REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
22-07-2010

2. REPORT TYPE
Proceedings

3. DATES COVERED *(From - To)*
JUL 2010 - AUG 2010

4. TITLE AND SUBTITLE
Results of X-Band Electronically Scanned Array Using an Overlapped Subarray Architecture

5a. CONTRACT NUMBER
FA8720-05-C-0002

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Sean Duffy, Francis Willwerth, Larry Retherford, Jeffrey Herd

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02420

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ESC/CAA
20 Schilling Circle, Bldg 1305
Hanscom AFB, MA 01731

10. SPONSOR/MONITOR'S ACRONYM(S)
ESC/CAA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: U			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Zach Sweet
U	U	U	SAR	6	**19b. TELEPHONE NUMBER** *(include area code)* 781-981-5997

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

MS-44519

Results of X-Band Electronically Scanned Array Using an Overlapped Subarray Architecture

Sean M. Duffy, Francis Willwerth, Larry Retherford and Jeffrey S. Herd
MIT Lincoln Laboratory Lexington, MA 02420-9108 (sduffy@ll.mit.edu)

Abstract
The measured results from an X-band electronically scanned array using an overlapped subarray architecture are presented. The 2D architecture uses a 12 x 12 element subarray with 3 to 1 overlapping. The active electronic scanned array is a receive only implementation consisting of switch, low noise amplifier, phase shifter and attenuator. Measured far-field patterns and excitation at the aperture using near-field scanner demonstrates desired design goals of a 20 degree sector beam with low sidelobes. Finally, the scan performance of the sector subarray beam is measured at 20 and 40 degrees. A three tile implementation is constructed and measured.

1. INTRODUCTION

Electronically scanned arrays require a minimum number of controls, N_{min}, given by the number of orthogonal beams that fill a prescribed scan sector [1]. Most practical antenna arrays require considerably more than N_{min} control elements, but overlapped subarray architectures can approach this theoretical limit. The overlapped subarray network can be designed to produce a flat-topped sector pattern with low sidelobes that suppress grating lobes outside of the main beam of the subarray pattern. Each radiating element of the array is connected to multiple subarrays, creating an overlapping geometry. It is possible to scan one beam, or a fixed set of contiguous beams, over the main sector of

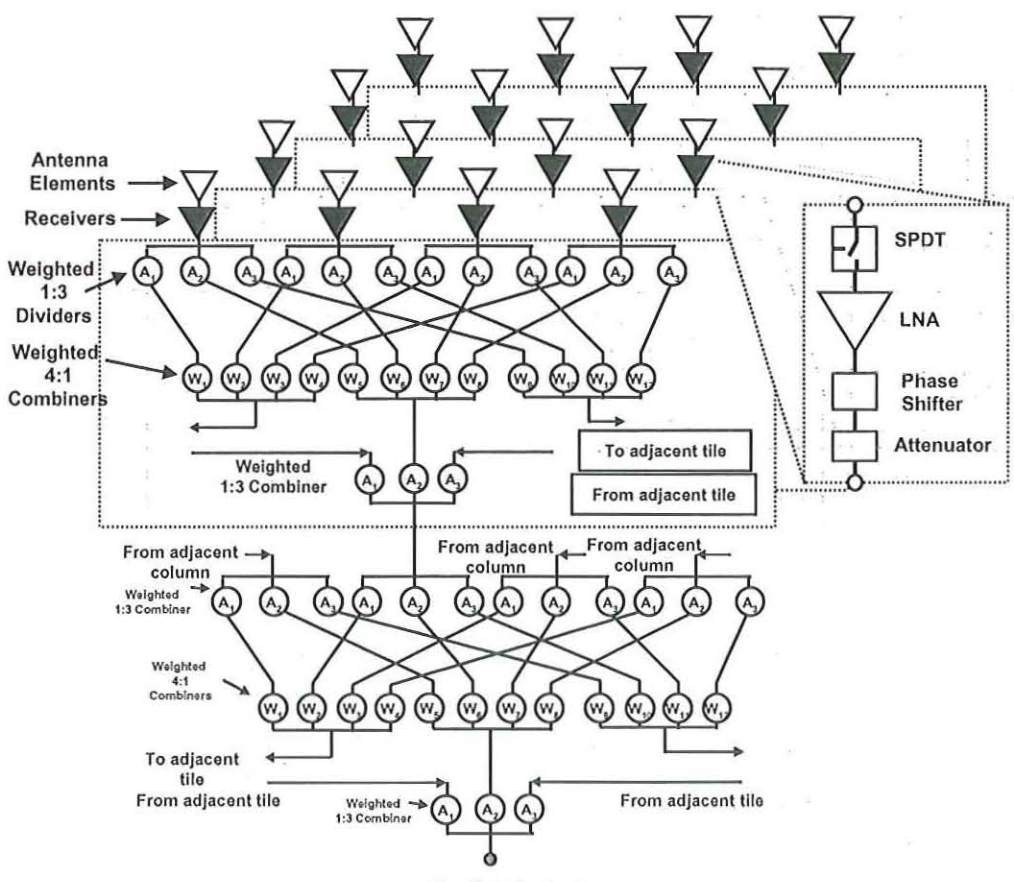


Figure 1 - Two dimensional 4 x 4 element 3-to-1 overlapping architecture

This work is sponsored by the Department of the Air Force under Contract # FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

the subarray with a set of N_{min} phase shifters. Alternatively, digital receivers can be connected to the N_{min} subarrays and multiple simultaneous beams can be formed digitally. Digital subarray architectures using a combination of element level phase shifters and subarray level receivers makes it possible to scan multiple beam clusters over all scan space.

The implementation of an X-band electronically scanned array (ESA) using an overlapped subarray architecture is described and results shown from the proof-of-concept array. A 48 element ESA composed of three 4 x 4 element tiles was built and tested. Measured data demonstrate the subarray beam scanning and an example of the performance of larger arrays is made using synthesized patterns using the measured subarray pattern. As an example, overlapping in 2 dimensions with an implementation of 9 x 9 tiles provides a 25 times improvement in beam coverage. Fundamentally, the design of the overlapped subarray architecture represents an approach for implementing an efficient trade-off between the agility and capability of fully digital arrays and the cost effectiveness of analog arrays.

Subarray Parameter	Goal
Sector coverage	±10° in az, el
Scan volume	±45° in az, el
Bandwidth	8.5 – 10.5 GHz
Size	12 × 12 elements
Overlap Ratio	3:1
Max Sidelobe	–25 dB

Table 1 – Overlapped Subarray Design Parameters

2. APPROACH

Design goals for the two-dimensional overlapped subarray considered in this paper are outlined in Table 1. A wide subarray sector beam of 20° is desired to electronically scan over a +/- 45° volume over the frequency range of 8.5 – 10.5 GHz. An overlapped subarray architecture using a 12 element subarray with 3-to-1 overlapping ratio provides the necessary sector beam coverage. The utilization of a low noise amplifier (LNA) and phase shifter at every antenna element provide a low noise method of providing the wide angle coverage.

The design utilizes a modular, tiled array approach to provide a low profile, piecewise conformal array, although only flat surfaces were investigated in this work. Each of the tiles has 4 × 4 stacked patch radiating elements operating at X-band. A set of 3 × 3 tiles constitutes a single overlapped subarray. A useful property of the design is that identical tiles are used over the entire array, and the shape of the array can be tailored to the platform and application. Figure 1 shows a block diagram of the two dimensional overlapped subarray tile. Note that crossovers are required between the tiles. In this design, the crossovers are accomplished by a set of backplane surface mount connectors shown on Figure 2 and interconnecting coplanar waveguide transmission lines. An identical subarraying scheme is used in the perpendicular plane. All of the weighting and summing functions are implemented in planar circuits contained on each tile and discussed in the next section.

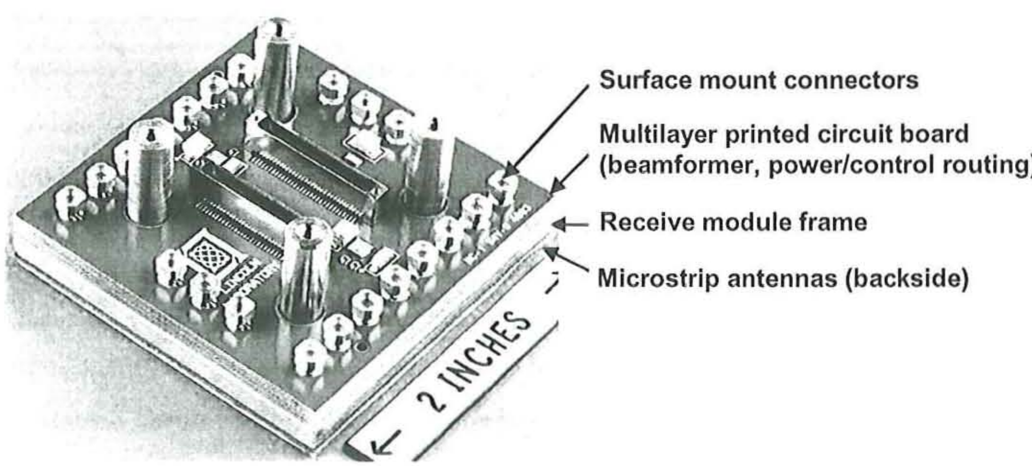
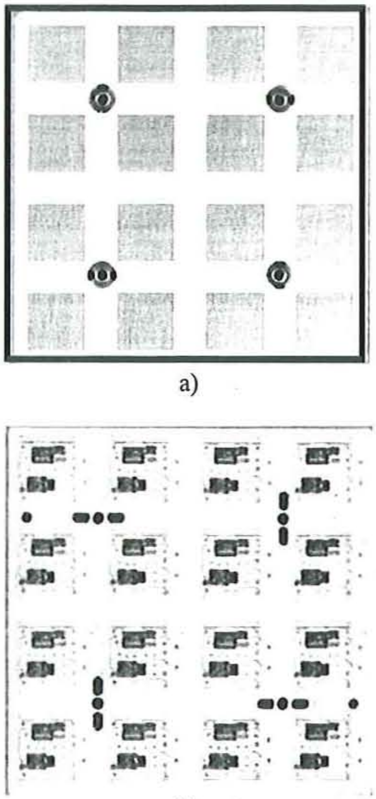


Figure 2 - Photograph of connector side of tile.



a)

b)

Figure 3 - a) 4 x 4 array of microstrip patch antennas, b) Receiver picture (SPDT switch, LNA, 5 bit phase shifter, analog attenuator)

3. TILE DESIGN

The tile building block includes a 4 x 4 array of microstrip patch antennas as shown in Figure 3. The microstrip antenna is a stacked microstrip patch with the outer patch on foam material (ε_r =1.17) of thickness 0.183 cm and the inner patch on PTFE material (ε_r =2.2) of thickness 0.076 cm connected through a pogo pin to the backside of the receive module. The tile dimensions are 5.9 cm x 5.9 cm. Element to element spacing is 1.5 cm which leaves 0.5 λ_o spacing at the center of the frequency band.

The receive module consists of 16 Alumina substrates each consisting of a Single Pole Double Throw (SPDT) switch, Low Noise Amplifier (LNA), 5 bit phase shifter and analog attenuator mounted in an aluminum silicon carbide metal frame. The metal frame is mounted to a backplane by four 0.64 cm diameter aluminum posts and provides the mechanical positioning and thermal path for the tile. A second set of pogo pins connects the top side of the Alumina substrate to the multilayer printed circuit board containing the overlapped subarray and the digital and power connections.

A custom weighting function for the overlapped subarray pattern was synthesized using an alternating projections method [2]. The design goal for the subarray coefficients is shown in Table 2. This weighting function provides the 20° sector beam pattern with low sidelobes outside the main beam of the subarray. Although the weighting could be implemented using attenuators, the resulting beamformer loss would require excessively large LNA gain to minimize the noise figure impact. Therefore, a reasonably low-loss beamformer was designed using unequal weighted Wilkinson dividers, couplers and several fixed attenuators. In addition, careful consideration of achieving the desired sector beam over the full 8.5 – 10.5 GHz band was given, and in fact the beamformer provides significantly more bandwidth than the antenna element. The overlapped subarray manifold was fabricated using multilayer stripline circuit boards. The boards are constructed of low dielectric constant materials (ε_r=2.94) with printed resistors, and the vertical transitions between layers are achieved by drilled and plated through-holes. The completed manifold consists of six stripline layers, 21 conductor layers and is 0.5 cm thick.

The multilayer board also provides power and control fanout for the receive modules. The power and control signals are received on the tile by two 70 pin connectors as seen in Figure 2. The signals are routed to the edge of the tile, through top to bottom plated holes and fanned into to mate with a pogo pin connector at each receive module. A digital backplane board not shown provides the interface between computer control software and the tile connector

Element Number	1	2	3	4	5	6	7	8	9	10	11	12
Magnitude (V)	0.219	0.504	0.767	0.966	1.0	0.873	0.599	0.283	0.005	0.170	0.225	0.149
Phase (degree)	0	0	0	0	0	0	0	0	180	180	180	180

Table 2 - Subarray excitation for ideal coefficient set

4. SUBARRAY RESULTS

Three fully functional overlapped subarray tiles were mounted in a test fixture as shown in Figure 4. A digital backplane (not shown in figure) provided an interface to a control computer for controlling the SPDT switches, phase shifters, and attenuators. Measurements at 10 GHz were performed on a planar nearfield range. The measured amplitude and phase at the array face after calibration are shown in Figure 5. The desired amplitude and phase were derived in [2] and provide the flat sector topped pattern with low sidelobes outside the main beam. The excitation in the vertical dimension should be that of elements 5 – 8 in Figure 6 since the tile is designed for 2 dimensional overlapping but is only a single tile in width. The horizontal cut of the amplitude data at y = 0.76 cm is shown in Figure 6 and compared with the desired excitation. The far field transformation of the nearfield measured data is shown in Figure 7. Also, shown are measurements for 20° and 40° scans. No additional calibrations were used for the 20 and 40 degree scans. The measured patterns demonstrate how the subarray pattern is scanned to provide wide angle coverage. The peak sidelobes of approximately -18 to -20 dB are slightly higher than desired, but it is expected that a more exhaustive calibration process could achieve somewhat better results.

The bandwidth of the far-field patterns of the subarray is a function of the bandwidth of the beamforming network and the antenna performance. The beamformer designed and used in this work covers the full X-band frequency range of 8-12.4 GHz. A 1-D version of the subarray discussed in detail in [2] was measured in a far-field anechoic chamber across an 8.5-10.5 GHz range. This frequency range exceeded the microstrip antenna bandwidth of 8.9-10.3 GHz but still demonstrated good patterns at reduced gain. The measured far-field patterns from 8.5-10.5 GHz in 50 MHz steps are normalized and shown on Figure 8. Note that the data in Figure 8 is the composite of 41 frequency steps. The subarray pattern holds up well over the entire bandwidth as expected.

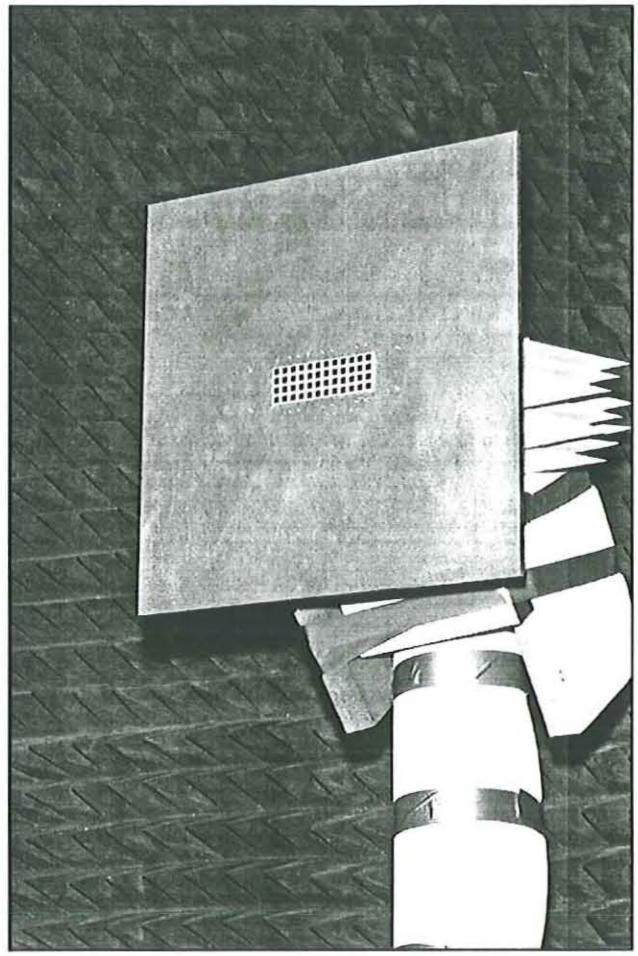


Figure 4 - Three tile subarray demonstration

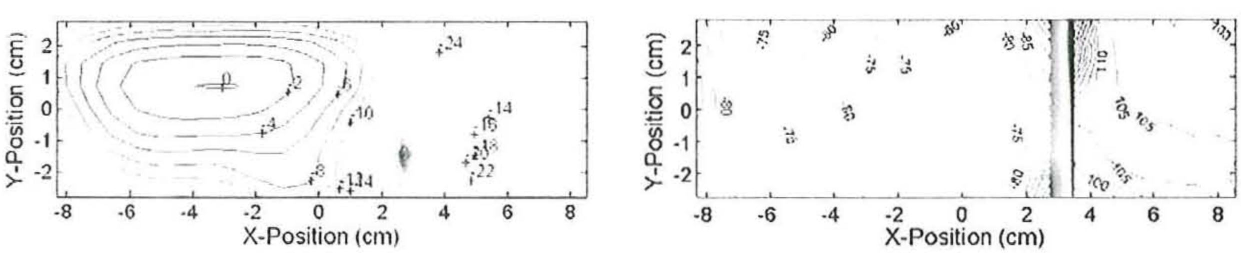


Figure 5 - Measured hologram illumination for 0 deg scan at 10 GHz. a) Amplitude in dB, contour lines = 2dB, b) Phase in degrees, contour lines= 5 degrees

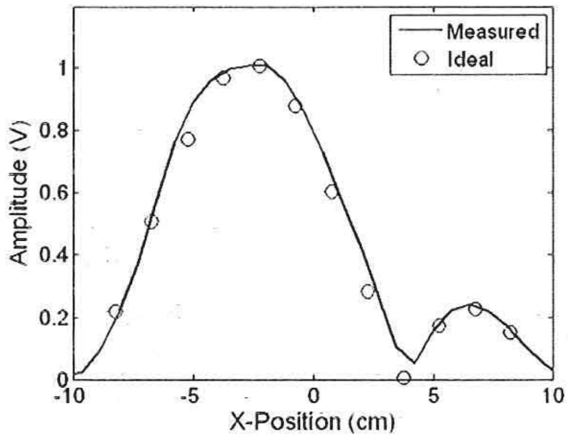


Figure 6 - Amplitude excitation for y=0.76 cm cut

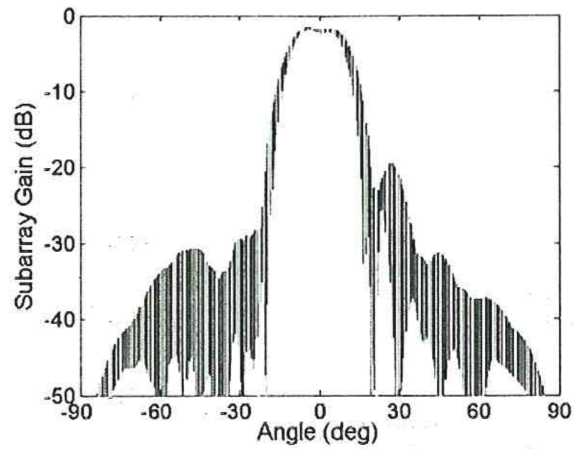


Figure 8 - Composite measured far-field patterns of 1-D overlapped subarray from 8.5-10.5 GHz with 50 MHz steps. Patterns are normalized for comparison.

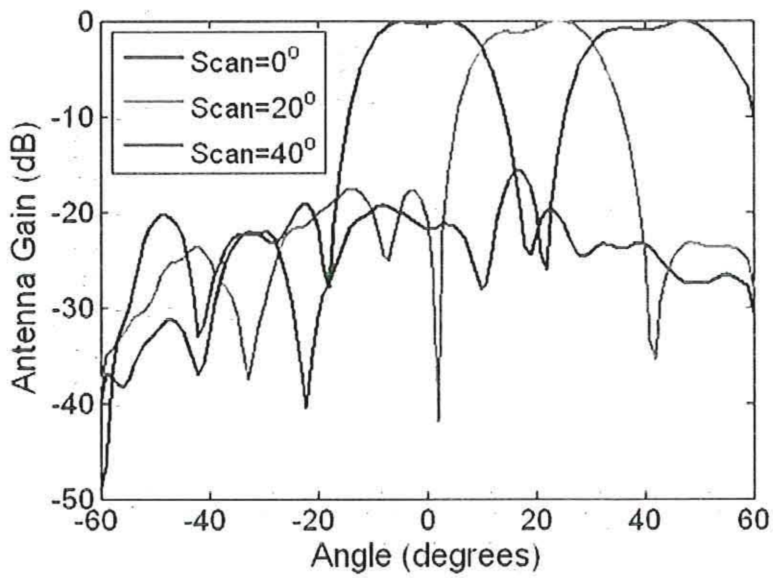


Figure 7 - Measured far-field patterns of scanned 3 tile subarray pattern at 10 GHz for 0, 20 and 40 degree settings

5. SYNTHESIZED ARRAY RESULTS

The measured subarray patterns demonstrate the utility of the overlapped architecture for fast beam scanning. As an example, 9 tiles are assumed along one dimension (array length is 55 cm) with a corresponding 7 overlapped subarrays (end tiles feed only single subarray). A 30 dB Chebyshev is applied to the array weights and digitally scanned within the main beam of the subarray pattern. The digitally applied array pattern is multiplied with the measured subarray pattern to arrive at the synthesized beam patterns at 0° and 40° in Figures 9 - 10. Five orthogonal beams fit within the subarray beam pattern providing a 5 times beam coverage with no loss of receive gain (assuming LNA gain is sufficiently high to overcome phase shift, attenuator, and beamformer losses). The use of the overlapped subarray in this example provides an efficiency of 5 beams from 7 receivers for 30 dB Chebyshev excitation. The use of a 20 dB Chebyshev provides up to 6 orthogonal beams within the 20 deg subarray beamwidth providing close to the N_{min} theoretical limit [1]. In operation, the transmit beam is spoiled or designed to cover the subarray footprint of 20°. Therefore within the subarray footprint, the two way sidelobe is determined only by the weighting applied by the receive array. Many system specifications would require the use of receive array weightings in excess of 30 dB. Extending the array example into 2 dimensions and using 30 dB Chebyshev, 25 independent beams are generated thus improving beam scan time of 25X over a conventional single beam ESA. The use of wide sector subarray beam with digital receivers at each subarray output allows fast updates when used as a radar receiver independent of array size.

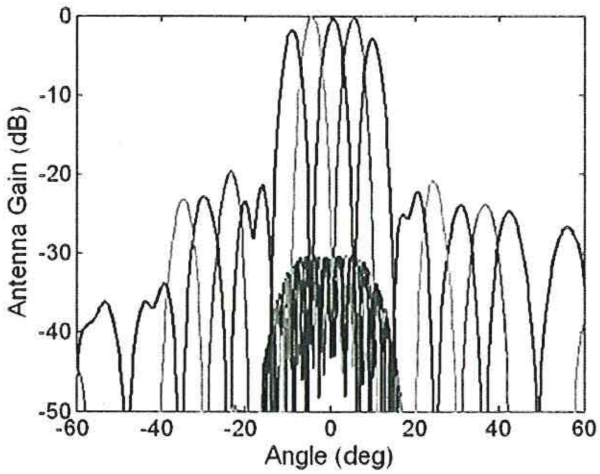


Figure 9 - Simulated Pattern using measured subarray pattern. Zero degree scan with 9 tiles (8 receivers) with 30 dB Chebyshev weighting.

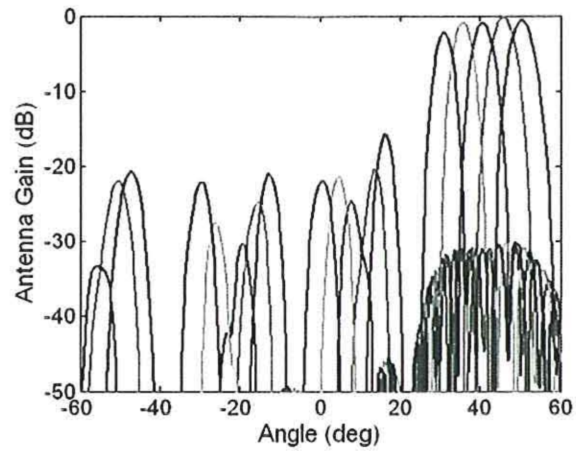


Figure 10 - Simulated Pattern using measured subarray pattern. Forty degree scan with 9 tiles (7 receivers) with 30 dB Chebyshev weighting.

6. CONCLUSION

The demonstration of an X-band overlapped subarray architecture is shown. Measured results agree well with design goals. The extension to full size arrays illustrates the capability of the overlapped subarray providing significant scan coverage improvements.

REFERENCES

[1] R. Mailloux, *Phased Array Antenna Handbook 2nd edition*, Artech House, Boston, MA (2005).
[2] J.S. Herd, S.M. Duffy, and H. Steyskal, "Design considerations and results for an overlapped subarray radar antenna," *IEEE Aerospace Conf. Dig.*, Big Sky, MT (2005).