A Procedure to Characterize and Predict Active Phased Array Antenna Radiation Patterns from Planar Near-Field Measurements

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***Abstract*—This contribution details a procedure to collect and process necessary data to describe the antenna patterns of Phased Array Antennas (PAA) using a planar near-field (NF) range. It is proposed that a complete characterization methodology involves not only capturing beam-steered antenna patterns, but also measuring embedded element patterns, exhaustive testing of the excitation hardware of the antenna under test (AUT), and performing a phased array calibration technique. Moreover, to demonstrate the feasibility of the proposed approach, the methodology is applied onto a 2x8 microstrip patch PAA, proving its utility and effectiveness. Finally, by means of the collected data, any array pattern could be predicted by post-processing, as proven by the great agreement found between a measured pattern and its computed predicted version.**

I. Introduction

The Advanced Radar Research Center (ARRC) at The University of Oklahoma is developing a high performance line replaceable unit (LRU) for weather observations. The LRU is an 8x8 S-band dual polarized, aperture-coupled microstrip patch array [1], Figure 1. After fabrication, it is critical to test the performance of the antenna by measuring its antenna patterns. The antenna pattern measurement procedure for a PAA can be very extensive due to the various excitation combinations an array can have, and its extent increases with the number of elements in the array. Moreover, added hardware needed for element excitation (e.g., attenuators and phase shifters), may introduce errors into the beamforming mechanism. To compensate the introduced errors, extra steps should be added to the already extensive pattern measurement procedure. In this context, the objectives of this study are to present all the steps and results of the pattern measurement procedure performed on the LRU, and to propose the used data collection procedure as a methodology to characterize the antenna patterns of a small size PAA, i.e., few elements.

The main advantage of PAAs over other antenna types is its electronic steering capability and fast scanning update. Hence, to assess the performance of a PAA, antenna patterns at different scan angles must be evaluated. As a consequence, several pattern measurements must be performed to capture all patterns of interest. On the other hand, an alternative to measure beam-steered patterns is to collect embedded element patterns, i.e., the antenna patterns of each antenna element when the rest are terminated [2]. These patterns can be post-processed to compute any beam-steered pattern, making redundant to steer and measure a PAA pattern. An example of this procedure can be found in [3]. Whether to choose one alternative over the other depends upon the number of active elements: when the number of elements is higher than the number of beam-steered patterns of interest, the former choice is preferable; for fewer elements the latter choice is more attractive, since it involves measuring as many patterns as the number of active elements in the array. Moreover, this option is also useful when a mechanism to shift the excitation phase of each element is not available. During the characterization of the LRU, both techniques were implemented in order to demonstrate that both are feasible options.

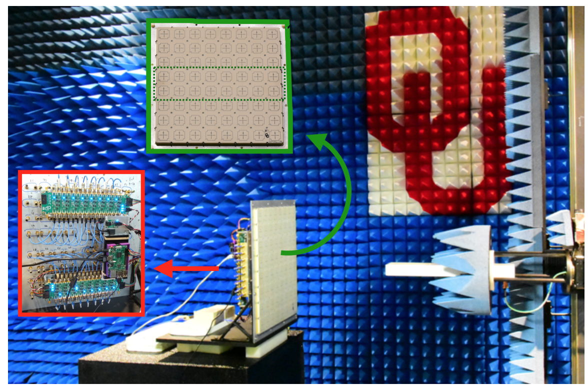

Fig. 1. LRU test setup. The LRU is positioned inside the NF chamber, and only the central two rows are excited. The two excitation boards are located on the back of the antenna panel.

Furthermore, when phase shifters and/or attenuators are part of the PAA system, the electrical path of the excitation of each element may be subjected to unknown changes. Therefore, a calibration is needed to compensate for possible excitation errors. Typically, a conventional phased array calibration technique is a procedure to quantify the differences in between electrical paths for different antenna elements and later use the collected data to choose the proper combination that will yield the fittest PAA pattern [4]. After calibration, the antenna pattern of the PAA is corrected, and the excitation hardware is completely characterized. Therefore, a phased array calibration can also be seen as a step towards the PAA pattern description.

If the embedded element patterns of a PAA have been measured, and the excitation hardware has been completely characterized, it is possible to process the collected data to accurately predict any possible PAA pattern. This document can be seen as a guide on how to collect and process all the necessary data to characterize and predict the antenna patterns of a phased array system. For this reason, in Section II, the setup utilized for the measurements is presented. Afterwards, in Section III, the characterization, and pattern measurement and prediction procedure is detailed. The results of applying the procedure onto the LRU are shown in Section IV. Finally, the conclusions are given in Section V.

II. Test Setup

Antenna pattern measurements are commonly performed in far-field (FF) or NF ranges. NF ranges yield an antenna pattern that extends for a wide range of azimuth and elevation angles from one scan, in contrast to FF ranges that return only one cut per scan. Moreover, planar NF ranges are great options for directive antennas (e.g., PAA). However, when the antenna pattern is too broad and only a portion of the radiated energy is captured, then the measurements are susceptible to truncation effects [5], [6]. For this study, all measurements were performed by means of a commercial planar NF range. This type of ranges are flexible enough to allow antenna pattern measurement and excitation characterization without any modification of the physical setup.

The PAA system to be characterized is shown in Figure 1. The antenna is an 8x8 S-band microstrip patch phased array, with dual-polarization. The antenna is excited by two phase-shifter-plus-attenuator boards each containing 8 channels which are digitally controlled. The attenuators have 5 bits ($2^5 = 32$ states), while the phase shifters have 6 bits ($2^6 = 64$ states). These boards are connected to the 2x8 central subarray of the antenna, obtaining a 16 active elements phased array system, capable of producing beam-steered array patterns. The boards and the NF robotic range are both controlled by a main computer, making it possible to automate the complete data collection process. Automation is usually recommended for these extensive and repetitive measurements, as it helps to avoid human errors and improve time efficiency.

III. Measurement Procedure

The main goal of the measurement procedure is to collect and correctly process all the data relevant to the antenna pattern. The recommended measurement steps will be detailed next.

A. Excitation Characterization

The excitation of each active antenna element is critical to define a PAA pattern. Logically, if the PAA system being tested includes a phase shift and attenuation mechanism, then the possible electrical excitation levels should be sampled. A suitable direct characterization method is the “park and probe” technique [7], [8], which consists in positioning a probe in front of each antenna element and sample the radiated magnitude and phase of all possible combinations of phase shift and attenuation levels. Other appropriate characterization techniques are mentioned in [9].

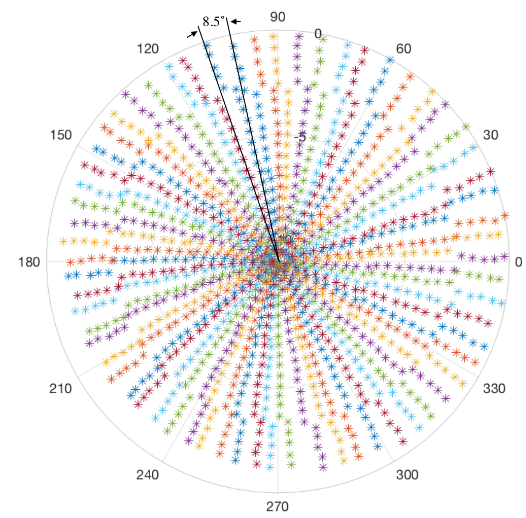

Fig. 2. Measured amplitude and phase at boresight of an active element obtained during the excitation characterization stage. Each sample point represents a sampled radiation for a given combination of phase shift plus attenuation. For simplicity only the lowest 20 attenuation levels are displayed. For the same phase shift levels, variations of up to 8.5° can occur depending on the attenuation the level.

For this study, the park and probe technique was applied to characterize the LRU using the planar NF range, by programming the robotic manipulator to position the probe in front of each antenna element and then sampling the forward voltage gain, i.e., the S_{21} parameter, with a network analyzer. In between samples, the phase shift and attenuation levels were configured by digitally commanding the excitation boards.

B. Embedded Element Patterns Measurement

Once the excitation has been characterized, the antenna patterns should be measured. One could start by acquiring the embedded element patterns. These antenna patterns are obtained by exciting a single active element and terminating the remaining elements to their corresponding impedance load. If these antenna patterns are known for all of the active elements of the array, then any desired PAA pattern that needs to be evaluated for the AUT can be indirectly obtained by post-processing, as it will be explained in Section III-E. Moreover, these measurements were performed on all 16 elements of the LRU.

C. Phased Array Calibration

The objective of a phased array calibration technique is to ensure a reliable and proper function of the system. For this, the calibration must quantify any deviation from the expected behavior of the system and propose a compensation

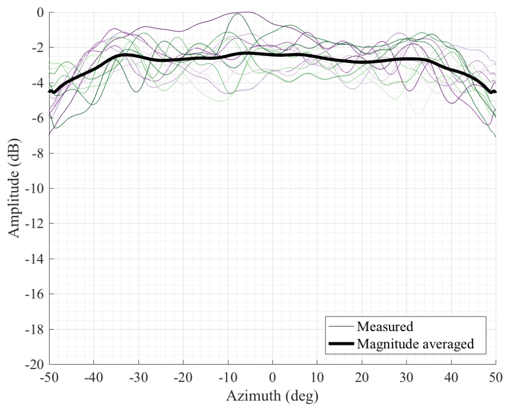

Fig. 3. Measured embedded element patterns of all 16 active elements of the LRU. The cuts are in the H-plane (along azimuth) of the V polarization. The thicker line in black represents the average magnitude of all curves.

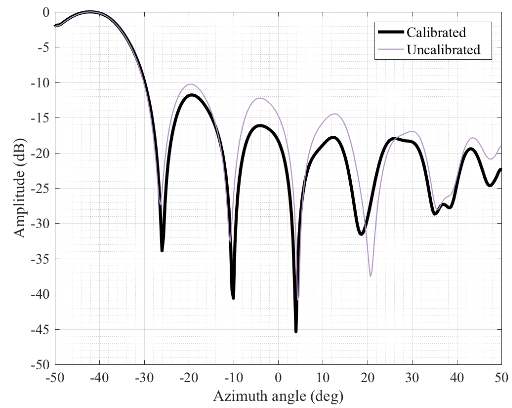

Fig. 4. Calibrated and uncalibrated versions of a measured 45° beam-steered antenna pattern produced by the LRU. Notice the lower sidelobe level and null depth when calibrated.

scheme. It is often necessary to perform a calibration while characterizing PAA patterns to produce and measure a desired pattern. Otherwise, the formed beam might not comply with the specifications and the measured pattern will be useless.

During the experiments of this study, the data collected in the excitation characterization stage were surveyed, and the closest values to the ideal complex weights required for the desired array patterns were selected. With this, the calibration procedure allowed the PAA system user to select the most suitable phase-shift plus attenuation combination for each element.

D. PAA Patterns Measurement

This step simply consists in configuring the excitations of the PAA to yield the desired pattern, and directly measure it. Usually, one can apply the selected excitation levels from the calibration step on the AUT, to form an array pattern that will closely resemble the intended pattern. During the assessment of the LRU, all the measured PAA patterns were calibrated. However, some uncalibrated patterns were measured only to demonstrate the importance of calibration during the measurement procedure.

E. Pattern Prediction

This step can be regarded as a consequence of the precedent ones. To support this statement, the equation to compute the array pattern F_a as a function of the observation angles θ and ϕ is presented as [10],

$$F_a(\theta, \phi) = \sum_{n=1}^{N} f_n(\theta, \phi) w_n, \tag{1}$$

where N is the number of active elements in the array, f_n is the embedded element pattern of the n-th element, and w_n is the complex excitation applied to the n-th element. As it can be appreciated from (1), the array pattern is a weighted sum of the embedded element patterns. Since the f_n of all N elements were obtained after performing the step detailed in Section III-B, and all possible excitations values were sampled during the excitation characterization stage (Section III-A), then it is possible to calculate F_a by applying (1). This is a useful mathematical tool provided that virtually any pattern that can be yield by the AUT, will be predicted by using measured values of f_n and w_n. As a result, by following the steps of the measurement procedure detailed in this document, the PAA patterns will be completely described and it is possible to predict any pattern that the AUT is capable of producing.

Moreover, in order to use the measured excitation values, first it is necessary to normalize them to the level at which the embedded element patterns were measured. In other words,

$$w_n = \frac{w_n^{select}}{w_n^{embedded}}, \tag{2}$$

where w_n^{select} is the measured excitation value that has been selected to be applied to the n-th element of the AUT, and $w_n^{embedded}$ is the measured excitation value with attenuation and phase shift configuration corresponding to the configuration used while measuring the embedded elements, for the n-th element.

IV. Results and Discussion

After performing the data collection methodology described in the previous section, the results are presented followed by a brief discussion.

The results from the characterization step are depicted on Figure 2. Each point represents the measured amplitude and phase of a given state defined by a combination of digital attenuation and phase shift level. Theoretically, all radial lines should look completely straight, however, due to the non-ideal nature of the excitation hardware and antenna, errors are introduced into the electrical paths of the signal, e.g. it was found that differences of 8.5° for same phase excitation levels can occur.

Figure 3 shows the cuts along azimuth of the measured embedded element patterns of all 16 active elements in vertical

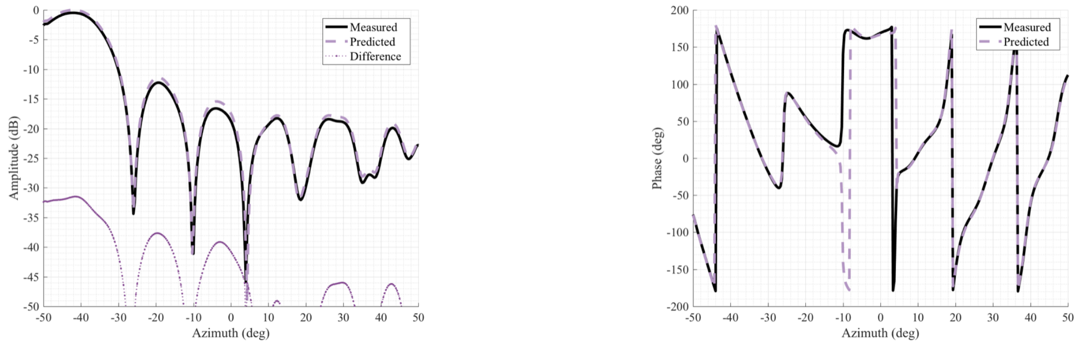

Fig. 5. Measured and predicted amplitude (left) and phase (right) of a 45° beam-steered antenna pattern produced by the LRU. The predicted pattern is calculated by using the measured embedded element patterns and excitation values on (1). The difference in amplitude corresponds to the Equivalent Multipath Level (EMPL), is calculated by subtracting the magnitudes of both curves, dividing by 2, and then converting to dB [6].

(V) polarization. Ideally, at FF, the magnitude of all embedded element patterns should be similar and smooth. However, as it can be noticed, the measured values are full of ripples produced by truncation effects, because embedded patterns are not directive, and also due to multiple reflection effects. Nonetheless, when the effect of all of them are added, the measured patterns produce a smooth curve, as it is demonstrated by the black curve which represents the average of the 16 cuts.

As an example of PAA measurements, a 45° beam-steered pattern is presented in Figure 4. Moreover, to illustrate the necessity of calibration during the pattern characterization procedure, both measured calibrated and uncalibrated versions of the LRU beam-steered pattern are shown. An important difference between both plots are the sidelobe levels, which are lower for a calibrated pattern. Also, the null levels are deeper for the calibrated pattern, indicating that the embedded element patterns are better added in phase due to the carefully chosen calibrated excitation values.

Finally, to support the assumption that any pattern can be accurately predicted by measuring the embedded element patterns and the excitation values, the 45° beam-steered pattern from Figure 4 was predicted using (1). Figure 5 shows the predicted amplitude and phase of the pattern and compares it with the measured ones. As it can be noticed, the prediction in both amplitude an phase follows the actual measured curve closely. The results are very similar to the extend that even the predicted depth of the nulls are in agreement with the measured values. The difference curve compares the amplitudes of both curves, a maximum error of -30 dB is found. With this, it has been proven that by following the procedure indicated in Section III, it is possible to collect sufficient data to predict what the radiation pattern of a phased array will be.

V. Conclusion

A procedure to characterize the antenna patterns of small-sized PAAs using a NF planar range was presented. A detailed step by step methodology was described on how to perform measurements of PAAs to collect the necessary information that will be critical to assess its antenna pattern performance. It has been shown that, in addition to antenna pattern measurements, capturing embedded element patterns, and characterizing and calibration the PAA under test are vital to fully describe the behavior of the system. The approach is recommended for PAAs with few elements, as a result of the large number of embedded element pattern that must be captured. The reliability of embedded element patterns measurements taken by planar NF ranges might be in question, due to the appearance of inexistent ripples caused by truncation and multiple reflection effects. However, as it has been demonstrated, the combined effect of all patterns produces an averaged smooth curve. Moreover, the most important evidence of their reliability is given by the noticeable similarity of the measured pattern and its predicted version computed using the measured embedded element patterns.

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