboratory in building A-59 and can be accessed through Door B, which is located on the Southwest side of the building. The Compact Range simulates a Far Field environment by over illuminating a parabolic dish antenna and by using edge treatment (serration's) to control diffraction effects. The fields that are produced across the test antenna are nearly the same as that occurs in the far field, i.e. constant phase and amplitude. This region is known as the quiet zone of the chamber. By using this type of chamber, the normal $2D^2/\lambda$ requirement used for antenna separation is not required. This allows for complete characterization of large antennas in a very short antenna range.

The dimension of the anechoic chamber, which houses the parabolic reflector, is approximately 20 x 30 x 40 feet in size and is environmentally controlled. The facility also has a control room, staging area and a light duty shop to support measurements in the range. The chamber utilizes a Scientific Atlanta 5706M Compact Range Reflector System that provides the quiet zone dimensions given in Table I. The reflector system uses a virtual vertex offset feed concept for illumination of the reflector. This technique minimizes the direct coupling between the reflector and feed combination and improves the quiet zone performance. A series of waveguide scalar feeds are typically used to feed the dish although other feeds can be substituted depending on quiet zone performance requirements. The chamber has feeds that range from 2 – 100GHz. The reflector-feed arrangement is shown in figure 9.

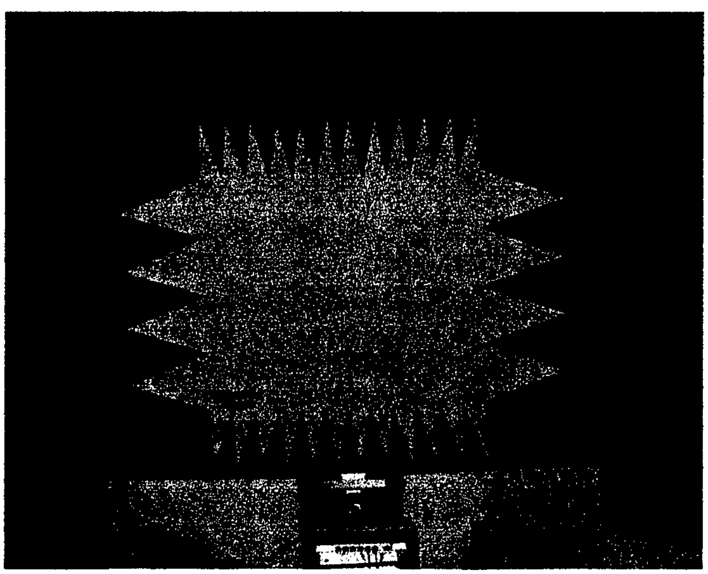

Figure 9. Compact Range Parabolic Reflector and Feed Arrangement

Table I. Chamber Quiet Zone Specifications

| **Frequency** | **Diameter** | **Length** |
|---|---|---|
| 6-100 GHz | 8' | 8' |
| 2-6 GHz | 6' | 8' |

The control of the RF and positioning equipment used in the compact range facility is done with the Flam and Russell (FR 959) antenna measurement software package. The software is used to control a HP 8530 measurement system as well as an 8 axis 4139 Scientific Atlanta position controller. The HP 8530 microwave receiver utilizes a multi-channel HP 8511 test set for the down conversion process which allows for the sum and difference channels of the antenna to be measured simultaneously. The software package also contains analysis software which is able to process the measured antenna data to obtain characterisictics of the antenna under test (i.e. beamwidth , gain, sidelobe levels) . The data can be analyzed using the FR959 analysis tools or it can be downloaded to an ASCII file to be analyzed off line. A block diagram of the measurement system is shown in figure 10.

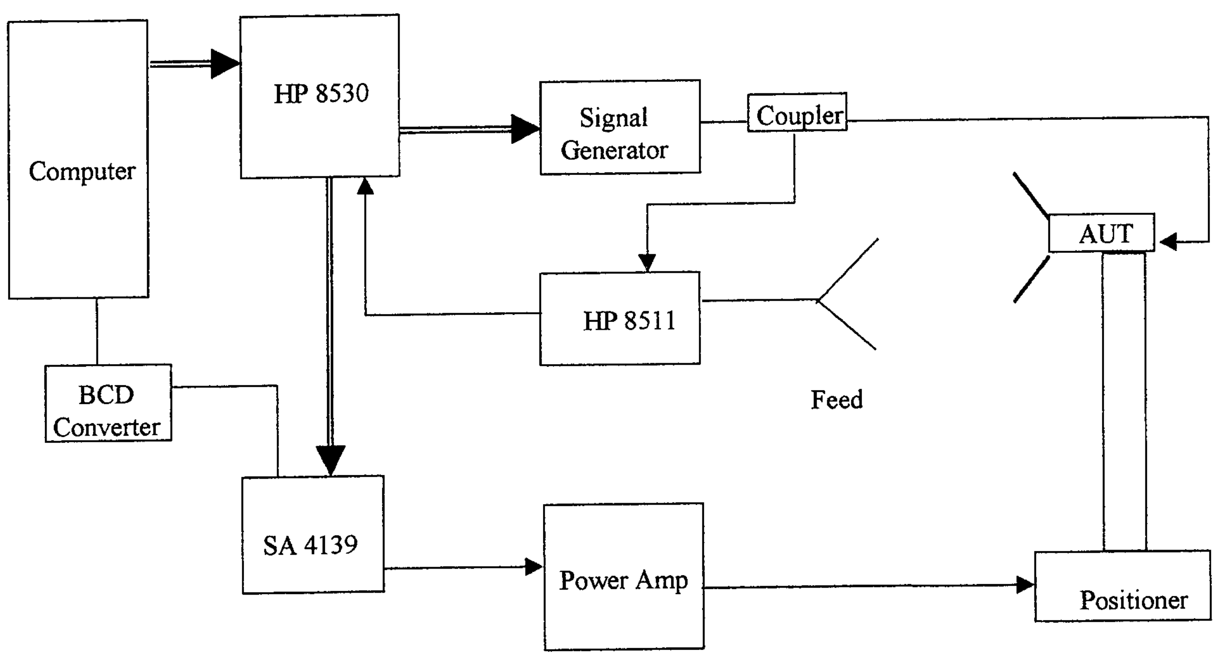


Figure 10. Compact Range Equipment Layout

Because of the weight and bending moment restrictions on the azimuth over elevation positioner (SA5315) normally used inside the chamber, a larger azimuth over elevation positioner (SA53150A) was configured over an existing azimuth positioner (SA51150A) in order to position the combined antenna system. The standard mount configuration, which is shown in figure 11, was removed and a new tower support was built and installed. The new mount and tower configuration is shown in figure 12 with the Engagement array mounted on it. To safely secure the two antennas to the positioner, a picture frame assembly was built to hold both the engagement array and the Radant lens. Figure 13 shows the mounted Radant lens with the Engagement array behind it. The assembly is in position for making E-plane pattern measurements.

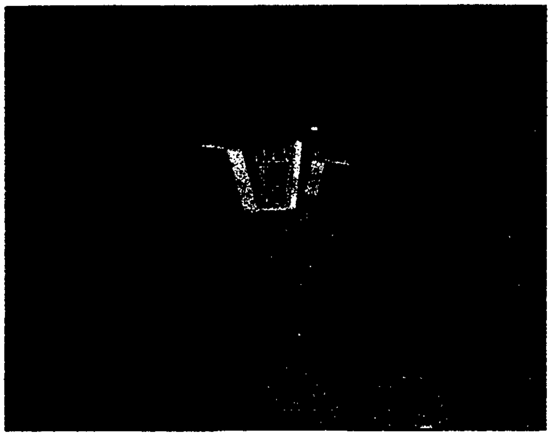

Figure 11. Existing Azimuth over Elevation Positioner

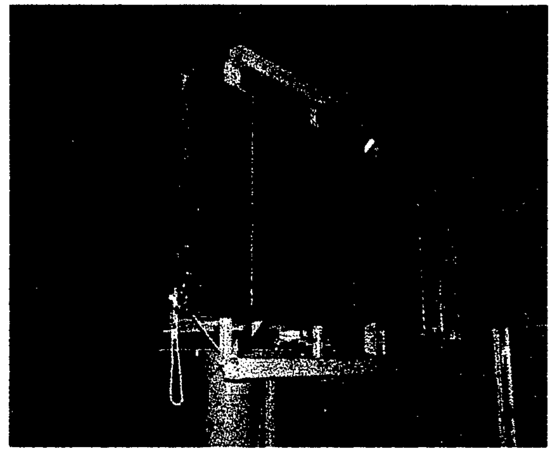

Figure 12. New tower with Engagement Array.

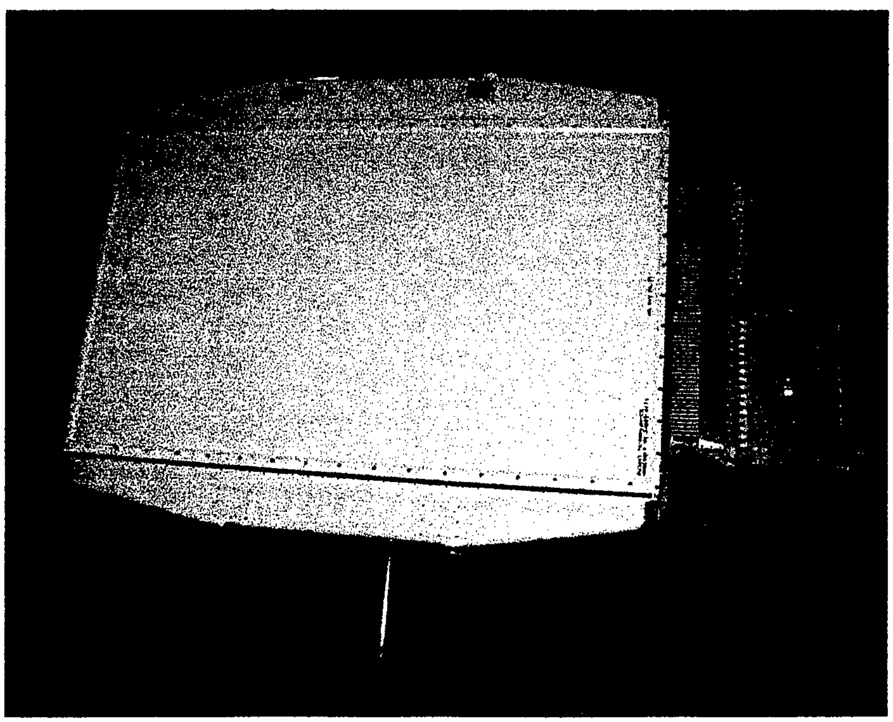

Figure 13. Experimental setup of the Radant lens in the compact range test facility with the Engagement array behind it.

The various pattern measurements of the antenna system were recorded over a ±50 degree azimuth rotation with typical steps of .25 degree. In order to characterize the antenna system in both the E and H planes, the antenna was mounted to allow a 90 degree rotation along its center axis. Figures 13 and 14 show the antenna assembly in position for E and H plane pattern cuts, respectfully. The feed polarization was also rotated to maintain the co-polarized antenna response. The antenna rotation was accomplished with the azimuth/elevation positioner that was mounted on the tower configuration.

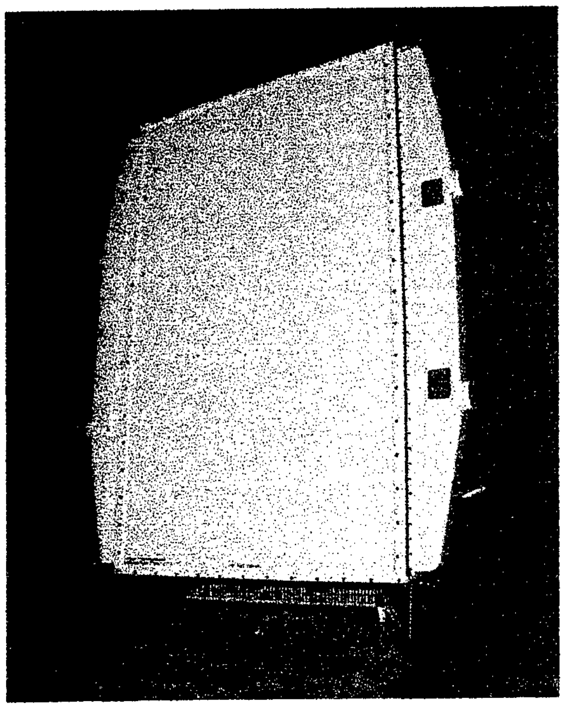

Figure 14. The antenna assembly positioned for H-plane cuts.

Due to the nature of the mounting configuration, (elevation over azimuth) the patterns that were taken are known as great circle cuts. Because a phased array antenna electronically scans the beam, the elevation angle of the positioner was chosen such that a pattern cut contained the main beam (maximum signal level) of the array. A simple coordinate transformation [10] between the scanned beam directions and positioner coordinates ensured that the maximum levels were always measured.

## 7. Experimental Results

Measurements of most interest were the lens losses and the effect of the lens on antenna sidelobes. Therefore, gain and radiation patterns measurements were made with and without the Radant lens. In addition to these measurements, others were done to calibrate the steering of the lens over the entire frequency band of interest (9.25 to 9.75 GHz). Data was collected in two sessions. First it was collected from the end of June through July 1998. After that time, the lens was repackaged and sent back to Radant Technologies, Inc. for further calibration and improvement. The lens was returned to NRL and final measurements and calibration were performed from the end of January to the middle of March 1999. The hybrid antenna system will be used at NRL's Chesapeake Beach Detachment as part of a 3D radar system.

Hundreds of antenna array patterns were collected, each one showed that the Radant lens has performed as expected, scanning the antenna beam with only small degradation in the antenna sidelobes. These conclusions are reached by comparing the antenna patterns of the slotted waveguide array by itself with the patterns for the slotted waveguide array with the Radant lens mounted in front of it. The patterns are shown in Figs. 15, 16 and 17. In Fig. 15, H-plane sum patterns for the slotted waveguide array only and the hybrid array are plotted on top of each other. In both cases the frequency is at 9.25 GHz and the slotted waveguide array is steered to 0°. The Radant lens is powered off, putting the lens in state 15. In state 15, the diodes are all reverse biased, providing no beam steering and allowing the two patterns to line up. Care was taken to ensure that the main beams were peaked in the elevation plane for these azimuth patterns. Fig. 16 shows the difference patterns that are associated with the sum patterns shown in Fig 15. From Figs. 15 and 16, it is readily seen that the Radant lens causes some loss in the main beam and very little deterioration in the sidelobes.

In Fig. 17, a comparison of E-plane sidelobe levels is shown. The frequency is 9.5 GHz and the slotted waveguide array is scanned to 15° in azimuth. The way this was done was to turn both antennas on their side and tilt the arrays back by 15°. In each case the beams were peaked and patterns were taken by rotating the array(s) about the vertical axis. In the E-plane there is a squint of 3.5° to 4.0° for each pattern, which happens because of the nature of the slotted waveguide array. There is also a 0.5° additional squint due to the non-uniformities of the Radant lens. This, of course, causes the sidelobes to change. Notice that the highest sidelobe of the slotted waveguide array is higher than the highest sidelobe for the hybrid array even with the loss correction included. Notice that the sidelobe deterioration is small in the E-plane, but not quite as small as in the in H-plane. Not all patterns are as good as these examples, however the sidelobe levels are well within the acceptable range for all patterns.

Fig. 18 illustrates the scanning capability of the Radant lens. In this plot, several over lapping patterns at 9.5 GHz are shown. These are E-plane patterns showing the lens ability to scan over large angles. In this example, the lens was scanned to 0°, ±10°, ±20°, ±30°, ±40°, and 45°. The main beams are not exactly at the correct angles due to the squint of the slotted waveguide array beam in this plane, which would be calibrated out when used with a radar system. Figs. 19 and 20 show E-plane patterns for two of the cases shown in Fig 18, the -30° (Fig 19) and 45° (Fig 20) scanned cases. For these two cases, no comparison pattern can be made to show how well it matches to the slotted waveguide only pattern. This, of course, is because the slotted waveguide array cannot be scanned to these angles. What is shown in these two patterns is that the relative sidelobe levels are reasonable and similar in level to the broadside case, indicating that the Radant lens did not introduce significant phase errors.

Figures 21 through 24 show E-plane patterns (elevation cuts) when scanned to two different azimuth angles and two different frequencies to demonstrate off-broadside sidelobe response. Figure 21 shows the E-plane patterns of the hybrid arrary and the slotted waveguide array by itself at 9.5 GHz when scanned to 15 degrees in azimuth. This gives a comparison of the patterns of the antennas at a 15 degree azimuth scan. Figure 22 shows the patterns at the same frequency but with a 45 degree azimuth scan. Figures 23 and 24 show similar patterns at 9.74 GHz. These patterns also indicate some loss in the mainbeam and negligible degradation in sidelobes due to the Radant lens.

Figures 25 and 26 show H-plane patterns (azimuth cuts) of the arrays for various azimuth scan angles. Figure 25 shows six patterns for scan angles from -45 to 30 degrees of the sum channel taken at 9.25 GHz. Figure 26 shows five difference patterns scanned from -30 to 30 degrees at 9.37 GHz. Again, these patterns indicate that the Radant lens introduces some loss in the mainbeam, but negligible degradation in sidelobes.

Now the transmission loss of the Radant lens is considered in some detail. This will be discussed from two main vantage points: The loss while scanning the beam and the loss while staring. In the staring mode, all diode phase shifters are set to the same state and the main beam does not change angle while passing though the lens (other than due to small non-uniformities). In the scanning mode, the main beam is steered in elevation and this can only be accomplished with the diode phase shifters in various states. With the diode phase shifters in various states, there are different numbers of forward and reverse biased diodes. This results in a different loss than the staring state. In each mode, the loss was measured by taking the difference of the main beam peaks of the slotted waveguide array by itself and the hybrid array. In the staring state, no power was applied to the Radant lens, which put all the diodes into state 15 or all diodes reverse biased. The loss for this case varied nearly linearly with frequency from 1.5 dB at 9.25 GHz to 2.5 dB at 9.75 GHz. In the scanning mode, the diode states are somewhat random in appearance. With the Radant lens scanned to 20°, NRL measured a loss of 2.4 dB at 9.25 GHz, increasing linearly to 2.5 dB at 9.75 GHz (Figure 27). These losses are higher than the theoretical predictions. Radant Technologies, Inc. discussed the reasons for these higher losses[8] and provided ways to reduce them. In fact, Radant Technologies, Inc., since this lens was made, have constructed another smaller lens that has a loss of approximately 1 dB across the band for the staring case. This gives hope that in any production Radant lens the losses can be limited to 1-2 dB.

## 8. Conclusions

An affordable hybrid phased array configuration is discussed. The hybrid configuration is made up of a modified AN/TPQ-36 antenna (a slotted waveguide array) and a Radant lens in front of it. The slotted waveguide array with the associated phase shifters at each column is used to scan the beam in the azimuth plane and the Radant lens is used to scan the beam in the elevation plane. Recently, a 4' × 8' Radant lens was procured from Radant Technologies, Inc. for this purpose. Experiments were performed at Radant Technologies, Inc. and then at NRL's compact range on this affordable hybrid array configuration to measure insertion loss, pattern distortion and scanning performance. Although the measured Radant lens loss is a bit higher than the theoretically predicted loss, the Radant Lens performed well with good scanning properties, low radiation pattern distortion and low return loss. The major result of this development has been the successful demonstration of a low cost Radant lens, which is an electronically steerable array antenna that could be employed for military and commercial applications.

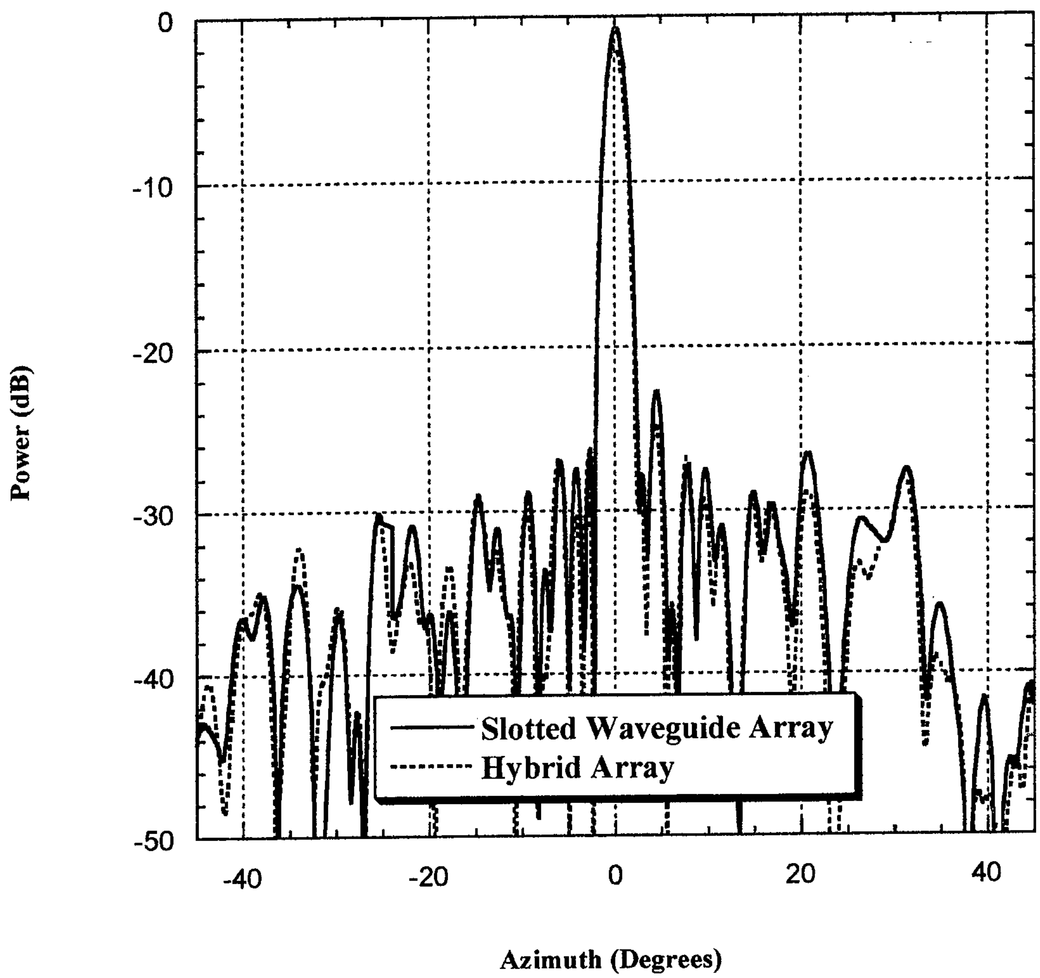


Figure 15. H-Plane sum channel patterns of slotted waveguide array only and hybrid array at 9.25 GHz.

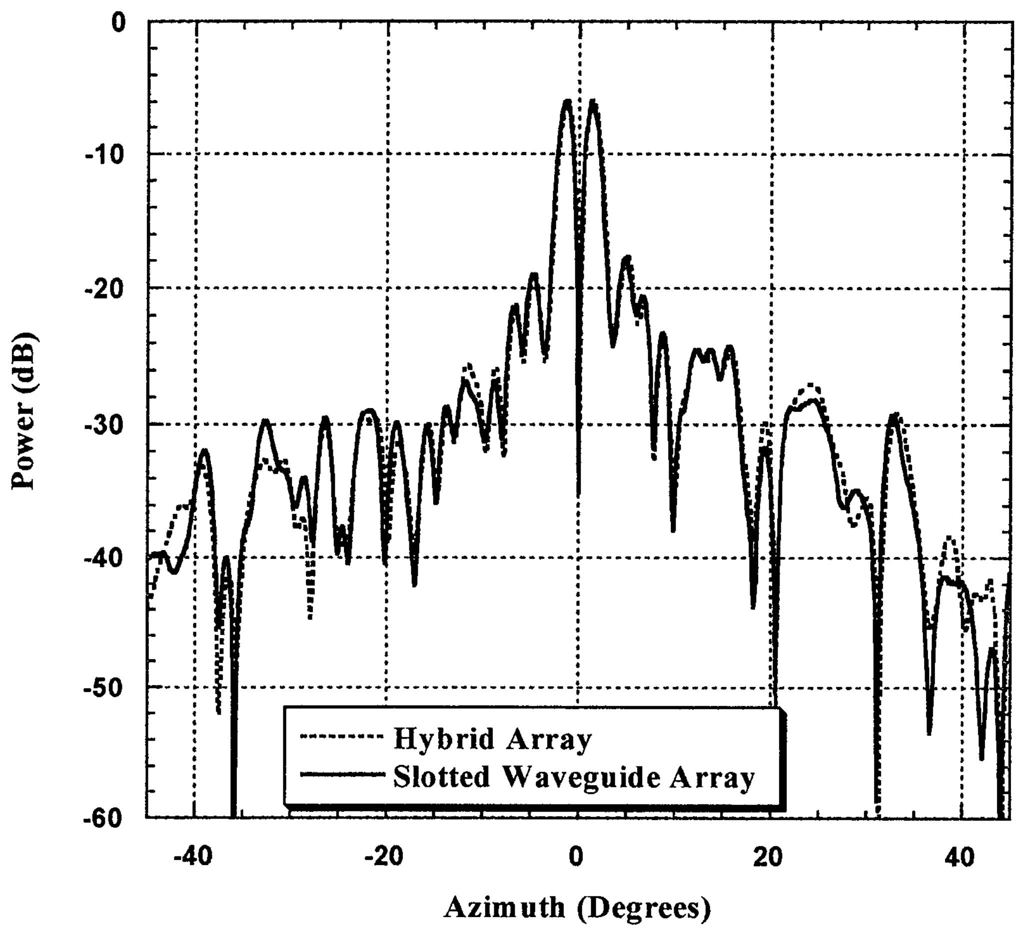


Figure 16. H-Plane difference patterns of slotted waveguide array only and hybrid array at 9.25 GHz

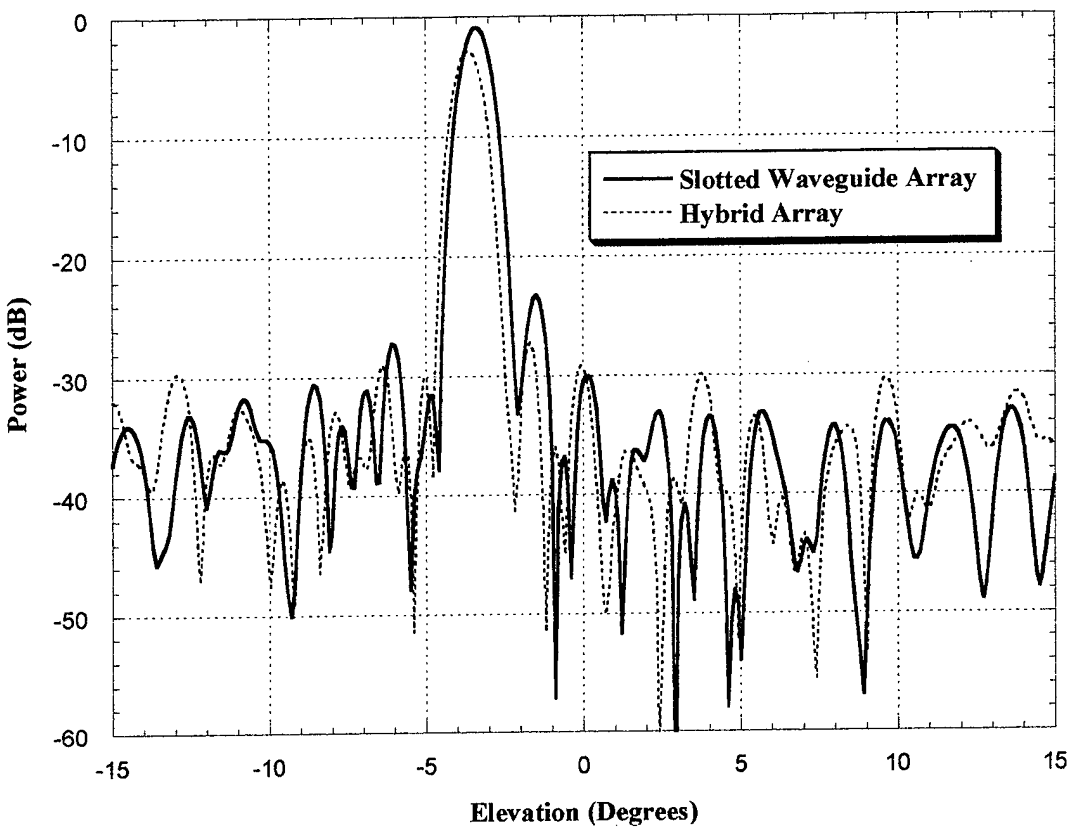


Figure 17. E-Plane patterns of slotted waveguide array only and hybrid array at 9.50 GHz.

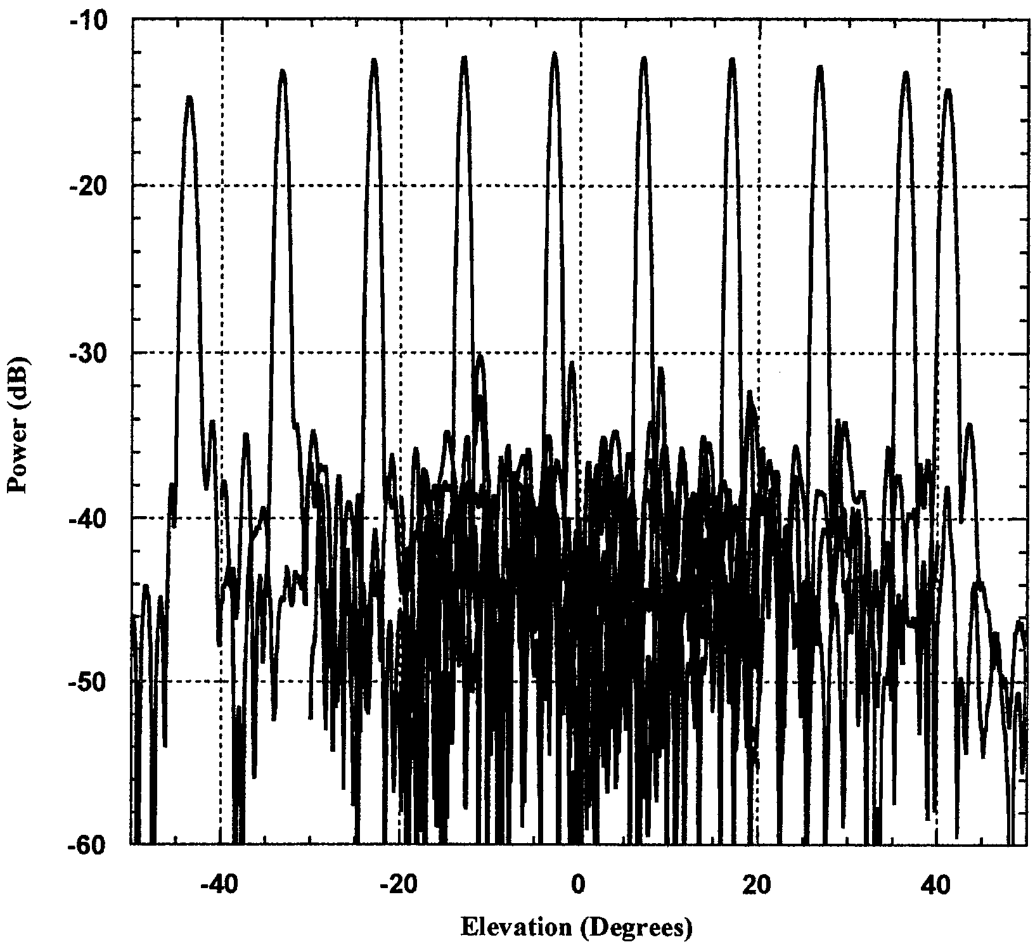


Figure 18. E-Plane patterns of hybrid array at various elevation scan angles.

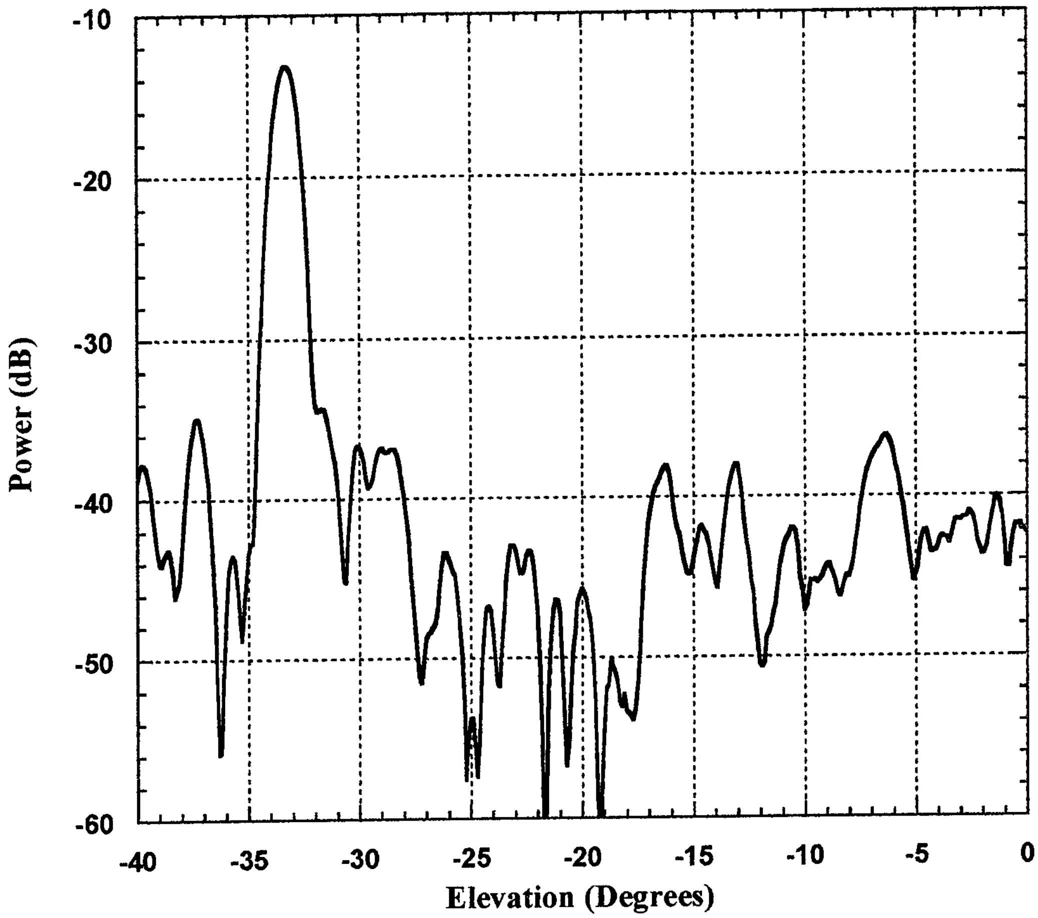


Figure 19. E-Plane pattern of the hybrid array scanned to -30° in elevation.

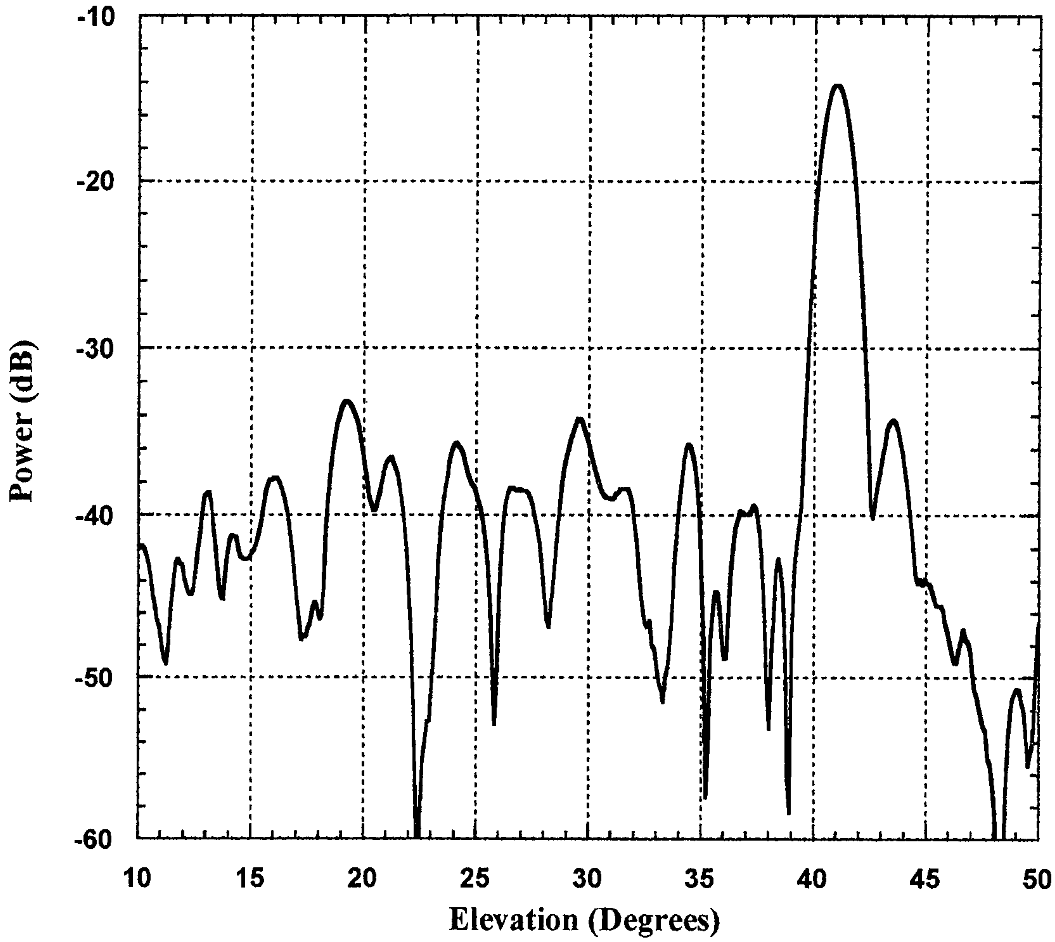


Figure 20. E- Plane pattern of the hybrid array scanned to 45° in elevation.

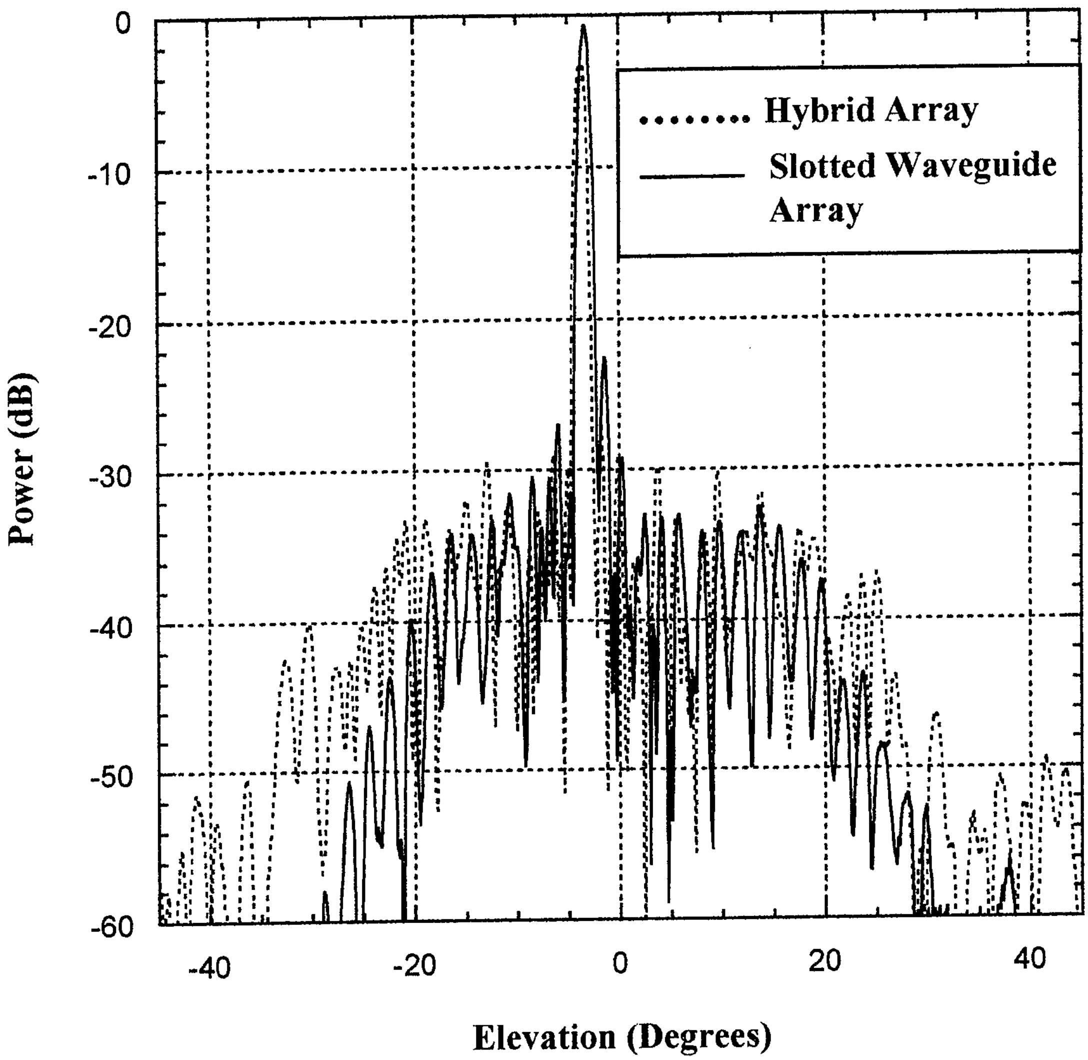


Figure 21. E-plane pattern cuts at 9.5 GHz when the slotted waveguide array is scanned to 15° in azimuth.

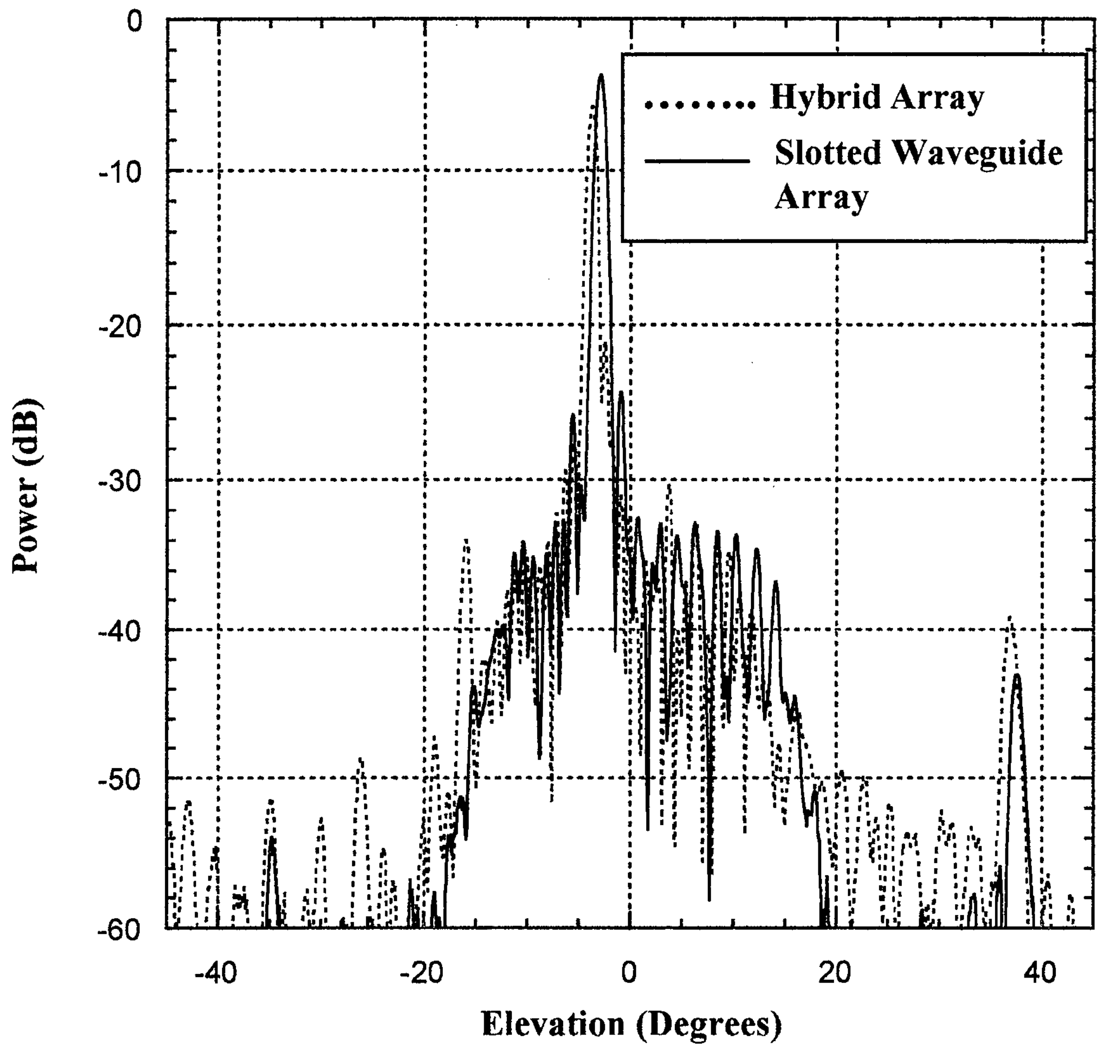


Figure 22. E-plane pattern cuts at 9.5 GHz when the slotted waveguide array is scanned to 45° in azimuth.

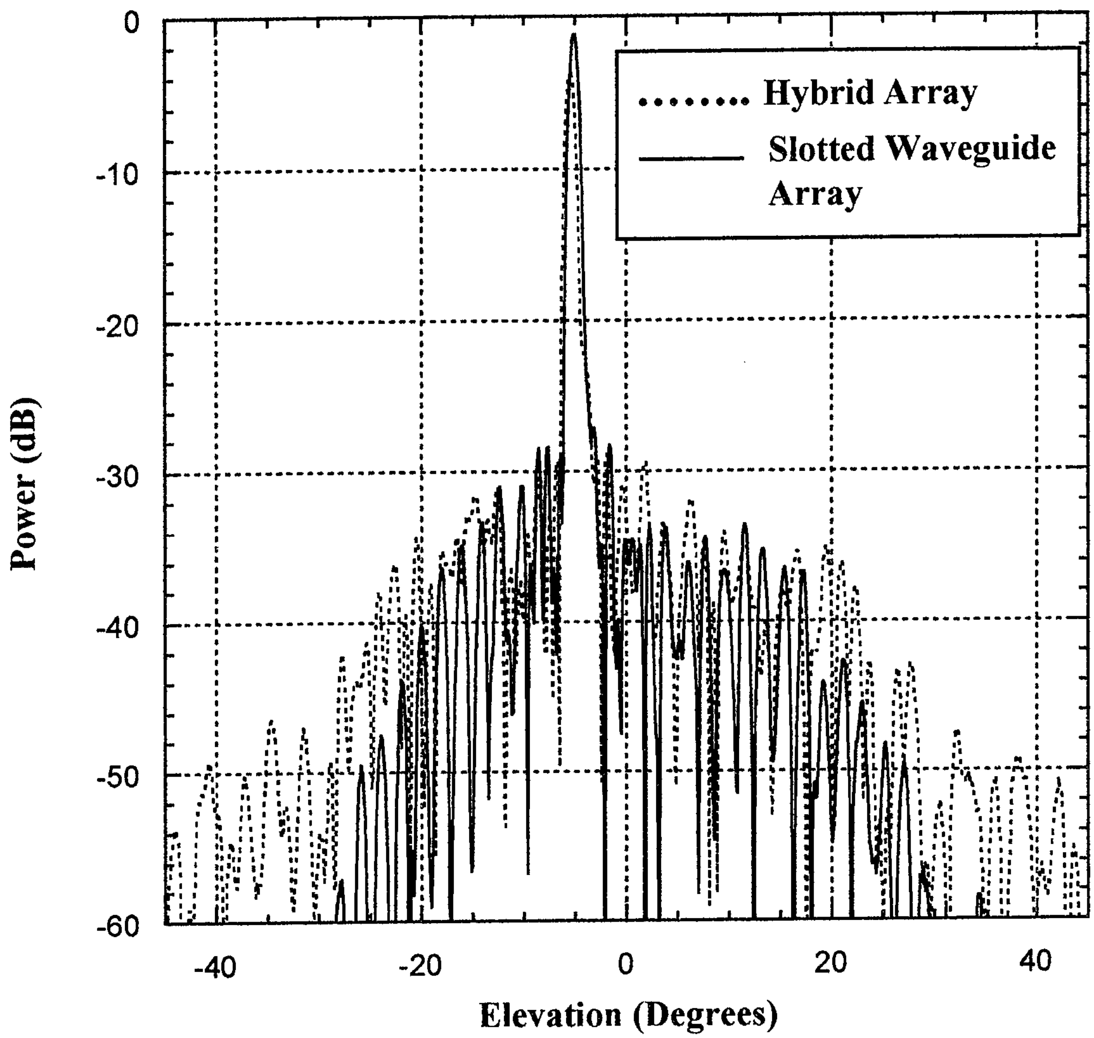


Figure 23. E-plane pattern cuts at 9.74 GHz when the slotted waveguide array is scanned to 15° in azimuth.

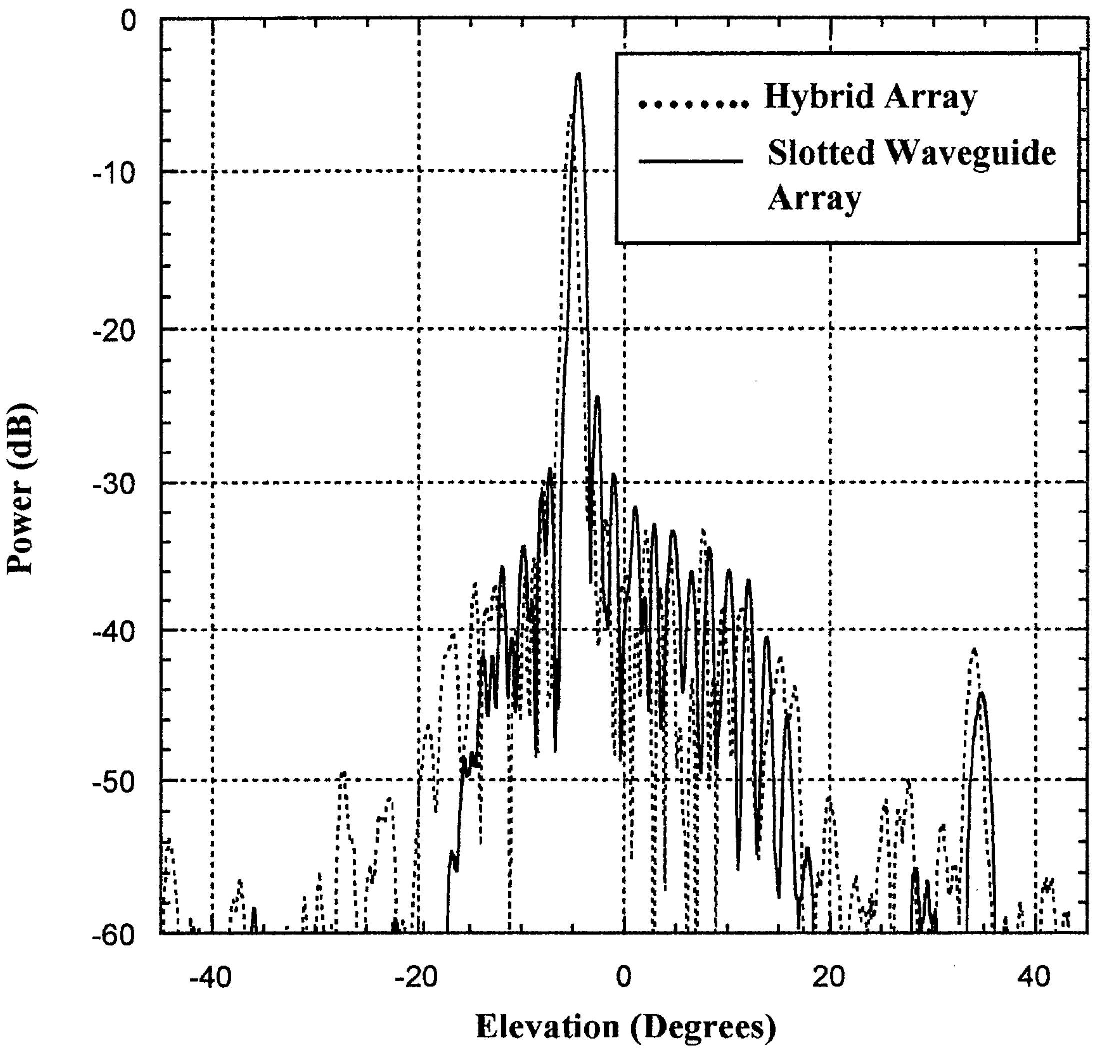


Figure 24. E-plane pattern cuts at 9.74 GHz when the slotted waveguide array is scanned to 45° in azimuth.

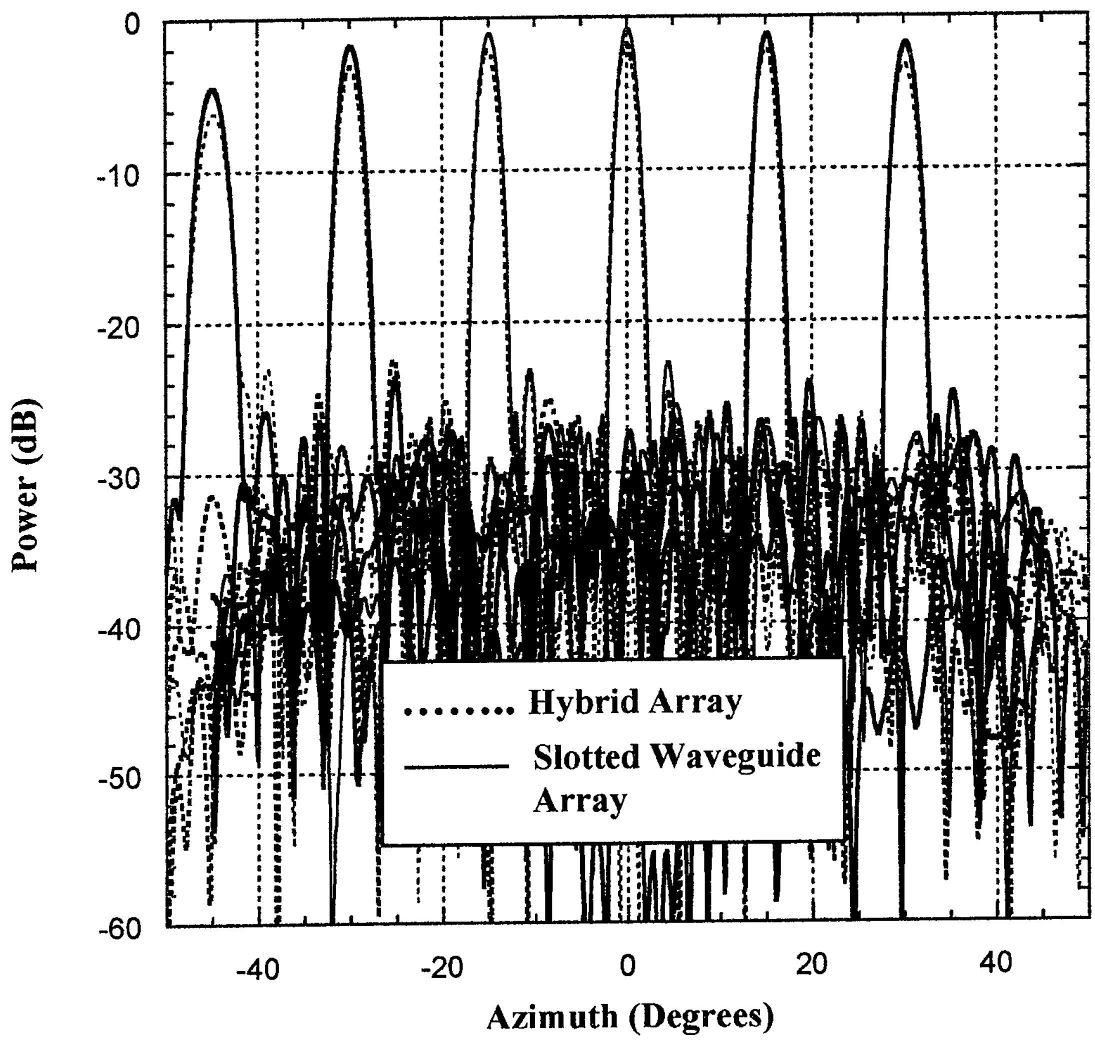


Figure 25. H-Plane sum patterns of the arrays for various azimuth scan angles at 9.25 GHz.

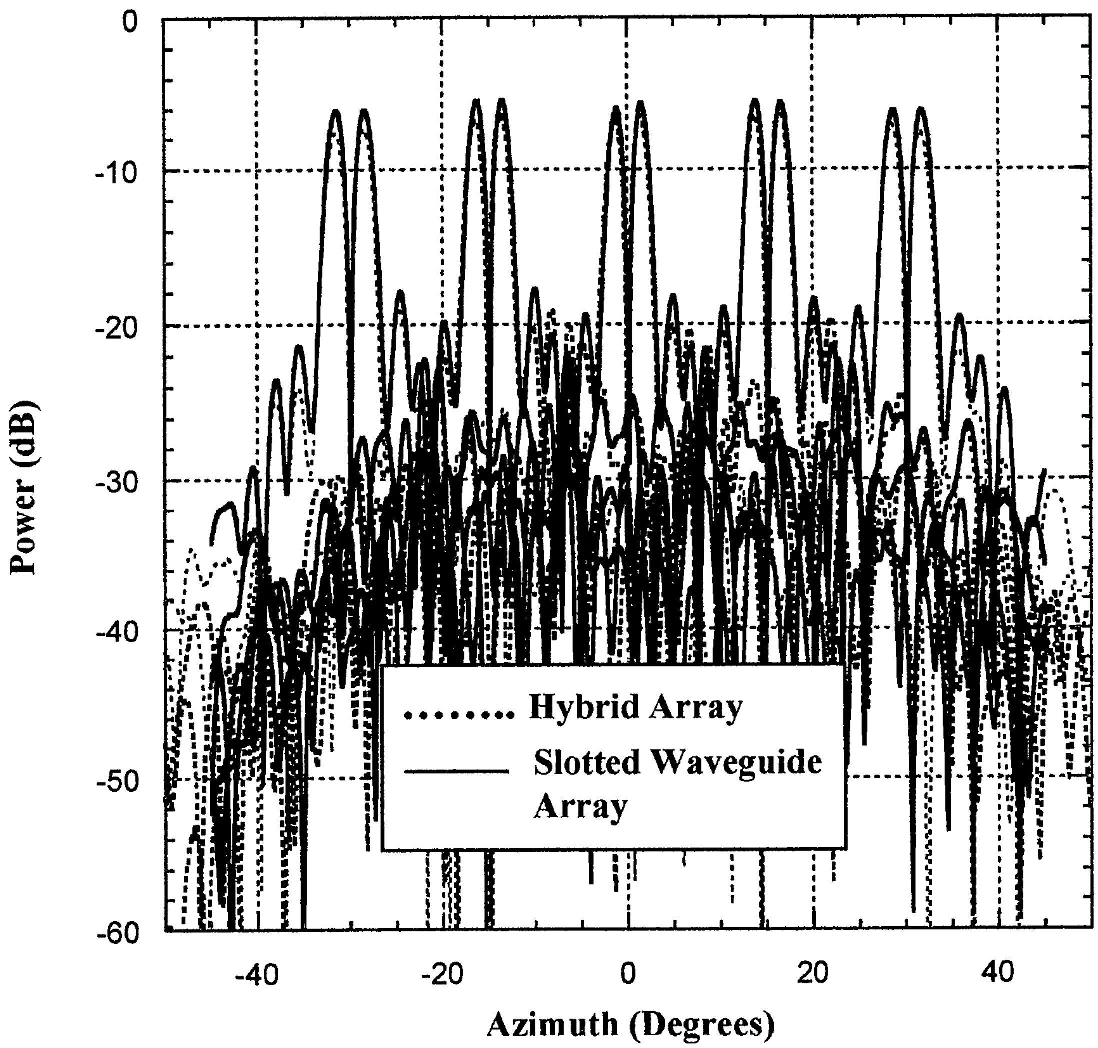


Figure 26. H-Plane difference patterns of the arrays for various azimuth scan angles at 9.37 GHz.

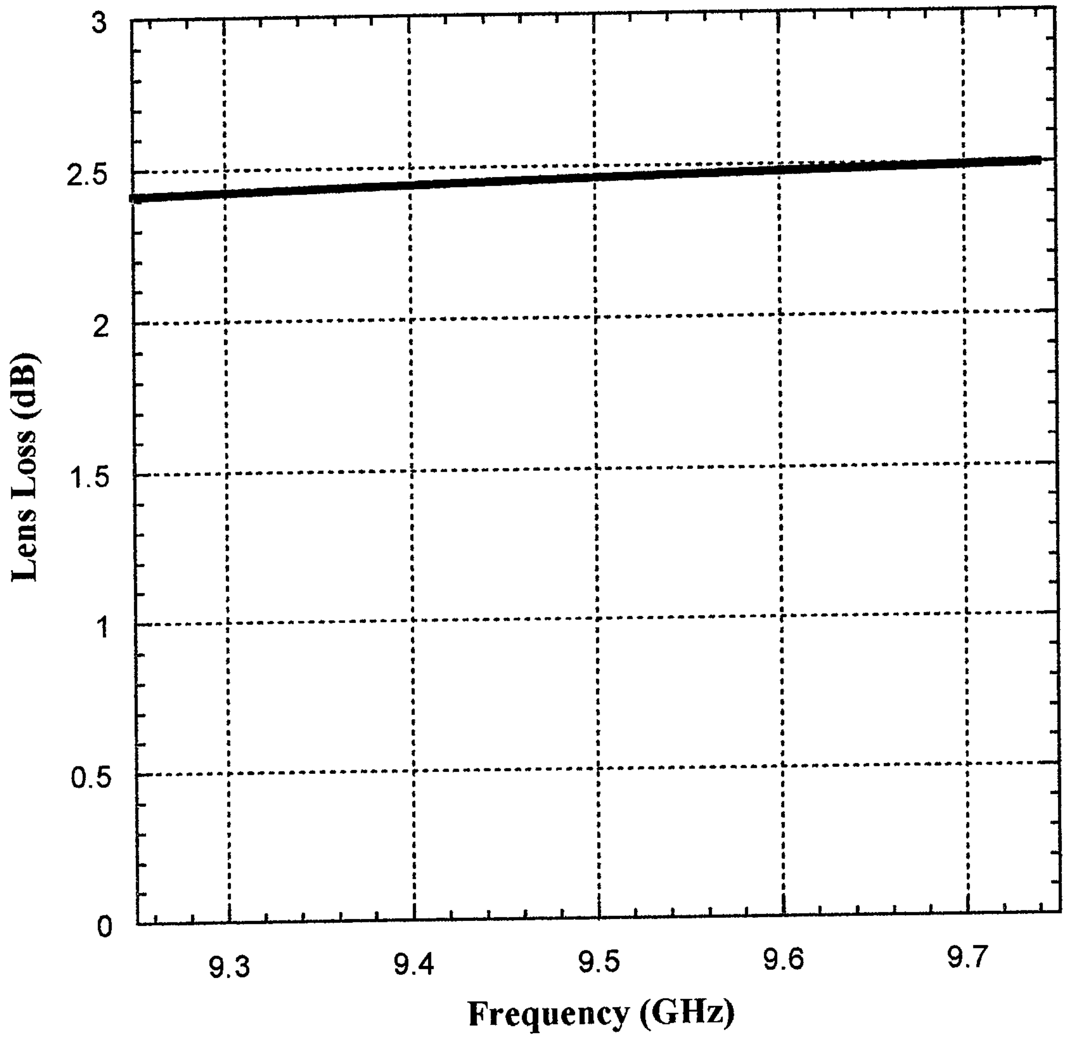


Figure 27. Measured lens loss over a frequency band, including approximately a 0.2 dB loss due to the radome.

## 9. References


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