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COMPACT RANGE MEASUREMENTS OF DIGITAL ARRAYS LEADING TO OUTDOOR RADAR EXPERIMENTS (Preprint)

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Final Report

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14. ABSTRACT
Digital array technology has advanced over the past few years allowing the design and manufacturing of large, wideband, multi-element digital arrays that can produce multiple steerable beams from the same aperture simultaneously. These types of systems often have the radio-frequency (RF) and digital components integrated directly to the antenna, requiring new measurement techniques as the antenna under test (AUT) cannot be connected to traditional RF measurement equipment. Several years ago the Air Force Research Laboratory (AFRL) Sensors Directorate developed a custom 32 element uniform linear array using commercial off-the-shelf (COTS) low-noise amplifiers (LNAs) and a multi-channel digital receiver. Custom software was developed to perform automated element and digital beam pattern measurements using the compact range position controller. Hand tuned calibration parameters were calculated to form the digital beams. This work demonstrated feasibility of digital array measurement within a compact range environment. Recently, AFRL has evaluated a highly integrated digital array with 1024 elements, LNAs, high-power amplifiers (HPAs), attenuators, phase shifters, transmit/receive switches, polarization switches, and eight multi-channel digital receiver/exciters. Measurements were required to not only test the functionality of the digital array, but also to build a calibration table for each element across the full frequency range of the array. The hand-tuned calibration method developed for the 32 element array was automated in order to build all the necessary calibration tables for the 1024 element array. Calibrated beam patterns were also collected to analyze beam shape and pointing angle metrics. Following compact range measurement, the 1024 element array was relocated to a 100’ tower for outdoor radar experimentation where the collected calibration tables were successfully applied on the system. This paper will discuss challenges and successes in measurement of digital arrays within the compact range environment.

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Compact Range Measurements of Digital Arrays Leading to Outdoor RADAR Experiments

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Abstract—**Digital array technology has advanced over the past few years allowing the design and manufacturing of large, wideband, multi-element digital arrays that can produce multiple steerable beams from the same aperture simultaneously. These types of systems often have the radio-frequency (RF) and digital components integrated directly to the antenna, requiring new measurement techniques as the antenna under test (AUT) cannot be connected to traditional RF measurement equipment. Several years ago the Air Force Research Laboratory (AFRL) Sensors Directorate developed a custom 32 element uniform linear array using commercial off-the-shelf (COTS) low-noise amplifiers (LNAs) and a multi-channel digital receiver. Custom software was developed to perform automated element and digital beam pattern measurements using the compact range position controller. Hand tuned calibration parameters were calculated to form the digital beams. This work demonstrated feasibility of digital array measurement within a compact range environment. Recently, AFRL has evaluated a highly integrated digital array with 1024 elements, LNAs, high-power amplifiers (HPAs), attenuators, phase shifters, transmit/receive switches, polarization switches, and eight multi-channel digital receiver/exciters. Measurements were required to not only test the functionality of the digital array, but also to build a calibration table for each element across the full frequency range of the array. The hand-tuned calibration method developed for the 32 element array was automated in order to build all the necessary calibration tables for the 1024 element array. Calibrated beam patterns were also collected to analyze beam shape and pointing angle metrics. Following compact range measurement, the 1024 element array was relocated to a 100' tower for outdoor radar experimentation where the collected calibration tables were successfully applied on the system. This paper will discuss challenges and successes in measurement of digital arrays within the compact range environment.**

I. INTRODUCTION

Work began in 2017 at AFRL to showcase the benefits of a compact, wideband, multi-channel digital array. Utilizing digital backend hardware developed under the Defense Advanced Research Projects Agency (DARPA) Arrays at Commercial Timescales (ACT) program [1] [2] [3], a custom 32-element uniform linear array, and 32 narrowband LNAs, preliminary measurements were completed using the Air Force Research Laboratory (AFRL) Sensors Directorate OneRY Indoor Range. The Indoor Range is a Compact Antenna Test Range (CATR) operating from 400MHz-50GHz with a 12 foot cylindrical quiet zone.

The CATR traditionally uses a network analyzer-based closed loop architecture for antenna characterizations, where one network analyzer port is connected to the feed antenna and a second is connected to the antenna under test (AUT). This configuration permits use of the gain-transfer method (removal of gain and loss terms caused by cables, RF switches, and amplifiers) that enables accurate amplitude and phase measurements between the two antennas. Given the direct RF to digital design of the systems under test this methodology was not attainable, as coaxial cables could not be easily connected to elements of the array antenna. This was especially the case with the 1024-element array where the radiating elements were mated directly to the analog/digital conversion hardware. This architecture presented challenges with complex amplitude measurement accuracy and test event synchronization between the array and measurement test equipment.

Measurements of the 32-element array showed that performing beam pattern measurements in a CATR were possible, but with the RF-to-Digital paradigm, standard antenna measurement techniques for capturing data and performing calibrations were not sufficient to properly capture the pattern and gain of the array. The 32-element array was ultimately tested on an outdoor tower where marginal beamforming performance relative to CATR testing was partially attributed to limitations of the simple calibration technique.

Following the 32-element array, work transitioned over to a 1024-element array that would be delivered to the AFRL Sensors Directorate Outdoor Range. This array utilized the same ACT-based digital backend hardware but included wideband HPAs and LNAs with various configuration options. Measurements were required to not only verify beam pattern shapes across multiple frequency bands and array tapers, but also to build the necessary calibration table entries across different frequency bands and for the multiple configuration options available to achieve the eventual desired beamforming functionality. Ultimately the in depth CATR measurements of the 1024-element array enabled good beamforming performance once installed in the outdoor environment.

II. 32-ELEMENT UNIFORM LINEAR ARRAY

In an effort to assess the limits of digital arrays, a 32-element linear array was fabricated and each element was integrated with an LNA and ACT common module channel. The goals of this effort were to investigate what measurement methods needed to be modified to support CATR measurements and to collect array calibration parameters that could be utilized in an outdoor environment. The array, LNAs, ACT common module, and all required power supplies and RF coaxial cables as utilized in the CATR measurement are shown in Figure 1.

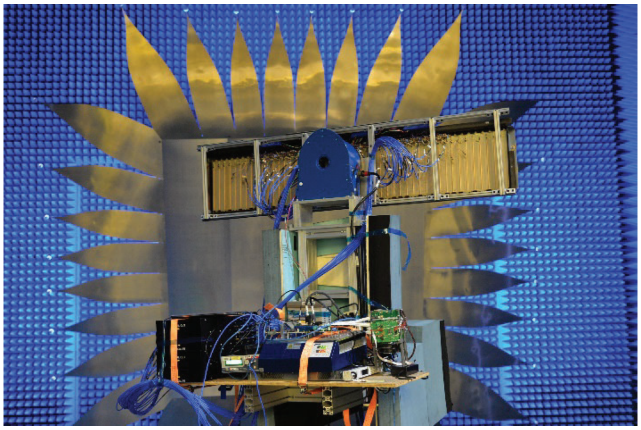

Figure 1. CATR Measurement Setup using 32-Element Uniform Linear Array

A. *Compact Range Measurements*

In order to perform measurements utilizing a digital array in the AFRL Sensors Directorate OneRY CATR, an in-house measurement program was utilized that allowed the motion axes to be remotely controlled via an external laptop. The external laptop was connected to both the CATR control computer and the digital array and orchestrated the measurement. With this externally controlled motion capability the digital array measurements were able to be automated in such a way that the external laptop did not require specific motion control software drivers. Instead, the specialized motion control software was run on a server PC that the external laptop maintained a simple socket connection with. This was important as the digital array hardware was controlled via complex software that could not otherwise be easily integrated with range motion control.

The primary frequency measured was 2.825 GHz. The ability of the ACT common module to capture multiple simultaneous receive beams was exercised in order to produce effectively scanned beams at various scan angles. The test laptop controlled an external signal source used to illuminate the array and subsequently triggered the ACT common module to capture data. The resulting 71 simultaneous beam patterns captured are shown in Figure 2. A selection of the many beams with a broadside and a 30 degree azimuth scanned beam are shown in Figure 3.

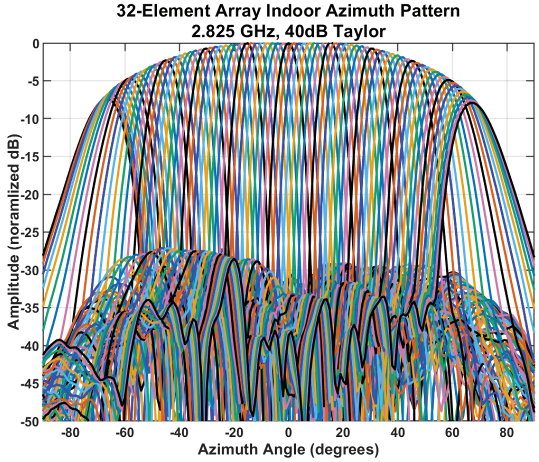

Figure 2. Simultaneous Multi-Beam Pattern Measurement for 32-Element Uniform Linear Array

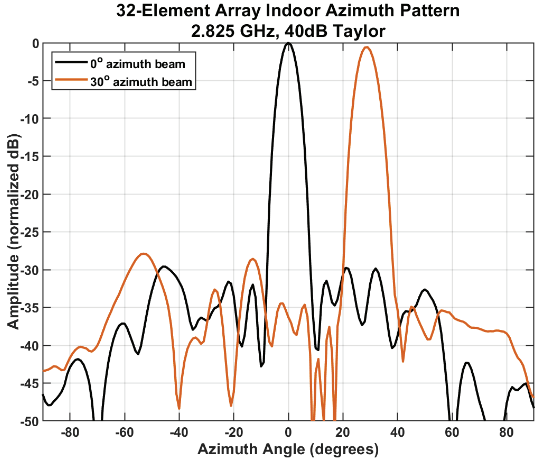

Figure 3. Selected Individual Beam Patterns for 32-Element Uniform Linear Array

During the CATR measurements it was determined that the existing 32-element uniform linear array had significant internal losses at the element level, so a custom 32-element array was designed and fabricated. Individual elements were tested in the Radiation and Scattering Compact Antenna Laboratory (RASCAL) chamber, a smaller CATR located at the AFRL Sensors Directorate. Measurements were completed for the individual embedded elements as well as a notional embedded 8-element uniform linear array to determine the best element spacing for the array. The full custom designed array is shown in Figure 4. After the custom array was fabricated measurements were completed in the AFRL Sensors Directorate OneRY CATR.

Figure 4. Custom 32-Element Uniform Linear Array

The primary goal of the CATR measurements was to build a calibration steering vector for the 32-element array. The method chosen was to build a complex vector with amplitude and phase weights that would align the received signal captured on each of the 32 digital channels so that all of the channels were balanced. This method was used for each of the frequencies that were measured in the CATR and saved for use in the outdoor measurements.

B. *Outdoor Measurements*

After all the CATR measurements were completed the custom 32-element array was installed in one of the 100’ towers located at the AFRL Sensors Directorate Outdoor Range as shown in Figure 5. Utilizing the same LNAs and ACT common module as was used for the CATR measurements beam patterns were collected in the outdoor environment and are shown in Figure 6. The beam patterns show a broadside beam and a beam steered to an azimuth angle of 30 degrees. A 30dB Taylor taper was applied, but realized sidelobe levels were only on the order of 9 dB from peak. While beams were able to be steered to the correct azimuth angles, sidelobe performance was less than expected. This performance degradation was attributed to inherent limitations of the simple calibration method.

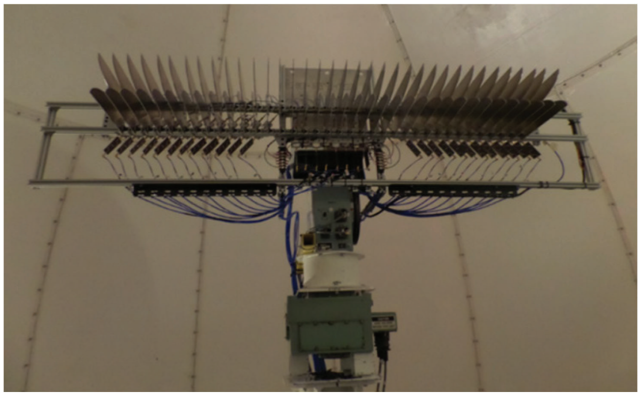

Figure 5. Custom 32-Element Array within Tower Radome

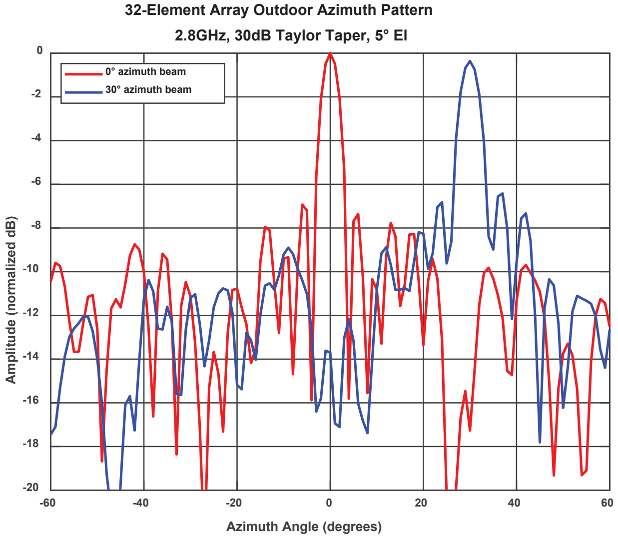

Figure 6. Measured Beam Patterns in Outdoor Environment

The results of the outdoor beam pattern collect revealed that the single frequency, amplitude and phase-only calibration methodology was insufficient to capture all aspects of the array, especially in regards to the off-angle beam pattern. Beamforming in the outdoor test was functional, but had much lower performance than expected.

III. 1024-ELEMENT WIDEBAND ARRAY

A. *Compact Range Measurements*

As with the 32-element array, the 1024-element array was measured in the Indoor Range CATR prior to tower installation in the AFRL Sensors Directorate Outdoor Range. This array front end was challenging to measure due to the sheer number of elements, wide frequency range, and direct connection between the radiating elements and digitization hardware, thwarting common techniques to extract antenna parameters. Additionally, the array size was close to the limitations of the CATR quiet zone, requiring careful consideration of feed selection to provide consistent performance across the array.

To overcome the instrumentation challenges presented by a direct-digital array, an open loop configuration was used where a real-time spectrum analyzer, signal generators, and a power meter were connected to the feed antenna. The test setup in the compact range is illustrated in Figure 7. A switching and amplification network was designed and constructed to enable transmit and receive measurements in both horizontal and vertical polarization from the same feed antenna, shown in Figure 8. Dual signal generators were used to enable two-tone testing and a real time spectrum analyzer was used to enable capture of short duration transmit pulses and transient effects. Calibrated power meters were included on the transmit and receive side of the network to quickly validate the amplitude accuracy of the spectrum analyzer and signal generators.

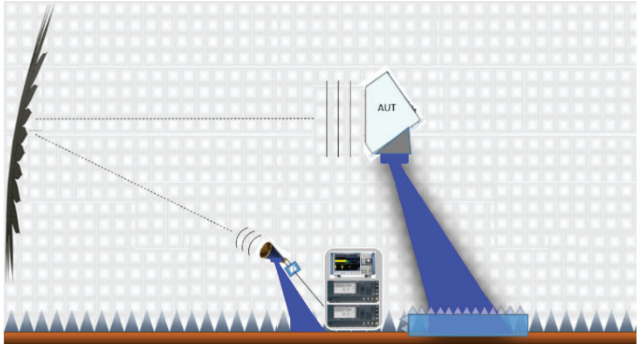

Figure 7. Indoor Range Layout

Careful measurements taken of all components in the switching and amplification network were used to form a link budget that estimated the losses between array under test and the signal sources/receiver located at the feed. This enabled relatively accurate (+/- 1 dB) measurement of array receive sensitivity and transmit power levels without a direct RF connection to the antenna.

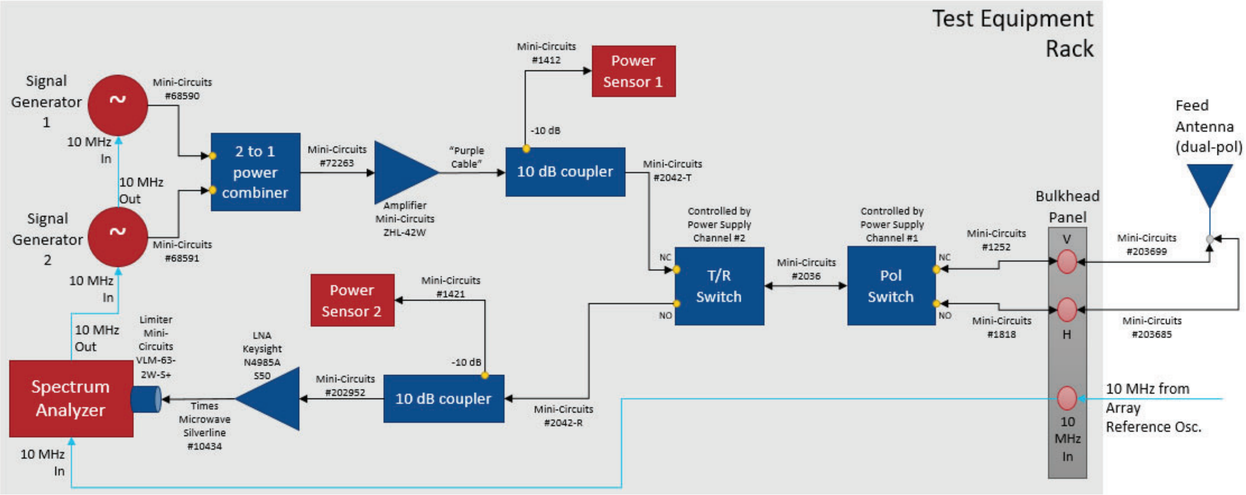

Figure 8. Indoor Range Measurement Setup Block Diagram

As with the 32-element array, calibration factors were measured in the CATR, but this time the measurement campaign was much more exhaustive. Several collections were taken of persistent calibration factors to account for unchanging hardware effects, such as attenuator insertion loss, time delay unit (TDU) delays, phase delays, amplifier compression curves, etc. These measurements are meant to be performed only once and then stored in look up tables for later a priori use. The array also used a runtime calibration routine to account for random element to element phase imbalances present upon system boot up. This leveraged the measured persistent calibration factors and was executed each time the system was powered on.

The large size and wideband nature of the 1024-element array presented challenges in feed selection. The dimension of the array was near the designed width limit of the quiet zone. Accurate measurement of beamforming performance was dependent upon minimizing amplitude and phase variations across the quiet zone, typically requiring the use of banded feeds that optimally illuminate the reflector to produce the desired flatness. Conversely, the wideband (UHF to S-Band) nature of the array meant that minimization of feed changes was also desirable to limit potential error sources and reduce measurement downtime.

To aid feed selection, previously collected field probe data from CATR feed antennas was analyzed and comparisons were made regarding amplitude taper, amplitude ripple, and phase deviation versus frequency. A sample of this comparison is shown in Figure 9. Additionally, the field probe data was processed to compute maximum beamforming performance for each feed given the array geometry of the 1024-element array. Ultimately, banded feeds (MVG QRFH350, Orbit AL-2310-1.5, Orbit AL-2310-3) were chosen to be used for critical calibration and beamforming performance measurements and a wideband feed (MVG QH400) was used for harmonic and power measurements where ideal performance across the quiet zone was not as important.

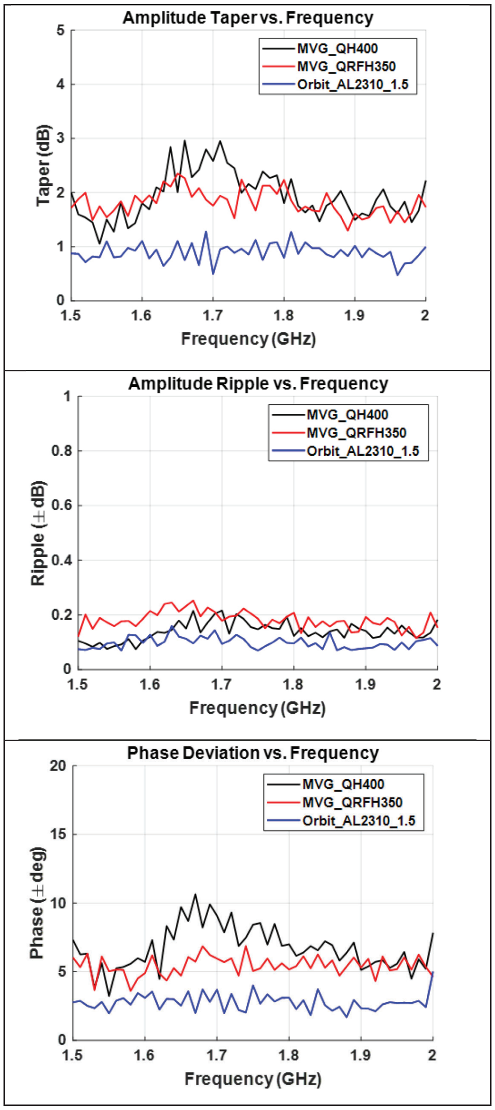

Figure 9. Sample Comparison of Feed Antenna Performance

The 1024-element array was installed in such a manner that it could be rotated azimuthally under computer control for mechanical pattern testing. Mechanical elevation patterns could not be taken in the CATR, as the mounting structure could not withstand the large amount of torque that would be generated if the array assembly were tilted to any angle other than zero elevation. Elevation patterns were later measured in the Outdoor Range where the array was installed on a larger positioner capable of both azimuth and elevation movements.

A significant portion of the indoor test campaign consisted of azimuth pattern measurements, both beamformed patterns and individual element patterns. This paper will discuss only beamformed pattern data as this is the primary mode in which the array will be utilized.

Sample collected azimuth patterns across the operating bandwidth are shown in Figure 10. For each frequency, two traces are shown. The solid trace is the mechanical azimuth pattern, where a beam was steered zero relative to the boresight of the array, and the array was physically rotated in azimuth using the range positioner. The dashed trace is a digitally scanned beam pattern, where the array is physically pointed towards zero azimuth, and many simultaneous receive beams are formed with linear spacing across a central azimuth region. A wider azimuth region was scanned for UHF (+/- 20 degrees) as the beam was broad, while smaller regions were scanned for L (+/- 15 degrees) and S (+/- 10 degrees) bands where tighter beam spacing was required to accurately sample the narrower main beam. These data collects used uniform beam weighting.

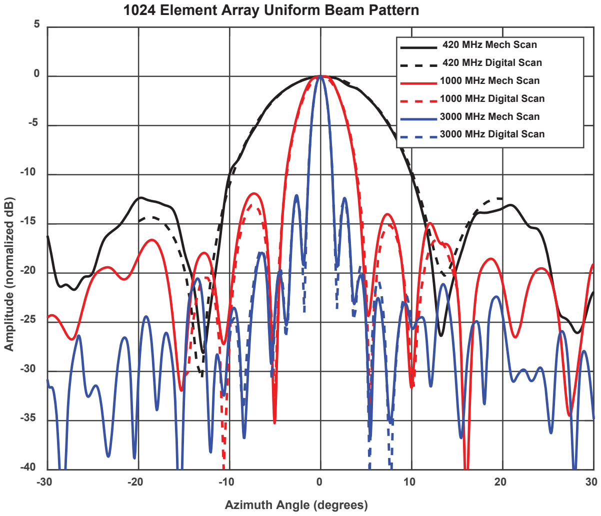

Figure 10. 1024-Element Array Beam Patterns Collected in CATR

The mechanically measured CATR patterns matched up relatively well with the patterns generated by digitally scanning beams. Main beamwidths and close-in sidelobe levels matched up with theoretical performance. The multi-layered calibration routine was determined to be effective in accounting for element to element variations within the array.

B. Outdoor Measurements

Upon completion of the CATR measurement campaign, the 1024-element array was installed on a 100’ tower at the AFRL Sensors Directorate Outdoor Range. This location provided the array good line of sight to a far-field calibration and measurement site located approximately 3.5 km away from the tower. The long baseline between the two locations enables far-field measurement criteria for large antennas such as the 1024-element array. The remote site is equipped with a signal generator and real time spectrum analyzer that are able to be controlled remotely over the network from within the main facility. Reference oscillators for equipment at both locations are provided by GPS disciplined rubidium oscillators, enabling stable measurement even over the long baseline.

After installation in the tower, the runtime calibration routines were again executed using the persistent calibration weights that had been collected during CATR testing. Next, beam pattern measurements similar to those run in the CATR were re-run to verify the calibration accuracy after the array was relocated from an anechoic chamber to an outdoor environment where significant multipath and external RF interference is present.

Two sample azimuth patterns created using digital beamforming are shown in Figure 11. A broadside beam is shown in blue and a beam steered to -10 degrees azimuth is shown in red. Both beams have a uniform amplitude taper applied. For this test, the far-field site was setup to transmit a CW tone at 3 GHz and the 1024-element array was set to receive. Beam performance was not quite as good as in the CATR, but still matched well with the expected result. Beams were able to be accurately steered across the azimuth region with sidelobe levels close to the expected 13 dB down from peak amplitude.

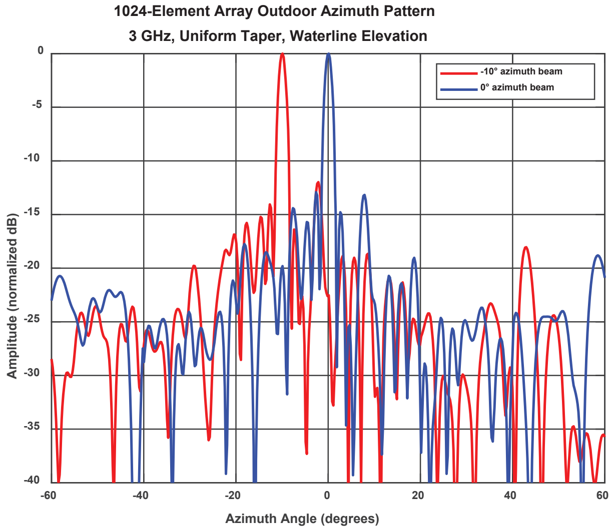

Figure 11. 1024-Element Array Beam Patterns Collected in Outdoor Environment

Overall, outdoor measurement results were significantly improved over the 32-element array. This was primarily attributed to the new calibration methodology employed on the 1024-element array and careful attention to detail during measurement of calibration weights during CATR testing.

IV. CONCLUSION

Recent improvements in digital array technologies have increased their prevalence in all types of RF systems. AFRL has developed and tested several digital wideband arrays within their Indoor and Outdoor range facilities. A 32-element custom uniform linear array was initially constructed and tested in both an indoor and outdoor environment. This test demonstrated the feasibility of CATR beam pattern measurement while also illustrating the limitations of traditional antenna measurement techniques for fully characterizing these types of systems.

A second effort involved measurement of a 1024-element wideband digital array. This array was built using a similar direct RF to digital architecture. This effort leveraged the lessons learned from the first test to carefully calibrate and measure the array in an automated manner. A multi-faceted calibration method was used to account for element-to-element variations, amplifier gains, beam shape tapers, and other configuration options available. Outdoor testing of the 1024-element array demonstrated improved beamforming performance over the 32-element array, highlighting the advantage of the improved calibration methodology and measurement techniques.

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