REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
17-01-2012	Final Report	3-Dec-2008 - 2-Sep-2011

4. TITLE AND SUBTITLE
Ranging and Acuity Enhancement for Terahertz Imaging Spectrometers

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W911NF-09-C-0024

5c. PROGRAM ELEMENT NUMBER
665502

6. AUTHORS
Daniel van der Weide, John Grade

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Tera-X, LLC
8551 Research Way
Suite 175
Middleton, WI 53562 -

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
54936-EL-ST2.3

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
We confirmed that polarization modulation is a viable technique for high repetition radar, particularly pulsed terahertz radar, through the use of a scaled experiment. We believe that our pulsing hardware, combined with a focusing dish, would prove a powerful standoff imaging solution. Though we encountered multiple fabrication issues that delayed the completion of a prototype system, we hope to have a working prototype by the second quarter of 2012.

15. SUBJECT TERMS
THz spectrometers

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			John Grade
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					608-345-1519

Report Title

Ranging and Acuity Enhancement for Terahertz Imaging Spectrometers

ABSTRACT

We confirmed that polarization modulation is a viable technique for high repetition radar, particularly pulsed terahertz radar, through the use of a scaled experiment. We believe that our pulsing hardware, combined with a focusing dish, would prove a powerful standoff imaging solution. Though we encountered multiple fabrication issues that delayed the completion of a prototype system, we hope to have a working prototype by the second quarter of 2012.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

S. M. Aguilar, M. A. Al-Joumayly, S. C. Hagness, and N. Behdad, "Design of a Miniaturized Dual-Band Patch Antenna as an Array Element for Microwave Breast Imaging," IEEE International Symposium on Antennas and Propagation, Toronto, Canada, July 2010.

M. A. Al-Joumayly, S. M. Aguilar, S. C. Hagness, and N. Behdad, "Multi-Band, Miniaturized Patch Antenna Elements for Microwave Breast Imaging Applications," IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting, Spokane, WA, July 2011.

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Hai Huang	0.20	
Chiya Saeidi	0.10	
Suzette Aguilar	0.10	
Matthew Dwyer	0.70	
FTE Equivalent:	**1.10**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Susan Hagness	0.03	
FTE Equivalent:	**0.03**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME	
Matthew Dwyer	
Total Number:	**1**

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
17-01-2012

2. REPORT TYPE
final

3. DATES COVERED *(From - To)*
4-Jul-11 to 3-Oct-11

4. TITLE AND SUBTITLE
Ranging and Acuity Enhancement for Terahertz Imaging Spectrometers

5a. CONTRACT NUMBER
W911NF-09-C-0024

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Grade, John, Ph.D., van der Weide, Daniel, Ph.D.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Tera-X 104 S. Shuman Street, Verona WI 53593

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
PO Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

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

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

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
We encountered multiple fabrication issues that delayed the completion of a prototype system, but we hope to have a working prototype by the second quarter of 2012. Regardless, we confirmed that polarization modulation is a viable technique for high repetition radar, particularly pulsed terahertz radar, through the use of a scaled experiment. We believe that our pulsing hardware, combined with a focusing dish, would prove a powerful standoff imaging solution.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Grade, John
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UL	16	608-345-1519

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

Enclosure 1

Final Report

We set out to wrap up the project by developing a prototype terahertz imaging system to test the polarization modulation scheme. The mask layout was finalized and the mask set was fabricated. See figure 1 for a sample of the receiver, and figure 2 for the entire layout (all layers).

Unfortunately, we encountered multiple fabrication issues that prevented us completing the system before the completion of this project. We hope to have a working prototype by the second quarter of 2012.Regardless, we confirmed that polarization modulation is a viable technique for high repetition radar, particularly pulsed terahertz radar, through the use of a scaled experiment. We believe that our pulsing hardware, combined with a focusing dish, would prove a powerful standoff imaging solution.

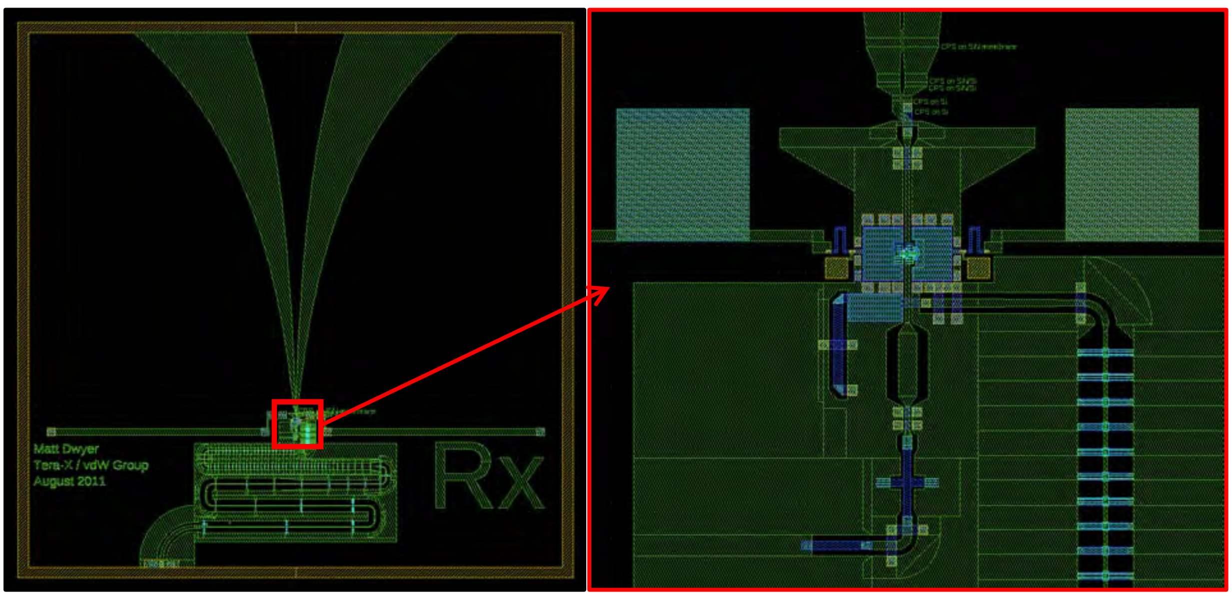


Figure 1: Receiver NLTL/antenna (left) and close up of sampler with transmission line transitions (right)

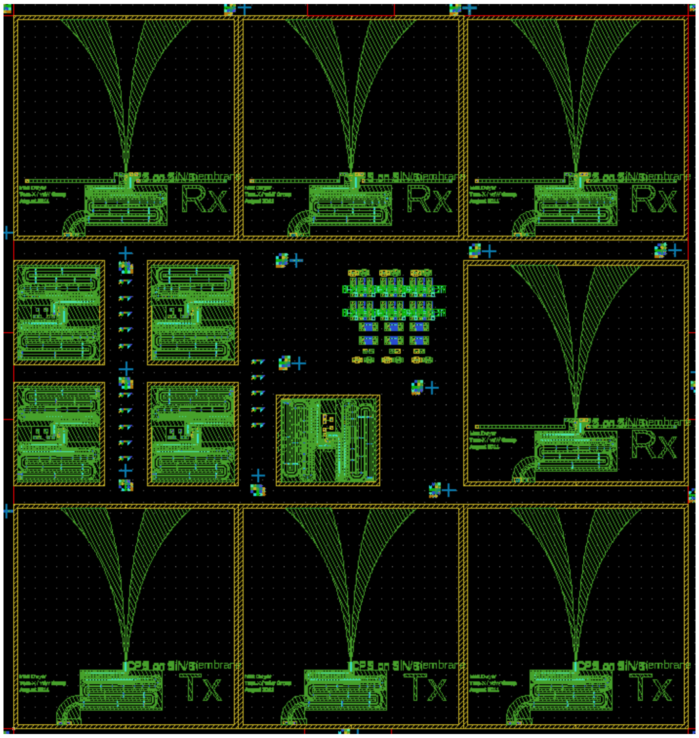


Figure 2: Full mask layout showing all layers

4-Apr-11 to **3-Jul-11** Layout and Device fabrication

Abstract: We set out to start the mask layout, devise a fabrication recipe and perform initial fabrication experiments.Progress was made in the mask layout, including devices for the terahertz imaging system, as well as test devices to evaluate specific components. An 18 step fabrication recipe was adapted from previous work, accommodating available equipment and additional steps needed for epitaxial lift off and membrane release. Membrane release tests were performed with silicon nitride membranes to ensure viability of process. We next plan on finalizing the mask design and beginning fabrication.

The mask layout was started using the layout software LayoutEditor (ex. figure 1). Results from component simulations in CST Microwave Studio were imported into the device layouts.The fabrication recipe was developed simultaneously with the mask layout so as to identify any problems that might be mitigated with clever design.

Eventually we plan to use ultrananocrystalline diamond (UNCD) membranes to support the devices due to the material's superior heat dissipation properties. However, for now we are exploring low-stress silicon-rich silicon nitride (Si_3N_4) grown in-house. We achieved 6 x 6 mm^2 membrane windows at a thickness of around 2 µm, sufficient for our application.

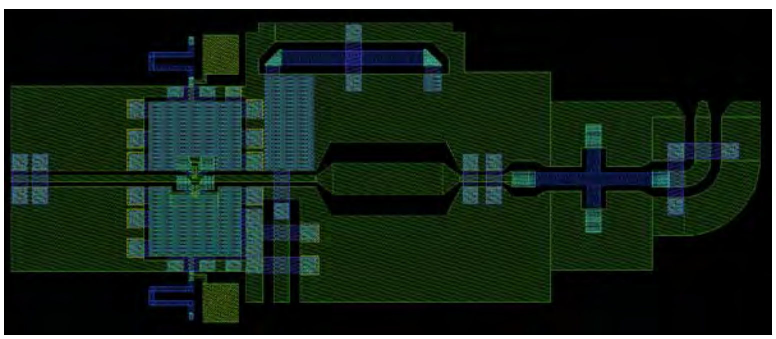


Figure 1: Diode sampling circuit mask layout

4-Jan-11 to **3-Apr-11** Integration Modeling

Abstract: We set out to model the integration of key components that make up the pulse transmitter and receiver, specifically the NLTL/sampler and antenna. Using an air bridge balun we achieved a simulated bandwidth of 60 - 400 GHz, enabling integration of a coplanar stripline (CPS) antenna with a coplanar waveguide (CPW) nonlinear transmission line (NLTL). Air bridge baluns have previously only been measured to 110 GHz. An exponentially flared CPS antenna was designed and optimized for the 60 - 400 GHz band with gain up to 15 dB. We now plan on laying out the masks for the devices and beginning device fabrication.

Traditionally, CPW to CPS baluns are implemented using a 3 dB resistive bridge (i.e. ≥3 dB loss). Our approach using an airbridge (figure 1, right) outperformed a resistive bridge over the 60-400 GHz bandwidth (figure 1, left). In addition to S-parameters, we also explored the radiation characteristics of this balun and found there was little radiative loss, even at higher frequencies. Further, we explored more complex, rounded airbridgebaluns and found no perceivable improvement.

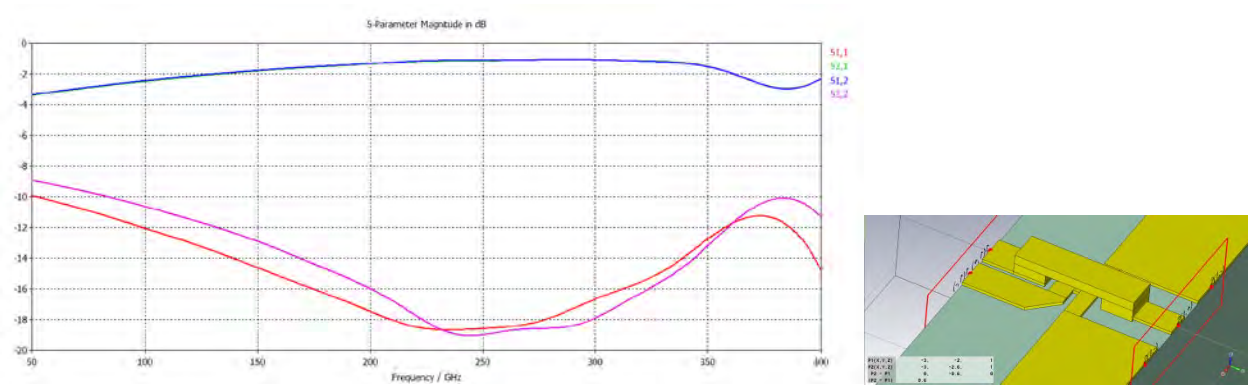


Figure 1: Coplanar waveguide to coplanar stripline transition

Initially, two antenna architectures were pursued: CPS flared antenna (figure 2, right) and TEM horn antenna. The latter was found to have a boresight that varied with frequency, so it was rejected. The CPS flared antenna implemented on a thin membrane has proved promising. To our knowledge, no other group has implemented a CPS flared antenna on a thin membrane for operation at terahertz frequencies. The return loss is largely under 10 dB over the 60-400 GHz bandwidth (figure 2, left) with gain up to 15 dB at the higher frequencies and closer to 6 dB at the lowest frequency.

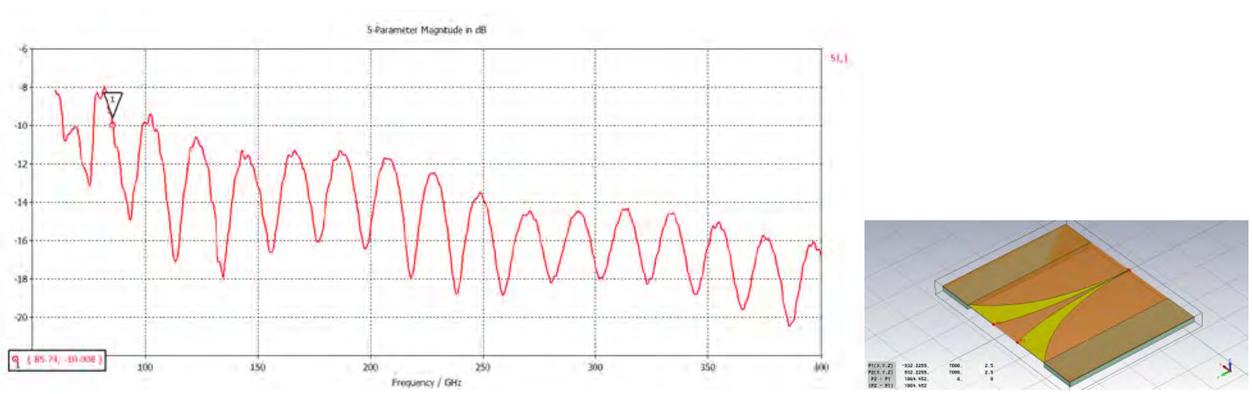


Figure 2: Return loss (left) and model (right) of the CPS flared antenna

4-Oct-10 to **3-Jan-11** THz antenna simulations and membrane NLTLs

Abstract: We set out to explore novel approaches to nonlinear transmission lines (NLTL) that would also benefit terahertz antennas. We simulated short NLTLs using the full wave solver CST Microwave Studio with SPICE diode models. This enabled us to evaluate complex transmission lines structures, such as diode-loaded microstrip, not possible with traditional Kirchhoff solvers.Terahertz Vivaldi membrane antennas were also simulated. We next plan on devising integrated devices that can be fabricated, optimizing these devices and beginning the mask layout.

NLTLs have for the large part been designed using Kirchhoff/SPICE solvers which do not take into account complex geometries. To confirm the benefits of our novel approaches, we sought to perform full wave (i.e. Maxwell's equations) simulations that called SPICE models at the location of active elements (i.e. diodes). This was possible in CST Microwave Studio for small nonlinear transmission lines (NLTL).

We compared two novel NLTL structures, thin diamond coplanar waveguide (CPW) (figure 1, middle) and microstrip (figure 1, right), with the tradition bulk GaAs substrate CPW NLTL (figure 1, left). These were modeled and simulated in CST using the EM transient co-simulator.

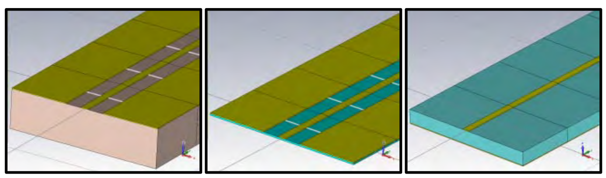


Figure 1: GaAs CPW (left), thin diamond CPW (middle) and microstrip (right).

We found that the two novel NLTL structures gave higher compression and lower loss than the traditional bulk GaAs structure. While these results were for a small (10 cell) NLTL, we believe these results will carry over to a real world (i.e. 50+ cell) NLTL.

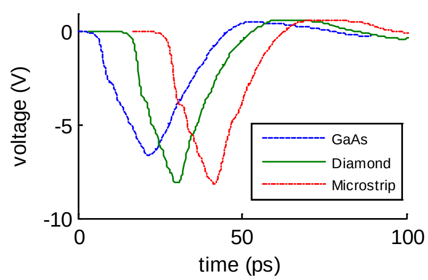


Figure 2: Compression achieved by the three NLTL configurations shown in figure1. (offset for clarity)

The reason for this increased performance was that by reducing the effective dielectric constant (either through thin substrate – diamond, or different dielectric – microstrip), we were reducing the capacitance of the transmission line, thus the nonlinear capacitance of the diode would have more effect on the total capacitance.

Vivadi antennas on membranes were simulated with promising results. However the issue of integrating a slotline antenna with a coplanar waveguide transmission line at terahertz frequencies was unresolved.

4-Jul-10 to **3-Oct-10** Improved Antennas

Abstract: We set out to investigate alternate antennas more compatible with planar integrated circuit fabrication. We explored Vivaldi travelling wave antennas on thin substrates with various modifications to the antenna opening. We found that removing material from the antenna opening actually had a negative effect on performance, particularly gain. Consistent with the literature, we found that reducing the substrate thickness greatly enhanced antenna performance. A novel balun was developed to allow easy antenna fabrication on thin substrates. We now plan on exploring novel approaches to NLTL pulsers based on what we have learnt from these results.

Following the successful implementation of the polarization modulation scheme at 20x scale, we looked to improve the antennas. While our original intention was to build a three-dimensional antenna and connect the NLTL with a flip chip process, we felt that an integrated approach would be superior both in performance and cost. Some prototype Vivaldi antennas were designed, simulated and fabricated for comparison with the original scaled antennas. These new antennas featured a novel coaxial feed for easier fabrication. The gain of these antennas was satisfactory, and the return loss superior to the original antenna. Our thinking was that these antennas could ultimately be used in a reflector setup which would dramatically increase the gain in an at-scale terahertz system.

Figure 1 shows the four prototypes explored.

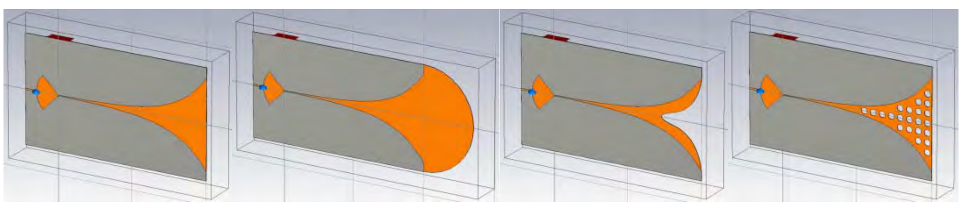


Figure 1: The Vivaldi antenna prototypes (l to r) A, B, C, and

Comparing the gain of the four prototypes (figure 2, left) shows that removing material from the antenna opening was not beneficial. Regardless, these Vivaldi antennas performed better over their scaled bandwidth than the original antennas developed for this project (figure 2, right).

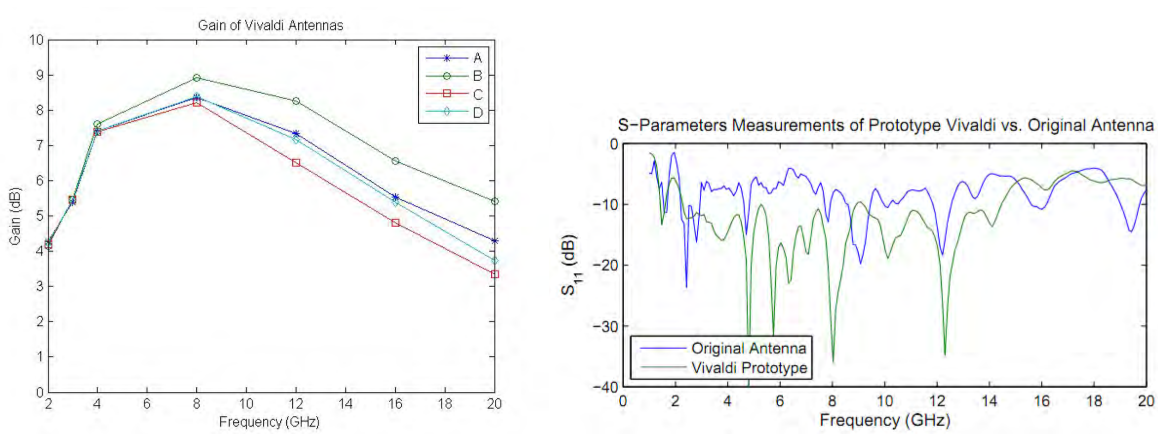


Figure 2: Gain of the four prototypes (left) and comparison with the original antenna (right)

A novel balun was developed that allowed for easier integration between antenna and coaxial connector (figure 3). By using a raised substrate under the microstrip feed, the line width could be increased greatly, allowing sufficient width for an expential taper to match the impedace of the slotline feed of the antenna.

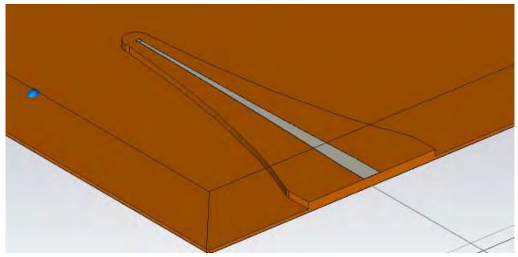


Figure 3: Novel microstrip to slotlinebalun

4-Apr-10 to **3-Jul-10** Conference Paper

Abstract: We set out to refine the scaled polarization experiment and conduct further testing.We replaced the gun silhouette with a similarly-sized polarized scatterer to highlight the scheme's polarization sensitivity. Rejection on the order of 10 dB was achieved, using an alternate pseudorandom bit sequence (PRBS) as the noise source. Rotating the polarizer confirmed the setup's polarization sensitivity. Displacing the scattering target confirmed respectable range resolution.We next plan on improving the antennas to increase the signal to noise ratio, as we are unable to increase the power in this setup.

We fabricated a polarized scatterer using a 1 ft^2 piece of cardboard with copper wire running parallel, spaced ¼" apart. This was then mounted on a rotating mount to easily assess the effect of polarization change. For most measurements the polarizer was rotated at an angle of 20°.

The rejection measurements involved correlating the received scatter of two different PRBS pulse streams and then comparing this with the autocorrelation of a single stream. The 10 dB rejection achieved (see figure 1) confirmed that we could use multiple transmitters simultaneously with the ability to filter out undesired streams using a matched filter.

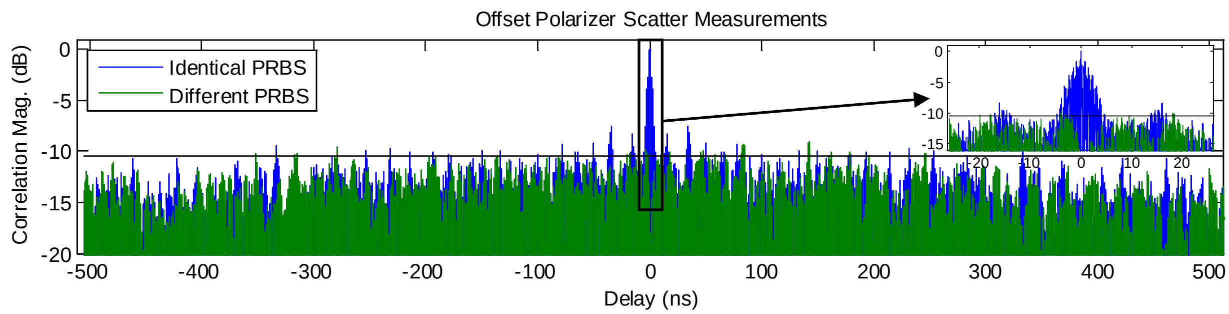


Figure 1: Scatter measurements with varying PRBS.

The polarizer was then rotated to highlight the benefit of polarization sensitivity (figure 2). When the polarizer was rotated at 45° to the receiving antenna, the correlation magnitude was reduced by 3 dB, as would be expected. When the polarizer was rotated orthogonally to the receiving antenna, the correlation magnitude was some 10 dB down, around the experiment's noise floor. This confirmed that the modulation scheme is polarization sensitive.

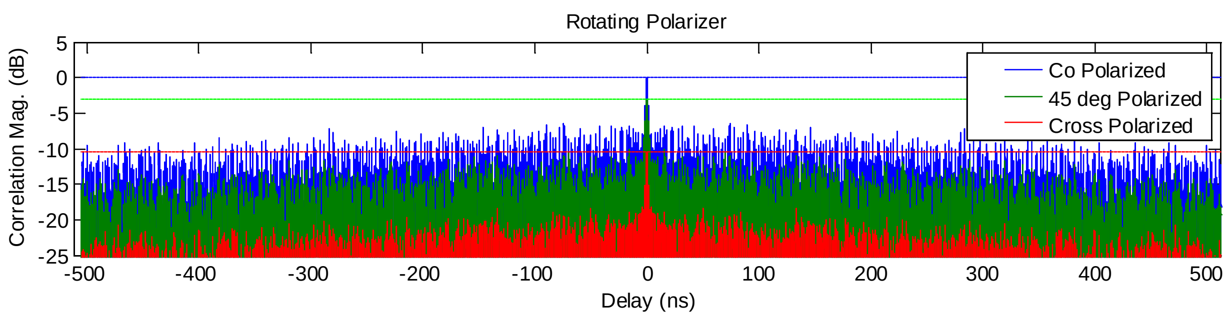


Figure 2: Scatter measurements with rotating polarizer.

Successful ranging was achieved, with a target distance change of 3 ft resulting in a 6 ns delay difference (Figure 3). Given there is a 6 ft round trip differential and light travels at roughly 1 ft/ns, this is expected. Unmodulated pulsed radar would have a range ambiguity (given by $R_u = c / 2 \cdot f_{pr}$) of only 1 ft at the experiment's pulse repetition frequency.

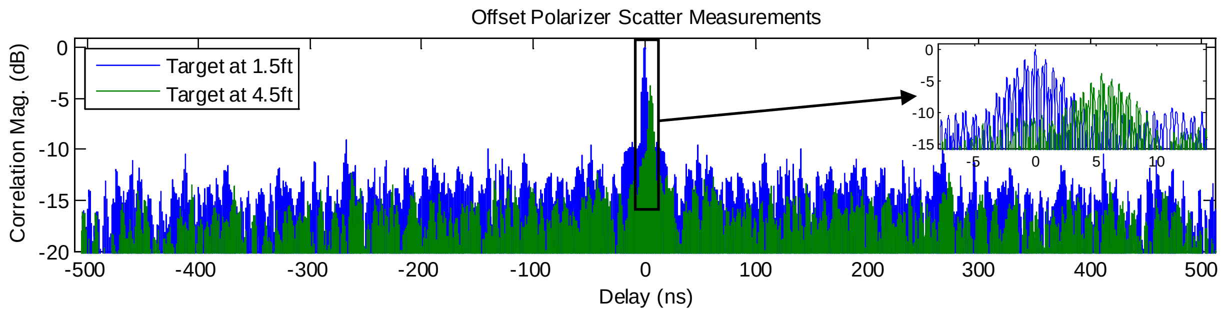


Figure 3: Scatter measurements with polarizer at varying range.

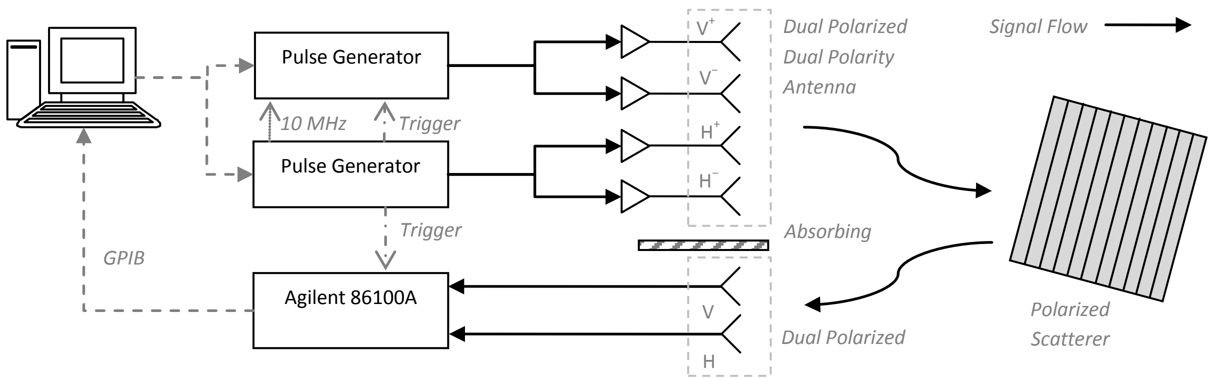


Figure 4: System overview of 20x scale proof of concept

4-Jan-10 to **3-Apr-10** Conference Abstract

Abstract: We set out to correct the Anritsu data generator issue, take scattering measurements, and evaluate the polarization modulation scheme.The Anritsu data generator issue was unable to be resolved, so the instrument was removed from the setup, and we developed a workaround. By splitting an existing channel and delaying by one bit, we were able to emulate a fourth pulse stream. Initial results were promising, with the scheme showing good rejection performance. We now plan on refining the experiment and conducting more tests.

The Anritsu data generator was found to be temporally unstable such that when repeating a pseudorandom bit sequence (PRBS) the instrument would occasionally delay a few bits. This resulted in the Anritsu-generated stream becoming out of sync with the three other pulse streams generated by Agilent instruments. The cause of this skipping was not found, nor could we find any workaround that still used this instrument.

A feasible workaround was devised that required only three pulse sources. By splitting a pulse source and delaying one of the two channels by one bit, we were able to "fake" a fourth pulse source. This required careful generation of PRBS for each channel, such that all four channels remained orthogonal. The one bit delay was achieved using a signal splitter and delay line, shown in figure 1.

Figure 2 shows that the delayed line approach (three unique channels, one delayed) compared favorably with the ideal case (four unique channels), with some negative correlation either side of the desired peak.

Scattering measurements were then performed using a scaled gun silhouette as the reflector. Figure 3 shows the improvement in increasing PRBS length, and also alternate PRBS rejection. That is, if a different PRBS is used than expected, then the matched filter would reject it as noise, allowing multiple transmitters to operate simultaneously.

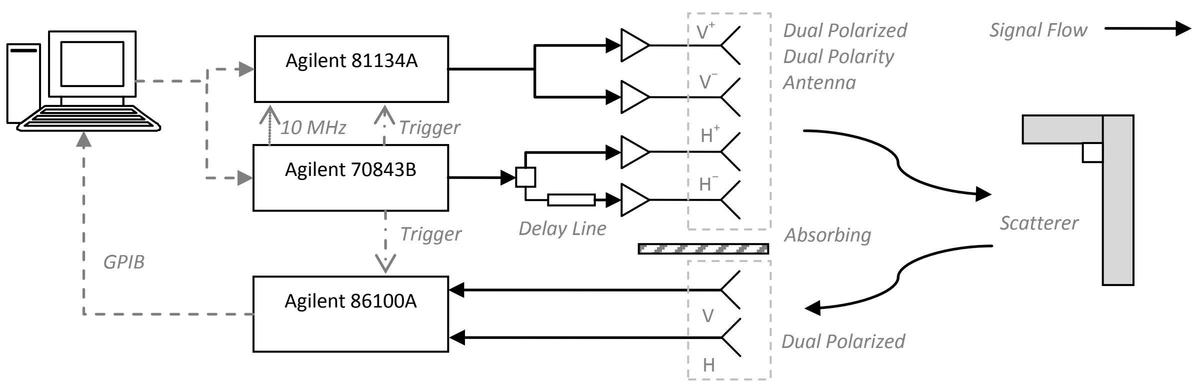


Figure 1: Scaled polarization modulation experiment setup

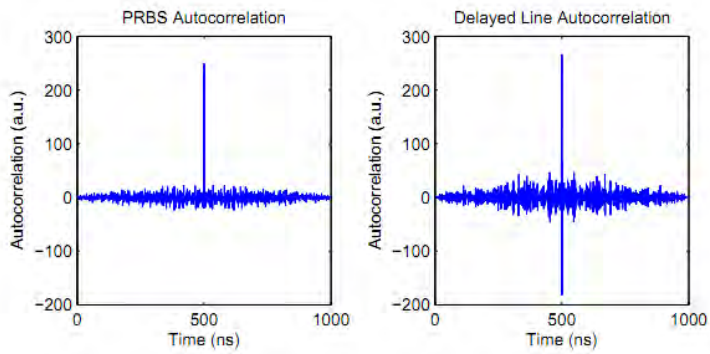


Figure 2: Autocorrelation of simulated response for PRBS (left) and PRBS with delay line (right)

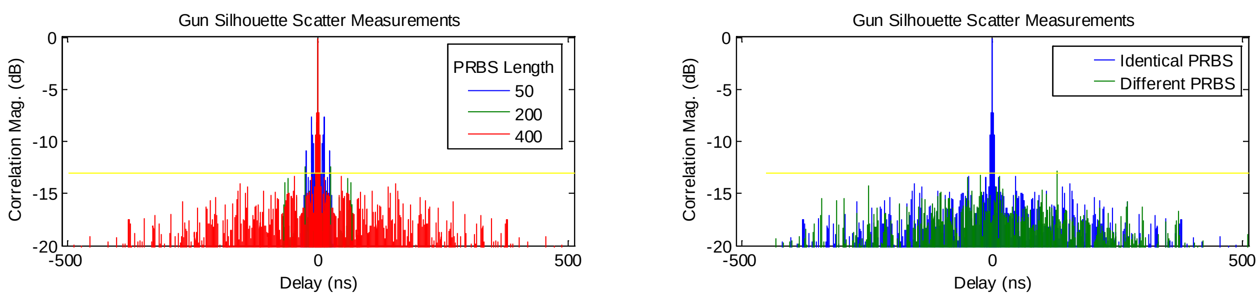


Figure 3: Scatter measurements with varying PRBS lengths (left) and varying PRBS (right).

4-Oct-09 to **3-Jan-10** Experiment development.

Abstract: We set out to design an experiment to verify our proposed polarization modulation scheme.We modified the scheme to include polarity modulation, enabling more intuitive matched filtering.We used pulse and data sources to simulate nonlinear transmission line (NLTL) pulsers, an equivalent time oscilloscope to simulate the sampler and scaled dual-polarity, and dual-polarized antennas for radiation/reception. The oscilloscope was found to have insufficient waveform memory, so we developed a workaround. The Anritsu data generator was found to have timing issues. We next plan on resolving this issue and performing scattering experiments.

Reviewing our polarization modulation technique, we generate a stream of pulses that vary in polarization and polarity with some pseudorandom bit sequence (PRBS). The polarity modulation was added so that, when matched filtering, the presence of an object would give a sharp peak rather than a triangle-like response.

An experiment was devised to test the proposed polarization modulation scheme at 20x scale with respect to terahertz operation (see Figure 1). Four channels containing pseudorandom time-orthogonal pulse streams were generated using various pulse/data generators, and then fed into a dual-polarization dual-polarity antenna. This produced a polarization/polarity encoded pulse stream that could then be decoded by the receiving antenna/oscilloscope as in a typical bistatic radar setup. All instruments were synchronized using a 10 MHz reference signal.

The pulse/data generators and oscilloscope were connected to a PC running Mathworks MATLAB via a GPIB/LAN interface. All signal processing and data presentation was done in MATLAB.

The oscilloscope proved limited when increasing the pseudorandom bit sequence (PRBS) to any usable length due to its limited ability to save long waveforms. Specifically, it was limited in the number of time-voltage points it could export. To get around this issue, we developed a MATLAB script that was able to step through an extremely long waveform and then stitch the pieces together to give the complete waveform.

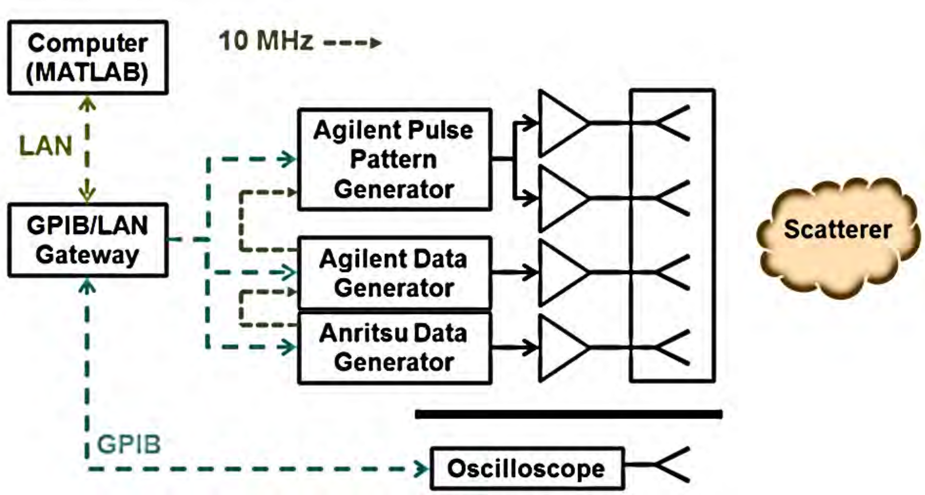
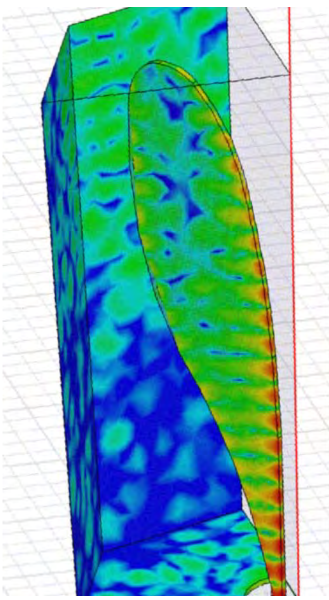


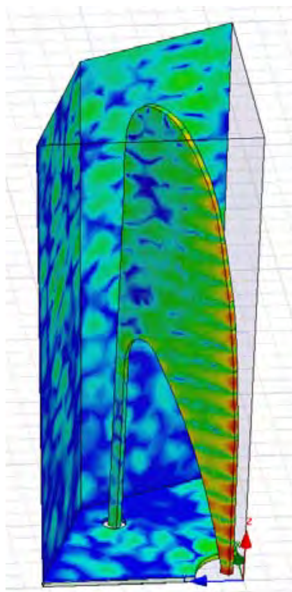
Figure 1: Scaled polarization modulation experiment setup

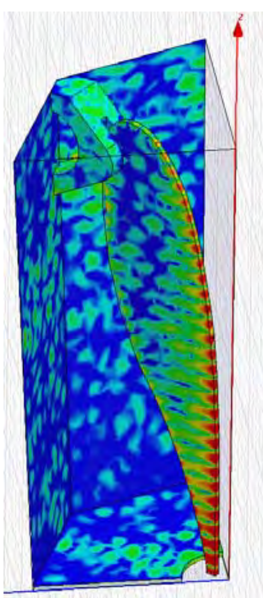
4-Jul-09 to **3-Oct-09** Device redesign and refabrication.

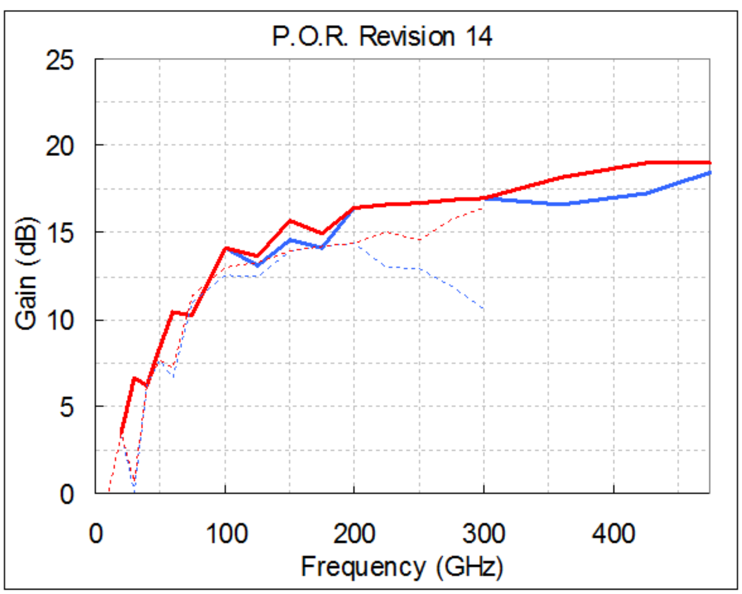
Abstract: We carried out an extensive battery of antenna simulations to explore the impact of different design modifications to improve mechanical stability. We chose the two most promising designs and fabricated 10x scale antennas for further testing. We next plan on measuring the new 10x antennas and comparing the results to the original designs.

Using HFSS, we ran a series of 170 simulations to bracket the design space of the quad vane differential antenna design. Our goals were to improve the gain, extend the frequency range, and eliminate the precarious simply supported drive vane. Several variants were explored, including drive vanes with secondary legs and drive vanes with Teflon supports. As a result of the HFSS testing, we chose the two most promising designs and fabricated two 10x scale antennas of each design for further testing.





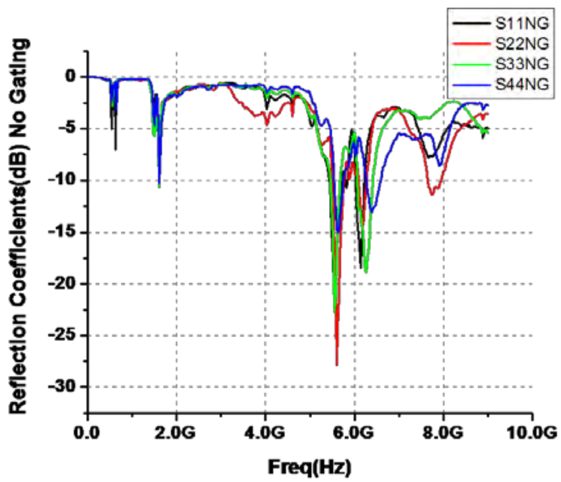


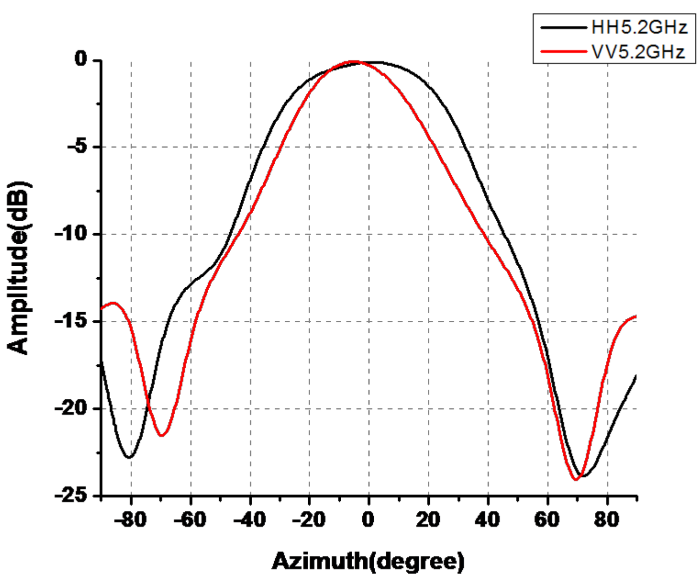


4-Apr-09 to **3-Jul-09** Device testing.

Abstract: We used an anechoic chamber and a reference antenna to measure the gain, cross-talk, and reflection coefficients of the 20x scale antennas. We next plan on revisiting the antenna simulations to create a design that is more mechanically robust and has better performance.

We mounted the 20x scale antennas to a mobile gantry in the anechoic chamber and used an ETS Lindgren 3164 quad ridged reference antenna to measure the transmission beam pattern along with the reflection coefficients. We ran into significant issues with the limitations of the test setup in terms of the maximum attainable frequency and the tendency of the gantry to tear apart the connectors. With the assembly process validated at 20x scale, we decided to use simpler models in the future and focus on ways of stabilizing the narrow drive vanes.





4-Jan-09 to **3-Apr-09** Device fabrication.

Abstract: Having agreed upon a plan-of-record antenna pixel design and assembly process, we began the process of sourcing off-the-shelf components and building the custom hardware required for a set of 20x scale antennas. We next plan to test the pixels to determine how well the gain and reflection coefficients match our predictions.

To demonstrate the feasibility of our proposed at-scale assembly process, and to validate our HFSS models for antenna gain, we created a solid model of the antenna assembly and had the individual antenna components fabricated. The primary conductors were CNC machined at GDI from 1/8" copper plates and brazed together. The mounting hardware and the dummy ceramic were created using metalized stereolithography at Fineline. Four standard coax cables were used as the input feeds. By the end of the quarter, two 20x scale antennas had been fabricated and assembled, and work was underway to setup the anechoic chamber.