Phased Array Antenna Calibration Measurement Techniques and Methods

Kim Hassett
NSI-MI Technologies, Torrance, California, USA, khassett@nearfield.com

***Abstract*— The adaptability of the phased array antenna makes it attractive for a variety of multi-beam applications. Previously, its use was limited mostly to military applications due to the large expenses associated with this type of antenna. In recent years, reduced costs have made phased array antennas viable for a variety of commercial applications. As this technology encroaches on new markets, with it comes the need to learn how to properly calibrate phased array antennas. To date, there have been numerous measurement techniques and methodologies developed for calibrating phased array antennas. This paper discusses those most commonly used in industry, and which could be easily and economically adapted for commercial applications.**

***Index Terms*—phased array antenna, calibration.**

I. INTRODUCTION

While phased array antennas have been in existence for several decades, their use has been confined primarily to military applications due to their complexity and cost. Recent advances in the RF component industry have made this technology viable for a variety of commercial applications including medical, communication, and automotive. This evolution has taken place through the miniaturization, cost reduction, and improved manufacturing techniques of the various RF components required to construct phased array antennas. This technology has also given birth to a new generation of adaptive or “smart” antennas. In order for these antennas to operate properly, they must first undergo a calibration process to compensate for relative RF variances between channels due to manufacturing tolerance differences of RF components and the beamforming network. A variety of techniques and methodologies have been developed over the years for calibrating phased array antennas. As phased array antennas become more prolific in the commercial industry, there will be increased interest in acquiring and/or developing this calibration capability, and the need to optimize the process for commercial applications.

II. BACKGROUND

Antenna theory defines a phased array as an array of antennas in which the relative phases of the respective signals feeding the antennas are set so that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions.[1] These relative phases can be either fixed or adjustable, allowing the direction of the antenna beam to be electronically steered. This type of phased array is typically referred to as an Electronically Scanned Array (ESA), and employs phase shifters or time delay devices to control the relative phase between radiating elements as shown in Fig. 1.

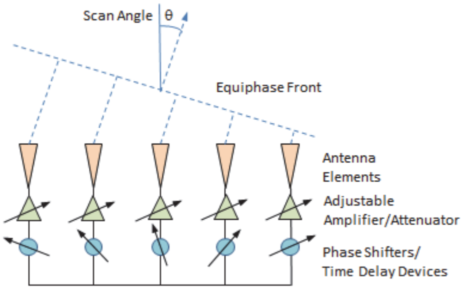

Fig. 1. Phased Array Antenna Architecture

The addition of adjustable amplifiers and/or attenuators, as shown in Fig. 1 above, provide amplitude control of the radiating power distribution for altering the antenna beam directivity. The ability to also control amplitude adds another layer of complexity as these devices must also be adjusted during the calibration process. To further complicate the issue, these devices may also be frequency and temperature dependent, requiring the calibration to be performed for varying operating parameters and conditions. This array calibration process can be performed using a variety of measurement techniques, which are presented in this paper.

III. CALIBRATION MEASURMENT TECHNIQUES

The calibration process for a phased array antenna requires adjusting the relative phase between individual radiating elements to form a collimated antenna beam. For an active phased array antenna, the amplitude for each element is also adjusted to achieve a desired aperture taper, or beam shape. The fidelity of the adjustment is limited by the number of control bits available for the variable device. Values are controlled using a digital command sent through a beam steering interface. An n-bit phase shifter providing 360 degrees of phase control has a total of $M=2^n$ phase states available and a least significant bit (LSB) phase resolution of $2\pi/M$. Likewise, an n-bit attenuator with a 16 dB range would have a step resolution of 16/M dB. As these devices are not ideal, there may be some non-linearity's associated with the component command state changes, which make the calibration process an interactive one to converge on an optimum array command set.

To calculate the required adjustments, the amplitude and phase of each individual element channel must first be determined. This can be accomplished using a variety of measurement and processing techniques. Choosing the optimal approach will depend on both the measurement system configuration and the antenna design. For example, in some applications the array control interface provides the availability to activate and deactivate the RF through individual channels, thus making it possible to deactivate all elements except the one being measured. In this way, a single element can be easily isolated. However, the validity of this approach is based on the assumption that mutual coupling from surrounding elements is insignificant. Otherwise, the contributions from surrounding elements must be accounted for during the calibration process. Often times, the array controller will not allow just a single element to be activated regardless. In either case, a modulation technique can be used to isolate the amplitude and phase value of a single element.

Prior to performing any calibration measurement process, a mechanical alignment must be performed to align the antenna coordinate reference plane with respect to the measurement reference plane, be it a far-field or near-field measurement system. This alignment will define the antenna beam pointing reference once the calibration process is complete. Any varying spatial difference between the measurement reference plane and the desired antenna phase plane will result in an unwanted equiphase front, as depicted in Fig. 1, being incorporated into the array calibration.

A. *Amplitude Modulation Technique*

In cases where the array control interface has the ability to activate an individual element channel, a simple amplitude modulation technique can be applied to determine the amplitude and phase of a single element. Two complex measurements are made: one with the entire array deactivated, and another with only a single element activated using the desired amplitude and phase command states. See Fig. 2.

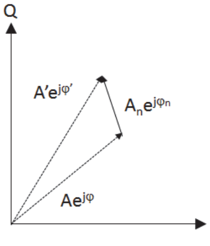

Fig. 2. Composite single element field vector using amplitude modulation technique

The vector A represents the measured system noise of the deactivated array, shown in the measurement reference coordinate system. A′ represents the measurement for a single activated element, n, which is a composite of the single element field vector and the system noise level. These two electric field vectors can be used to determine the resulting amplitude and phase of the single element state.

$$A_n\exp(j\varphi_n) = A'\exp(j\varphi') - A\exp(j\varphi) \quad (1)$$

While this approach provides the simplest method for determining the amplitude and phase contributions of each element, it requires having the ability to excite only a single element channel and requires 2 * N * M measurements to calibrate the entire array, where N is the number of elements in the array and M is the number of unique element states. For large arrays with many elements, this can be a time consuming process. In addition, is also relies on the assumption that the mutual coupling contributions from surrounding elements is not a significant factor. In the case where both amplitude and phase settings are being adjusted, undue component phase or loss modulation variations can also prevent convergence using this technique. Should any of these conditions apply, using phase modulation may prove to be a better approach.

B. *Phase Modulation Technique*

Using a similar technique, multiple complex measurements are made while the phase state of a single element channel is varied over 360 degrees. This technique is also known as the rotating-element electric field vector (REV) method [2], and is depicted in Fig. 3. Using the resulting measurement field vector results, a mathematical algorithm, such as Single Value Decomposition [3], can then be applied to resolve the element's amplitude and phase response for all phase states. An advantage of this technique is it can be applied in the presence of other RF contributors, such as scattering or reflections from antenna mounts or support fixtures, as well as contributions from surrounding elements. The measurement can also be optimized using a reduced number of phase states, depending on the linearity of the device. For example, Fig. 3 depicts the vector measurement results of a 5-bit phase shifter using all 32 phase states. Assuming the loss modulation of each bit setting is minimal and the phase response is linear, the number of measurements could be reduced to a minimum of 5, thus reducing the overall measurement time considerably.

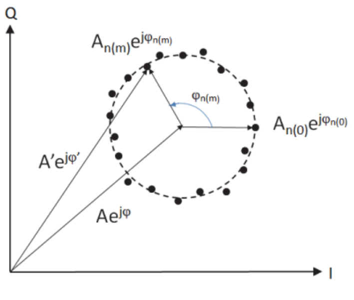

Fig. 3. Rotating field vector using phase modulation technique

Using either of these modulation techniques, each element's amplitude and phase is determined with respect to a common reference signal, and the difference between these two vector signals is used to determine the required phase and amplitude adjustments needed to achieve the desired radiating antenna pattern. The array is updated with the new device settings and the entire process is repeated until an array command set is converged upon.

IV. ARRAY CALIBRATION METHODS

A. Park & Probe Method

The previously discussed modulation measurement techniques can be employed in either the far-field or the near-field. When performed in the near-field of the antenna, the near-field measurement probe is positioned in front of each radiating element while its RF is modulated. This is typically referred to as the "park & probe" method. The probe positioning accuracy with respect to the element is not critical as long as the probe sampling delta matches the element spacing. In other words, the probe sampling grid does not need to be perfectly aligned to the element grid as long as the delta spacing of both grids is the same. The measurement process for this calibration method can be time consuming as the probe positioning system is operated in stop motion and must be positioned in front of each element while measurements are made for the varied command states over all dependent operating parameters, such as frequency and temperature.

It should be noted that while the probe need not be perfectly positioned in x and y relative to the element under test, the probe z positioning is critical and can introduce significant errors using this method. The two equations for the effect of nearfield z probe position errors on the main beam and sidelobe region are,

$$\Delta G_{dB}(\theta,\phi) \le \frac{43}{\sqrt{\eta}}\left(\frac{\delta_z(rms)}{\lambda}\right)^2 \cos^2\theta_B \, g(\theta,\phi)\,[Main\,Beam] \qquad (2)$$

$$\Delta P_{dB}(\theta,\phi) \le \frac{13.5\,\delta_z(\theta,\phi)}{\lambda} \cos\theta_B \; g(\theta,\phi)\,[Sidelobes] \qquad (3)$$

and also represents the error that will be incorporated into the array calibration during the measurement process [4]. If the near-field scanner has been configured with an automated probe z-translation stage, this error can be reduced by dynamically correcting the z position at each probe xy position during the course of the calibration measurement process. This requires an a priori knowledge of the error over the scan plane, which is acquired beforehand using optical measurement techniques. A z-error < 1/100 of a wavelength (λ) is recommended for most near-field measurement applications. Equations (2) and (3) can be used to determine the actual z error tolerance needed for a specified gain and/or siddelobe accuracy requirement.

B. Nearfield Holographic Imaging Method

Alternatively, nearfield holographic imaging can be employed to obtain the electric field at the antenna radiating aperture. This required back projecting the acquired near-field data, after probe correction, to the antenna aperture plane. The element pattern must be divided out from the holographic image data in order to derive the array pattern from which the amplitude and phase of the individual elements can be directly obtained. To resolve individual element amplitude and phase values, the hologram must be registered with the array element grid. This registration process can be performed beforehand, during the mechanical alignment process, using mechanical reference points on the antenna or its mounting fixture, or afterwards through the use of registration element(s). The phase or amplitude state of the registration element(s) is purposely altered for easy identification in the resulting holographic image, as shown in Fig. 4.

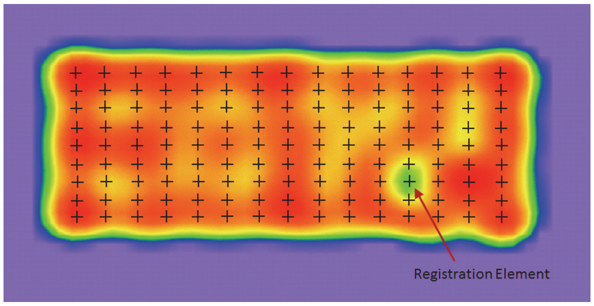

Fig. 1. Hologram array grid alignment using registration element

There are several advantages for using this measurement technique over the other previous discussed approaches. Nearfield measurement systems that support multi-beam acquisitions can be used to collect multiple array command states and frequencies over the course of a single data scan. This can result in a measurement time savings when using continuous probe motion scan acquisitions. This calibration method uses the entire activated array and can capture mutual coupling, scattering and reflections from the array structure, and temperature affects that may go undetected using the previously discussed park & probe method. However, there are several considerations that must be deliberated when using this measurement approach.

As previously mentioned, the antenna must first be properly aligned so that the array aperture is parallel to the measurement scan plane prior to the calibration process, and the measurement scan planarity < (1/100) λ.

An adequate size measurement scan plane is required to capture at least 80% of the significant energy to minimize the truncation error. At the onset of the calibration process, randomized element vector field components will produce large discontinuities in amplitude and/or phase across the array, resulting in higher far out sidelobes and evanescent modes. As a result, truncation of the near-field data will be a major error contributor. To minimize this error, a scan plane lager than that used to measure the properly formed antenna beam may be required. Error signal levels of holograms using varying measurement scan sizes can be evaluated to determine if the scan plane size is adequate. [5]

V. ADDITIONAL ARRAY CALIBRATION ERROR SOURCES

A. Phase stability

As discussed previously, the calibration process requires adjusting the relative phase between all the element channels so that the correlated phases form a collimated directional beam. These relative phase differences are measured with respect to a single measurement reference signal. Therefore, it is critical that the measurement reference remain stable over the course of measuring all elements for a particular array operating condition (i.e. frequency, temperature, etc . .). This can become a challenge for arrays with large number of elements and device command states. In these cases, additional measures must be taken to either minimize or compensate for any systematic RF measurement drift over the course of the entire calibration measurement process. This can be accomplished by using either reference element(s) or an external horn antenna to monitor the drift by periodically re-measuring the reference during the course of the calibration process and adjusting for the drift accordingly.

RF cable movement can also introduce an additional phase error component in the array calibration. This is particularly true when using the “nearfield holographic imaging method” described above where the probe is in continuous motion. Using the park & probe method, where the probe is stopped for each element measurement, can minimize this error.

B. RF Leakage

RF leakage, either external or internal to the array antenna, can be a potential problem that affects the accuracy of the array calibration. For cases where the leakage remains constant and is independent of the element phase and amplitude state, one of the measurement modulation techniques described above can be used to minimize the leakage contribution. However, it may become an issue when the resulting collimated beam is electronically steered. An RF leakage measurement of the measurement system configuration should be performed prior to the array calibration process to verify leakage is not a significant issue.

VI. CONCLUSION

There have been numerous phased array antenna calibration measurement techniques and methods explored and developed over the past several decades. This paper touches on some of the more rudimentary approaches that use relatively simple implementations, and which could easily be adapted for commercial phased array antenna applications. Common error sources encountered using these approaches were also discussed. Additional phased array calibration methods have been developed using more sophisticated measurement techniques and system configurations, but are beyond the scope of this paper.

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