A CALIBRATION TECHNIQUE FOR ACTIVE PHASED ARRAY ANTENNAS

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ABSTRACT

In active phased array antennas, transmit and receive functions are distributed at the aperture using transmit and receive (T/R) modules. Active phased arrays are typically calibrated in a near-field antenna range at the factory. The performance of active phased array antennas would degrade over time due to changes in the characteristics of active devices and would require recalibration in the field. In this paper, we present a calibration technique for active phased array antennas that uses a small number of passive array elements dedicated to calibration. The dedicated calibration elements are passive in that they do not have T/R modules behind them. The measured mutual coupling data in the field are compared with the measured data at the factory.

I. INTRODUCTION

Active phased array antennas require amplitude and phase calibration of each element throughout the deployment period. Initial radiating aperture calibration is generally accomplished by adjusting the amplitudes and phases of attenuators and phase shifters, respectively, in a near-field range. This calibration is generally referred to as array alignment. Near-field range array alignment involves placing a probe sequentially in front of each array element, with that element in either transmit (T) or receive (R) mode and the remaining elements terminated in matched loads. In this way, the amplitude and phase of each radiating element is accurately measured and adjusted for transmit and receive modes. The required array amplitude and phase distribution is achieved by adjusting the T/R module amplitudes and phases as indicated by the measurements.

A phased array antenna may be deployed for a long period of time. The performance of an active phased array antenna may deteriorate over time as a result of changes in the solid-state components. In addition, failed T/R modules must be repaired or replaced in the field. As a result, the amplitude and phase settings need to be adjusted to compensate for active component drift and replacement or repair of components. This measurement and readjustment of the element amplitude and phase settings during array deployment is known as field calibration.

Several techniques for field calibration have been proposed and implemented, each having various advantages and disadvantages [1-3]. The calibration technique described in [1] employs external horns that provide transmit and receive couplings to each active array element. These horns are located around the perimeter of the array. The array is first aligned in the near-field range and then mutual coupling between the horns and array elements are measured, with radiating elements either in the receive or transmit mode. These measurements become the factory standard for the array. Field calibration is accomplished by comparing mutual coupling measurements taken during deployment with the factory standard. This calibration technique increases the effective array size footprint and increases antenna radar cross section (RCS). Furthermore, as the array size increases, the signal-to-noise ratio resulting from coupling between the external horns and central array elements may not be high enough to provide the required measurement accuracy for calibrating the array to its original state.

The calibration techniques described in [2] and [3] use mutual coupling measurements between adjacent elements to initially align the array and then to calibrate the array in the field using the same technique. The calibration procedure involves sequentially transmitting from a single array element and receiving from only the adjacent elements through two independent beamformers, with all other elements turned off. This technique is very complex, and internal coupling between transmit and receive chains of the T/R module may result in erroneous results. To avoid internal coupling, very high isolation is required between transmit and receive paths in each T/R module. When one element is turned on to transmit and the other to receive and all the other elements are turned off, the internal coupling from all the elements through the beamforming network may alter the measurement. Furthermore, separate transmit and receive beamformers are required, resulting in increased antenna system complexity. This technique may not be suitable for

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arrays with high-power T/R modules, since the coupling to the adjacent elements may be large enough to saturate the low noise amplifier, resulting in erroneous results.

In this paper, we describe a calibration technique that uses mutual coupling between a few dedicated internal passive elements and all active array elements. The dedicated calibration elements are passive in that they do not have T/R modules behind them. By using passive elements, the accuracy of mutual coupling measurements is increased significantly. In addition, separate transmit and receive beamformers are not required. This new calibration technique is described in Section II. Sections III through V discuss the active element receiver sensitivity, calibration accuracy and impact on array packaging, respectively

II. ACTIVE ARRAY CALIBRATION TECHNIQUE

To overcome some of the drawbacks of the external calibration source technique and the complexity of the full mutual coupling based auto-calibration technique, we describe a new calibration technique that uses internal array elements as passive calibration elements. This technique is a mutual coupling based calibration technique employing a small number of passive calibration elements. A notional phased array aperture employing passive calibration elements is shown in Fig. 1. A block diagram of an active phased array antenna architecture is shown in Fig. 2. The passive calibration elements are chosen from the array elements and are directly connected to a calibration unit. These calibration elements are passive since they do not have T/R modules behind them and do not share active array RF beamformers. Calibration is achieved by sequentially measuring the mutual coupling between each passive calibration element and a selected group of active array elements. A switch network is used to route the calibration signals between the calibration unit and one passive calibration element at a time. A block diagram of an array with a calibration unit and switch network is shown in Fig. 3. As shown in Fig. 1, a calibration element is used to calibrate a group of elements beyond a certain distance from the calibration element, so that the active elements can be calibrated by more than one calibration element for similar dynamic range.

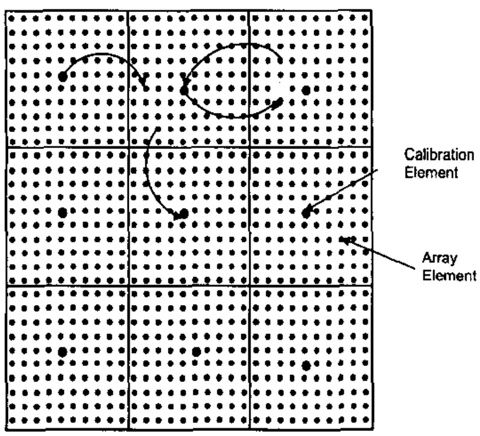

Figure 1. Active phased array antenna calibration scheme using internal array elements

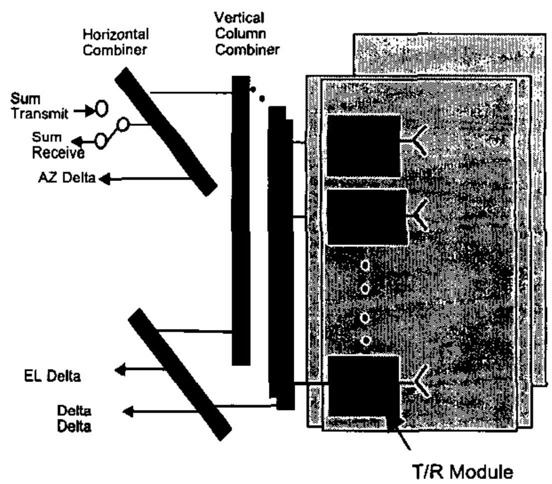

Figure 2. Active phased array architecture

This calibration technique does not require high isolation between active array elements and does not increase the array footprint. In comparison, the increased footprint with large external calibration horns [1] increases the antenna radar cross-section and packaging complexity, particularly for airborne and shipboard antennas.

The required number of passive calibration elements is a small percentage of the total array elements and is proportional to the size of the array. For a large array of approximately 10,000 elements, 9 passive elements are sufficient for calibration. It will be shown later that the required number of passive calibration elements has a negligible effect on the gain and sidelobe performance of the array.

Calibration Procedure

The array is split into several blocks, with a single passive calibration element located near the center of each block (Fig. 1). The initial mutual coupling measurements are taken immediately after array alignment in the near-field antenna range. To begin calibration on the near-field range, the transmit signal from the calibration unit is routed through the switch network to a single passive calibration element. All other active elements in the array are initially turned off. Then a single element in a block adjacent to the passive calibration element block is turned on to receive. The transmit signal from the passive calibration element is received via mutual coupling by the active element under test.

When this process is completed, the active element is turned off and an adjacent active element in the same block is set to receive the calibration signal from the passive calibration element. This process is repeated for every active array element in a block. When all the elements in the block are calibrated, the elements in other blocks adjacent to the passive calibration element block are calibrated. Then, a new passive calibration element is chosen, and the active elements in adjacent blocks are calibrated. This process continues until all active elements in the array are calibrated. This process is repeated for the remaining blocks until all active array elements are calibrated.

The above procedure calibrates array active elements in the receive mode. To calibrate array elements in the transmit mode, the above process is reversed. The signal is transmitted through the active element and received by the calibration element. The near-field range calibration process results in a factory standard mutual coupling data set.

Since all the blocks can be calibrated by at least two passive calibration elements, it is possible to calibrate the active elements in each block more than once. Calibration of active elements using multiple passive calibration elements provides redundancy to protect the system in the event of an unlikely failure of a passive calibration element.

When the antenna is deployed in the field, the mutual coupling between calibration elements and array elements is measured in exactly the same manner as the initial near-field range mutual coupling data. The mutual coupling data measured in the field are then compared to the factory standard data. Finally, the amplitude and phases of the attenuators and phase shifters in the active element T/R modules are adjusted to bring the antenna to the factory standard.

This calibration procedure can also be used to detect failed elements. The health of the radiating elements can be monitored on a continual basis by running the calibration procedure for a small fraction of the system time. When failed elements are replaced with new elements, the array is calibrated to bring the replaced elements and the array to the factory standard.

Required Number of Calibration Elements

To avoid undue antenna gain and sidelobe degradation, the number of elements dedicated to calibration should be small, ideally less than 1% of the elements. As shown in the following example, 9 calibration elements (0.2%) are sufficient for calibrating a 10, 000-element active array antenna. Figure 1 shows the location of the calibration elements.

By using a relatively small number of passive elements dedicated to calibration, the effective isotropic radiated power (EIRP) loss and sidelobe degradation can be minimized. For instance, in a 10,000-element array, if 9 elements are used as dedicated calibration sources, the EIRP loss is only 0.004 dB. Peak and root mean square (RMS) sidelobe degradation for a 10, 000-element array were evaluated using a planar array analysis code. The results are plotted in Fig. 4 for –40 dB peak and –58 dB RMS sidelobe levels, with 1.0 dB RMS and 5 deg RMS amplitude and phase errors, respectively. For a 10,000-element array with 9 passive calibration elements (0.09%), peak and RMS sidelobe degradation are each less than 0.25 dB.

A 10, 000-element square array can be divided into 9 square calibration blocks of 1111 elements each, asshown in Fig. 1. In general, these calibration blocks do not have to be squares but can take any appropriate regular shape. For circular or elliptical arrays, the edge calibration blocks can be partial blocks as required by the array shape. Each calibration block has a dedicated calibration element near its center. Each calibration element is used to calibrate all active elements in the adjacent calibration block. As shown in Fig. 1, a calibration element can be used to calibrate the active elements in more than one calibration block. These additional data provide measurement redundancy.

The block size determines the total number of calibration elements in the array. The block size, and therefore the required number of calibration elements, is dependent on several factors, including mutual coupling levels between the passive calibration elements and the active elements, low noise amplifier (LNA) input third order intercept (TOI) point, and calibration unit transmit power. For the chosen calibration block size, the calibration unit output power level is chosen so that the farthest element in the adjacent block has sufficient coupling and the nearest LNA in the adjacent block is not saturated (stays in the linear region).

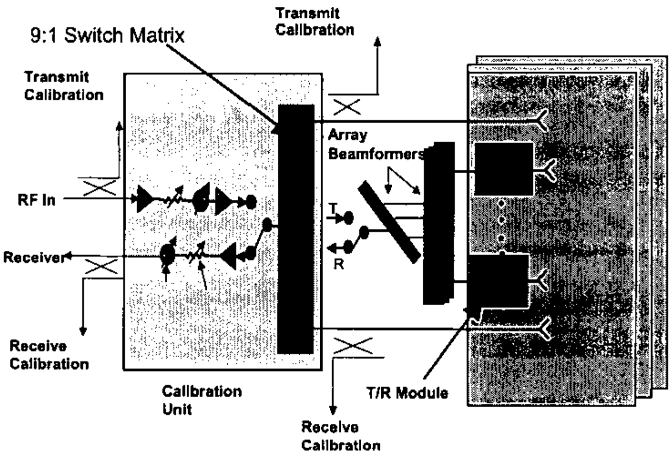

Figure 3. Active phased array architecture for the calibration scheme

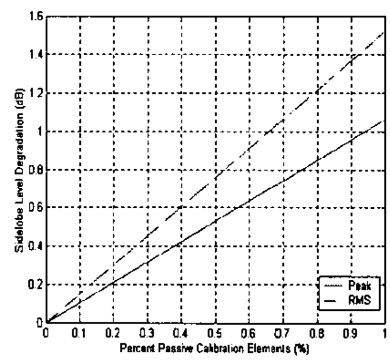

Figure 4. Sidelobe degradation as a function of failed elements for a large array

III. ACTIVE ELEMENT RECEIVER SENSITIVITY AND MINIMUM CALIBRATION UNIT OUTPUT POWER

For a planar array, coupling will generally be stronger in the E-plane than in the H-plane, and different element types will couple differently. In general, the coupling between two adjacent elements spaced 1/2 wavelength apart will be between –15 dB and –25 dB (depending on the plane and element type). For this study, a moment method analysis was done to analyze the coupling between widely spaced simple probe-fed microstrip patch elements. The mutual coupling between these elements as a function of distance is shown in Fig. 5. Similar mutual coupling data can be obtained for other types of elements by analysis or measurement. However, these patch element mutual coupling data are representative of typical radiating elements.

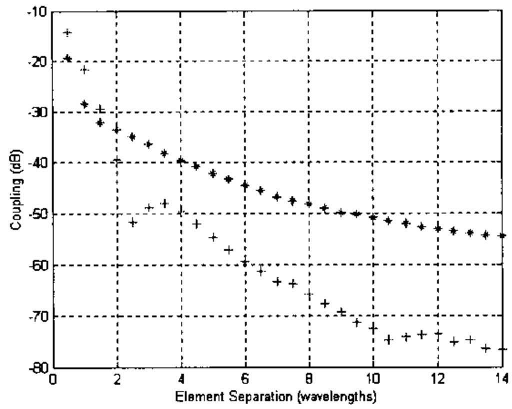

Figure 5. Mutual coupling between widely spaced probe-fed microstrip patch elements in 30 x 5 E-plane (*) and 5 x 30 H-plane (+) planar arrays

The receiver sensitivity of the farthest active element in the adjacent block will determine the required minimum calibration unit output power and the maximum calibration block size in the array. For square calibration blocks, the distance between a passive calibration element and the farthest active element in the adjacent block is approximately 3 times the distance between the calibration element and the nearest element in the adjacent block. For the example 10, 000-element array (50 wavelengths on a side), 9 blocks of approximately 1111 elements (17 wavelengths on the side) were chosen to limit the number of blocks. For this example the coupling between the calibration element and the nearest and farthest elements will be 45-55 dB and 85-95 dB, respectively. Therefore, a 10 dBm transmit signal from the calibration unit will provide a coupled signal of approximately –80 dBm at the farthest element in the adjacent block, which is above the sensitivity of most receivers. These calibration unit output power and coupled signal levels are given as an example; the actual numbers for a given application may be different.

The LNA input third orders intercept (ITOI) of the closest active element in the adjacent block limits the maximum calibration unit output power and the minimum calibration block size. For the above example, the coupling between the calibration element and the nearest element in the adjacent block is approximately 50 dB. For a 0 dBm LNA ITOI, the maximum allowable input signal to the LNA to avoid saturation is –10 dBm. Therefore, the maximum calibration unit output power is approximately 40 dBm.

This analysis shows that the calibration unit output power can be between 10 and 40 dBm. Since output power levels exceeding 10 dBm are easily achievable, even larger blocks could be considered for the above example and 9 calibration elements may be sufficient for arrays of greater than 10,000 elements. For providing redundancy and symmetry, 9 calibration elements are deemed as the minimum required for a large array.

In summary, in the active array element receive case, the calibration block size is influenced by the element coupling levels, element receiver sensitivity, and minimum calibration unit output power and only weakly by the active element input TOI. The preceding examples illustrate that only a small number of dedicated calibration elements is required for a large array and that a reasonable calibration unit output power is sufficient to implement this technique.

The preceding discussions centered on the calibration of an active element in the receive mode, with the passive calibration element transmitting. In the active element transmit case, the active element output power and the passive calibration element receiver sensitivity limit the calibration block size. Most large arrays have sufficient active element output power (>10 dBm) to provide sufficient coupling to limit the passive calibration elements to a reasonable number. For a very high output power active element, a variable attenuator can be placed before the calibration unit LNA to avoid saturation. So once again, the receive (calibration unit) LNA input TOI is not a limiting factor.

IV. CALIBRATION ACCURACY

Near-field antenna measurement ranges typically can provide a high degree of amplitude and phase accuracy (on the order of one degree phase and 0.1 dB amplitude errors). To provide accuracy similar to that of a near-field range, the calibration technique must also provide similar measurement accuracy. The calibration technique presented in this paper would provide the desired measurement accuracies by using standard test equipment configured for this purpose. Because this calibration system would itself be periodically calibrated, the accuracy of the mutual coupling measurements will not degrade over time and will therefore maintain factory-level performance. This is a unique feature of this technique. The consistently accurate calibration of active antenna elements in the field reduces antenna life-cycle cost by maintaining performance to factory standards.

An important consideration in a calibration system is calibration path stability over time. Inevitably, drifting in phase and amplitude will occur in any active components in the calibration path. If left uncorrected, this drift could eventually result in unacceptable errors in calibrating the array. To overcome this problem, the calibration unit (Fig. 3) should be calibrated periodically both in transmit and receive cases.

The calibration unit can be calibrated by coupling signals at the input and the output ports in transmit and receive modes. Any changes in amplitude or phase can be corrected by resetting the phase shifters and attenuators in the path to reset the amplitude and phase to the original levels. Calibration of the calibration unit would be required less often than full calibration of the array and can range from weeks to months.

VI. CONCLUSIONS

We have presented a new calibration technique for active phased array antennas for calibration in the field. This calibration technique uses a small number of passive array elements dedicated to calibration, resulting in insignificant gain and sidelobe degradation. The mutual coupling measurements are first made at the factory and are repeated in the field for comparison. Since the calibration elements are passive, the accuracy of measurement is not affected by variations in the active elements and isolation between elements. The accuracy of calibration is high and does not degrade over time as the calibration unit can be calibrated periodically using standard test equipment.

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