Digital Array Planar Near-Field Calibration Using Element Plane Wave Spectra with Iterative Search

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***Abstract*—Phased array antenna performance (sidelobe level, directivity, null depth, pointing accuracy, etc.) is dependent on calibration quality at each scan angle. Typically phased arrays are calibrated only at broadside scan. In some cases, particularly with smaller, high performance arrays, much time is spent determining calibration coefficients over the scan volume and array weighting, each requiring many pattern measurements. In contrast, digital receive arrays offer the possibility to greatly reduce range time for calibration coefficient extraction. Due to their access to element level I-Q data, superposition can be used to derive the calibration coefficients at all scan angles/weightings (within good measurement practice) with just one near-field scan. In this paper, we derive the theory underpinning the technique, give a calibration algorithm, and show an example array calibrated with the proposed method which drives sidelobe levels (SLLs) to near ideal levels.**

I. Introduction

Phased array antennas are used in many domains from radar and electronic warfare to communications. Parameters such as sidelobe level (clutter reduction and electronic protection), null depth (adaptive nulling), directivity, and beam steering accuracies, among others, all depend on calibration quality. Thus, large amounts of time are routinely spent measuring array patterns to extract calibration coefficients. Further, for improved performance, calibration coefficients must be found over the operational scan volume due to changes in mutual coupling over scan [1].

In traditional phased arrays, the need for calibration coefficients at every scan angle requires many pattern cuts (far-field or compact range) or near field scans (near-field range) to build up the calibration tables. However, for digital arrays, superposition can be used to derive the calibration coefficients for all scan angles and array weightings (within good measurement practice) with just one near-field scan, constituting a large savings in range time. Others have used superposition to derive digital receive array calibration coefficients [2], but did not address the generality of the approach.

II. Near-Field to Far-Field Transform

Near-field measurements are conventionally used for phased array characterization due to the production of a full pattern with a single scan. Further, planar arrays typically use a planar near-field scan for calibration due to their high gain characteristics. Therefore, we will focus on this type of measurement to align with the conventional state of practice.

A. Element Level Plane Wave Spectra Equivalence

Via superposition, the total field present in the near field scan plane is the summation of the fields from each individual source (digital array element) as seen in

$$\boldsymbol{E_a} = \sum_{i=1}^{N} I_i \boldsymbol{E_a^i} \tag{1}$$

where N is the number of sources, I_i is the complex excitation of the i^{th} source (applied in software for a receive digital array), and $\boldsymbol{E_a^i}$ is the tangential near-field electric field components of the i^{th} source with an excitation of unity. Inserting Equation 1 into the expression for the plane wave spectrum and switching the order of the summation and integration (linear operators) produces

$$\boldsymbol{f}(k_x, k_y) = \sum_{i=1}^{N} I_i \iint \boldsymbol{E_a^i}(x', y') \mathrm{e}^{j(k_x x' + k_y y')} \mathrm{d}x' \mathrm{d}y' \tag{2}$$

where $\boldsymbol{E_a^i}(x', y')$ contains the tangential electric field components sampled in the near-field scan plane at points x' and y', and k is the wavenumber. Equation 2 reveals that the total plane wave spectrum can be found by summing the weighted plane wave spectra of the individual sources. This finding indicates the near-field scan and associated array plane wave spectrum for any digital array weighting can be produced, in post-processing, from a single near-field scan. Likewise, we can use this fact to find calibration coefficients for each scan angle/weighting of interest.

III. Calibration Process

Using the findings in Section II, we can determine calibration coefficients over array scan. Specifically, as seen in Figure 1, we can

1) Collect element near-field, $\boldsymbol{E_a^i}(x', y')$
2) Apply NF-FF transform to each element near-field
3) Apply phase shift for desired scan angle, ϕ_i
4) Apply desired excitation, w_i
5) Apply calibration coefficients, c_i
6) Evaluate array pattern
7) Return to step 5) if pattern not acceptable

Note, calibration coefficients cannot be found directly from the element plane wave spectra since they contain truncation errors. Instead, the calibration coefficient quality must be evaluated after beamforming.

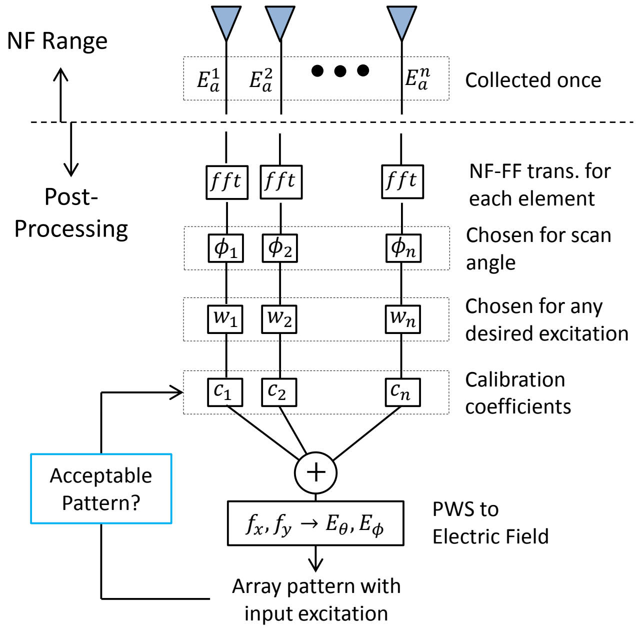

Fig. 1. Digital receive array calibration process

The process of finding calibration coefficients is inherently an iterative process, but one that is relatively simple. The task can be accomplished by a range of optimization/search techniques. In our case, element truncation errors are generally small implying starting conditions are close to ideal. Thus, we employ the Nelder-Mead simplex optimization [3] since the optimization will begin close to the global minimum. For our cost function we use

$$Cost = \begin{cases} 100 + SLL & D(\theta_0) < D_{uc}(\theta_0) \\ SLL & D(\theta_0) \geq D_{uc}(\theta_0) \end{cases} \quad (3)$$

where $Cost$ is the quantity that will be minimized in our optimization, SLL is the sidelobe level of the resulting patterns, $D(\theta_0)$ is the directivity at $\theta = \theta_0$, and D_{uc} is the directivity of the weighted and scanned uncalibrated array. This function minimizes the SLL while maintaining the gain. More complex functions may be used in its place, but this will generally produce an efficient taper for the given taper loss.

IV. Calibration of Array with Defects

Realistic arrays will have small defects causing differences in radiated power from element to element. To capture this, a near-field scan of an 8 element linear wire dipole array positioned a quarter wave above an infinite ground plane, was simulated in FEKO. Each dipole was modeled as a slightly different length ($0.495\lambda \leq L \leq 0.504\lambda$). These small differences in length change the impedance and therefore the radiated energy of each element. A $80\lambda \times 80\lambda$ near-field scan plane was placed 5λ above the array to achieve accurate patterns out to beyond $60°$.

With this model, we executed the process laid out in Section III to find calibration coefficients. The calibration coefficients were then applied to the array and simulated in FEKO to find the calibrated pattern. No calibration, $\theta = 0°$ calibration, $\theta = 60°$ calibration, and ideal pattern (normalized array factor of the desired excitation - gives idea of expected SLL) cases were simulated to produce their far-field patterns (Figure 2).

Calibration at $\theta = 60°$ gives $2.9dB$ and $5.8dB$ SLL improvement over no calibration and $\theta = 0°$ calibration, respectively. We note it is likely that larger SLL improvements would be seen for larger defects.

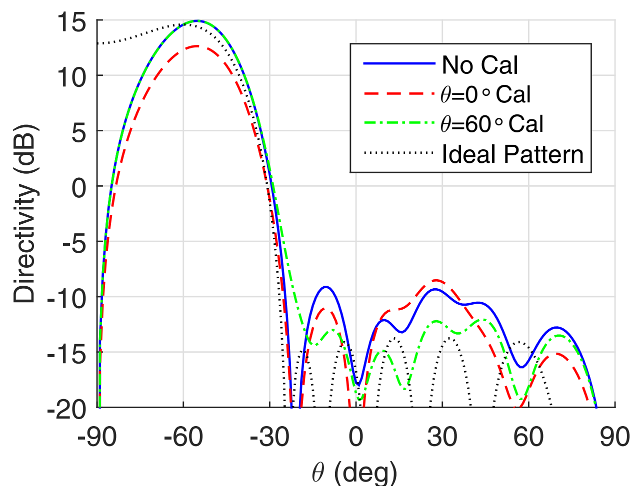

Fig. 2. Directivity of an 8-element wire dipole array with defects simulated in FEKO with a Taylor taper ($\bar{n} = 4$, $SLL = -30dB$, $\theta = 60°$ scan) for various calibrations as well as the ideal pattern (array factor of excitation)

V. Conclusion

A novel process for reduced chamber time digital receive array calibration has been presented. By collecting the near-field received at each element, desired excitations can be applied in post-processing. With one near-field scan, the array pattern for any excitation is obtained. In this way, calibration coefficients are derived in post-processing. The technique presented has the potential to improve cost, schedule, and array performance over conventional array calibration approaches.

Acknowledgement

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