Calibration of phased array antenna with the minimum point finding method of the array factor

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Article Info

Article history:

Received Jul 15, 2024
Revised Oct 9, 2024
Accepted Oct 30, 2024

Keywords:

Array factor
Calibration
Minimum point finding method
Phase shift
Phased array antenna

ABSTRACT

The problem of phased array antenna calibration with the minimum point finding method of the array factor is investigated. A mathematical model of the minimum point finding method is presented. Then, the proposed method is applied to the phased array antenna and compared with the traditional rotating-element electric-field vectors method. Experimental verification of the mathematical model of the proposed method showed the following: the minimum point finding method determines the phase shift more accurately than the maximum point finding method of the array factor; the proposed method showed a better detection range per phase change corresponding to a 35 dB higher resolution. The error ranges of the minimum and the maximum point finding methods were 5^0 and 70^0, respectively. The peak of the combined beam when using the minimum point finding method is higher than the maximum point finding method which is 3.7 ... 4.1 dB. One can use the research results in large-scale phased array antenna calibration systems during the production phase.

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1. INTRODUCTION

Currently, phased array antennas are widely used in radio engineering and communication systems [1]–[4]. The efficiency of the phased array antenna (PAA) in processing the signal reflected from the target is contingent upon the state of the signal receiving channels. Consequently, the asynchrony in amplitude and phase of the received signal between channels significantly impacts the accuracy of subsequent signal processing. This asynchrony is due to different channel delays, signal attenuation, channel noise, external impacts, and many other factors. To synchronize phase and amplitude between channels, phased array antennas must be calibrated at the production stage and during operation [5]–[8].

This problem is solved using various calibration methods: calibration lines [7]–[10], peripheral fixed probes [11]–[14], mutual coupling [7], [15], [16], and rotating-element electric-field vectors (REV) [17]–[19]. The evaluation results of the aforementioned methods [20]–[24] show that the REV method [17]–[19] has advantages over the remaining methods [7]–[16] in terms of accuracy and system complexity. The REV method entails the measurement of the combined electric field vector of the PAA by the reference antenna situated within the field region, to calibrate the magnitude and phase of each element [17], [19], [25], [26]. This method allows for the straightforward calibration of the amplitude and phase of each element, based on the measurement of the received power alone. The working principle of the REV method is as follows: this method rotates the phase of each antenna element from 0^0 to 360^0 and finds the maximum point (REVmax) of the array factor.

In [25], [26], the composite power curves as a function of the phase change of the REV method are expressed using both theoretical and measured values. The small dynamic range of the REVmax method [17]–[19] significantly affected the determination of precise phase calibration values. In other words, the system cannot identify the appropriate phase calibration values due to the restricted power resolution near the maximum point of the combined electric field vectors, resulting in calibration inaccuracy. However, the PAA calibration method should be highly accurate in the initial production phase. Consequently, it is essential to investigate and develop a novel approach based on the REV method that enhances accuracy and simplifies the system complexity.

The aim of the work is to develop the REV method based on the minimum point finding method of the array factor for calibrating the phased array antenna. The proposed method utilises a minimum level tracking approach to enhance the dynamic range per phase change. The high dynamic range near the null enables more precise detection of changes in the received power level, facilitating higher calibration resolution per phase adjustment. The rest of this article is organized as follows. In Section 2, mathematical model and the simulation of proposed method are presented. In Section 3 the proposed calibration system is designed and measurement. Then, the proposed method is compared with the traditional REV method. Finally, this paper is concluded in Section 4.

2. METHOD

2.1. Mathematical model of the minimum point finding method

The proposed method is founded upon the principles of array factor equations. Consider the array with N elements, which is receiving a signal from a plane wave incident at angle θ to the plane of the array Figure 1, then the array factor is written as follows:

$$AF_N = x_0 * \omega_0 + x_1 * \omega_1 + x_2 * \omega_2 + \dots + x_{N-1} * \omega_{N-1} = A_0 e^{j\beta_0} * B_0 e^{j\Upsilon_0} + A_1 e^{j\beta_1} * B_1 e^{j\Upsilon_1} + + A_2 e^{j\beta_2} * B_2 e^{j\Upsilon_2} + \dots + A_{N-1} e^{j\beta_{N-1}} * B_{N-1} e^{j\Upsilon_{N-1}} = A_0 B_0 e^{j(\beta_0+\Upsilon_0)} + A_1 B_1 e^{j(\beta_1+\Upsilon_1)} + + A_2 B_2 e^{j(\beta_2+\Upsilon_2)} + \dots + A_{N-1} B_{N-1} e^{j(\beta_{N-1}+\Upsilon_{N-1})}. \quad (1)$$

where, $x_m = A_m e^{j\beta_m}$ – the complex incident wave equation at the m-th element, m = 0, 1, 2, ..., N-1; A_m, β_m – the amplitude and phase of an incoming plane wave respectively; $\omega_m = B_m e^{j\Upsilon_m}$ – the complex representation formula for amplitude shift B_m and phase shift Υ_m.

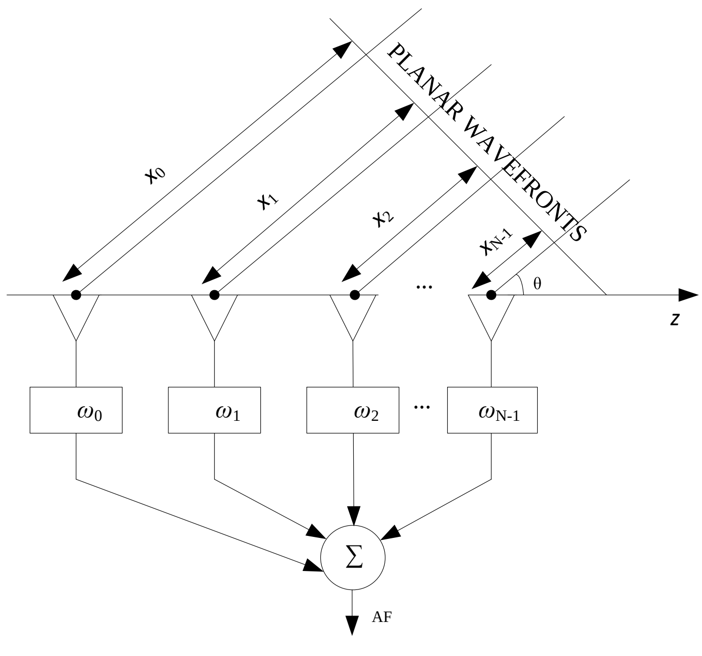


Figure 1. Ray diagram for linear reviewing array

Now we consider the case where all array elements are separated by the same distance d, leading to a linear array of total length $D = (N - 1)*d$ Figure 2. From Figure 2, we can see that the phase of element $m + 1$ leads that phase of element m by some $\varphi = kd\ cos\theta$, where $k = 2\pi/\lambda$ – wave number, λ – wavelength, since the path length to element $m + 1$ is $d*cos\theta$ meters longer than that to m. Then, if we arbitrarily set the reference point to element 0, so that $\beta_0 = 0$, we can write the array factor (1) as (2).

$$AF_N = 1 + A_1 e^{j\varphi} * \omega_1 + A_2 e^{j2\varphi} * \omega_2 + \dots + A_{N-1} e^{j(N-1)\varphi} * \omega_{N-1} = 1 + A_1 e^{jkd\ cos\theta} * B_1 e^{j\Upsilon_1} + A_2 e^{j2kd\ cos\theta} * B_2 e^{j\Upsilon_2} + \dots + A_{N-1} e^{j(N-1)kd\ cos\theta} * B_{N-1} e^{j\Upsilon_{N-1}} = 1 + A_1 B_1 e^{j(kd\ cos\theta + \Upsilon_1)} + A_2 B_2 e^{j(2kd\ cos\theta + \Upsilon_2)} + \dots + A_{N-1} B_{N-1} e^{j((N-1)kd\ cos\theta + \Upsilon_{N-1})}. \quad (2)$$

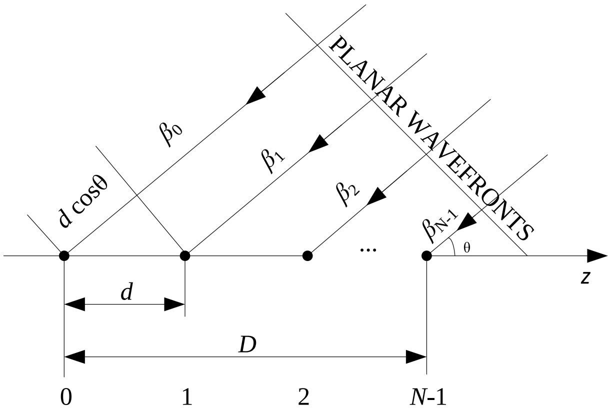


Figure 2. Linear array geometry

Consider the case where each element of the array is excited with a signal at an amplitude of 1, but because the transmission paths between elements are not equal, the phase shift of each element will be different. Hence, we can write the array factor as (3).

$$AF_N = 1 + e^{j\varphi} * e^{j\Upsilon_1} + e^{j2\varphi} * e^{j\Upsilon_2} + \dots + e^{j(N-1)\varphi} * e^{j\Upsilon_{N-1}} = = 1 + e^{j(kd\ cos\theta + \Upsilon_1)} + e^{j(2kd\ cos\theta + \Upsilon_2)} + \dots + e^{j((N-1)kd\ cos\theta + \Upsilon_{N-1})} \quad (3)$$

We know that the angle of incidence θ takes values from 0º to 180º, so the parameter φ will have a value in the range of -kd to kd. Then, to determine the phase shift Υ_m using the minimum point finding method, we need to find the angle Υ_i at the minimum point of e (3):

$$\Upsilon_m = \underset{min\ AF_N(\Upsilon)}{\Upsilon_i} + 180^o, \Upsilon = \overline{0^o\ 360^o} \quad (4)$$

2.2. Simulation of proposed method

By changing Υ_m, we study the calibration of the PAA using the minimum point finding method (4) by analyzing the dependence of the array factor (3) on the phase difference between the receiving channels and the minimum point position according to the angle of incidence θ.
Assuming that, $N = 2$, (3) can be written as (5):

$$AF_2 = 1 + e^{j(\varphi + \Upsilon_1)} = 1 + e^{j(kd\ cos\theta + \Upsilon_1)} = 1 + e^{j(2\pi d\ cos\theta/\lambda + \Upsilon_1)}, \Upsilon_1 = \overline{0^o\ 360^o} \quad (5)$$

then, to determine the phase shift Υ_m using the minimum point finding method, we need to find the angle Υ_i at the minimum point of (5):

$$\Upsilon_1 = \underset{min\ AF_2(\Upsilon)}{\Upsilon_i} + 180^o, \Upsilon = \overline{0^o\ 360^o} \quad (6)$$

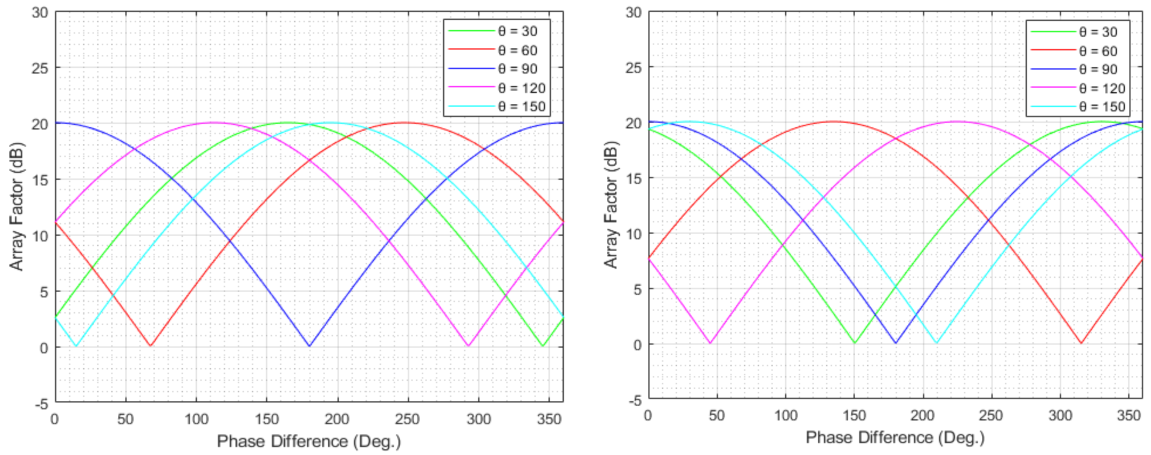
The simulation results of (5) in MATLAB are shown in Figure 3. Figure 3 shows the array factor according to the phase difference between the two antennas, and the location of the minimum point according to the angle of incidence θ with different distance between the two antennas D. We can find the angle Υ_i at the minimum point as (6) and make several important observation about this plot: the minimum point finding method determines the phase shift Υ_m more accurately than the maximum point finding method of the array factor by up to 15°. For example, when the angle of incidence θ = 60°: Figure 3(a) shows that with the minimum point finding method the phase shift Υ_m= (70°+180°) = 250° , and with the maximum point finding method Υ_m receives a value in the range of 235° to 265°; Figure 3(b) shows that with the minimum point finding method the phase shift Υ_m = (315°+180°) = (135°+360°) = 135° (because $\omega_m = B_m e^{j(135^0+360^0)*\pi/180^0} = B_m e^{j(135^0)*\pi/180^0}$), while with the maximum point finding method Υ_m reveives a value in the range of 120° to 150°. In addition, for all cases $\theta \neq 90°$ when the distance between the elements of PAA d changes, the phase shift Υ_m changes, and with the minimum point finding method, when the angle of incidence θ = 90°, the phase shift Υ_m = 0°.

In the subsequent step, an exemplary calibration scenario is simulated to describe the proposed method. The reference antenna and antennas to be calibrated are distant from each other in the near-field region as shown in Figure 4. The reference antenna is aligned toward the middle of the two antennas to be calibrated to accurately detect minimum point of the array factor. In the step, antenna 1 (green column) and antenna 2 (light blue column) are calibrated through reference (orange column) using the proposed method.

Figure 5 shows the simulated transmission characteristics of proposed array when using the maximum point (REVmax) and minimum point (REVmin) finding methods. The dynamic range of the calibration magnitude by the proposed method over the 60 phases around the minimum point is approximately 42 dB, whereas the REVmax method demonstrates a dynamic range of 2 dB around the maximum point. The simulation results indicate that the REVmin method exhibits a resolution that is 40 dB higher than that of the REVmax method.

Figure 6 demonstrates the simulated radiation patterns for the case N = 2, $D = 0.625\lambda$ and θ = 90°. Figures 6(a) and 6(b) show the calibration results when using REVmax and REVmin methods. The results of the simulation demonstrate that the REVmin method exhibits superior phase calibration accuracy in comparison to the REVmax method, the beam were tilted by 15° occurred in E-plane after REVmax method.

Consequently, the minimum point finding method has advantages over the maximum point finding method. In the case of an array of N elements (N > 2), this method is continued until the final sequence has been reached. Once an initial pair of elements has been selected for comparison and calibration, one of the two elements is retained as the reference element for comparison with the next element. This approach also serves to minimise the phase variation among the phase shifters, which is attributable to the intrinsic nature of the active component. The minimum point finding method helps to find the precise determination of the phase shift, thereby enabling the calibration of large-scale PAAs achieve the maximum combined beam peak after calibration. Conversely, the maximum point finding method inaccurate phase shift in the initial two elements, which can result in an inaccurate phase shift for subsequent elements. This can lead to a reduction in the amplitude of the combined beam at the output combiner, which in turn affects the efficiency of subsequent signal processing.



(a) (b)

Figure 3. Dependence of function AF_2 on Υ_1 (Deg.) for different angles of incident θ (Deg.) in the cases (a) – $D = 0{,}625\lambda$ and (b) – $D = 1{,}25\lambda$

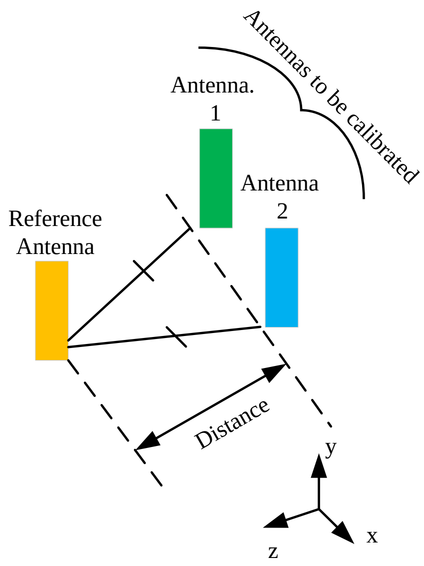


Figure 4. Simulation environment for the calibration: orange column – Reference; Green column – Fixed; Light blue column – Calibrated

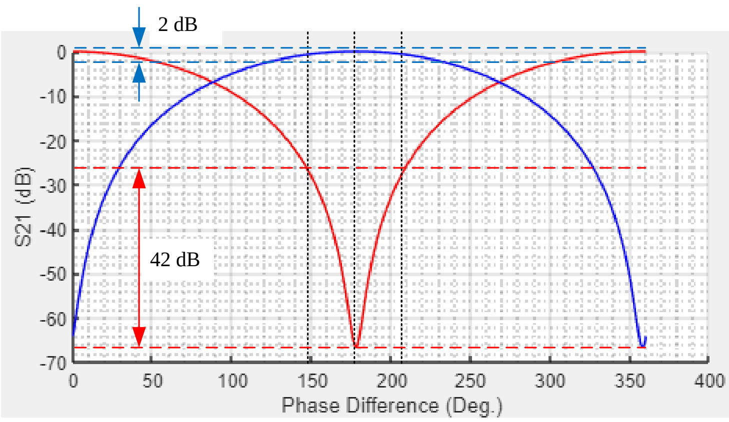


Figure 5. Simulation results of calibration with S_{21} by phase difference of antennas to calibrated after the REVmax and REVmin methods: Blue line – REVmax method; Red line – REVmin method

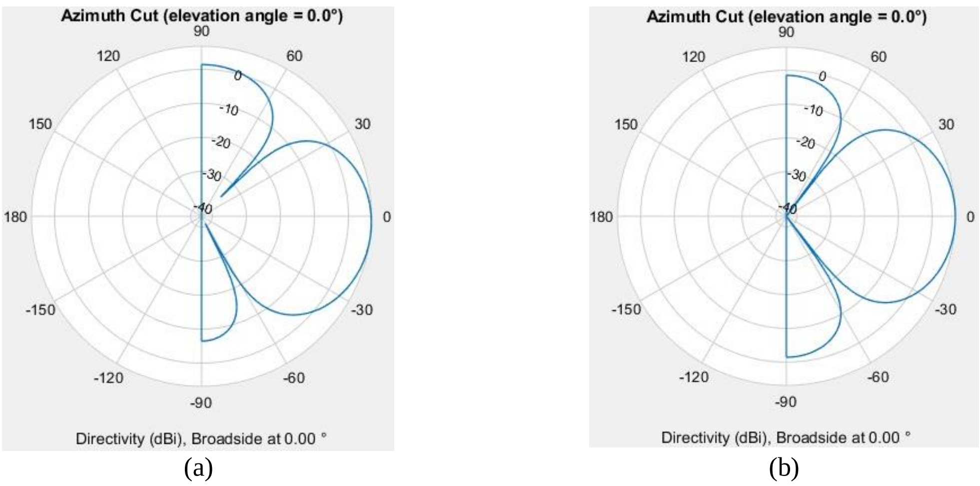


Figure 6. Radiation pattern of the combined beam in E-plane when using different calibration methods: (a) REVmax method and (b) REVmin method

3. RESULTS AND DISCUSSION

In this section, to experimentally test the mathematical model of the minimum point finding method, a series of experiments were conducted utilizing a calibration system design. The transmission characteristics of the proposed array and the radiation patterns of the proposed array following the implementation of a phase shift on received signals when employing disparate methods were compared. Subsequently, the experimental calibration system design employed to perform the aforementioned tasks is described in detail. This is followed by a discussion of the results obtained.

Figure 7 illustrates the calibration system for determining the transmission characteristics of the proposed array when using different methods. The system includes the following components: laptop with installed MATLAB 2022a; rotary control block and rotary platform; power supply 12V, 5V; the signal processing block, which is described in Figure 8, comprising AD9361 card, control board and a ZC706 Xilinx FPGA board; 01 reference antenna and 02 calibration receive antennas. The reference antenna and calibration receive antennas are distant from each other in the near-field region as shown in Figure 7. The reference antenna is aligned toward the middle of the two antennas to be calibrated. The phased array calibration process is described as follows: we are using a reference antenna to transmit the calibration signal. Then, digitizing the signal received from the 02 receiving antennas using the AD9361 card. The signal from the AD9361 card is transferred to the ZC706 card to determine phase shift on the laptop when using REVmax, REVmin methods, and non-calibration. Further, the entire calibration system was controlled through the designed a graphical user interface as shown in Figure 9.

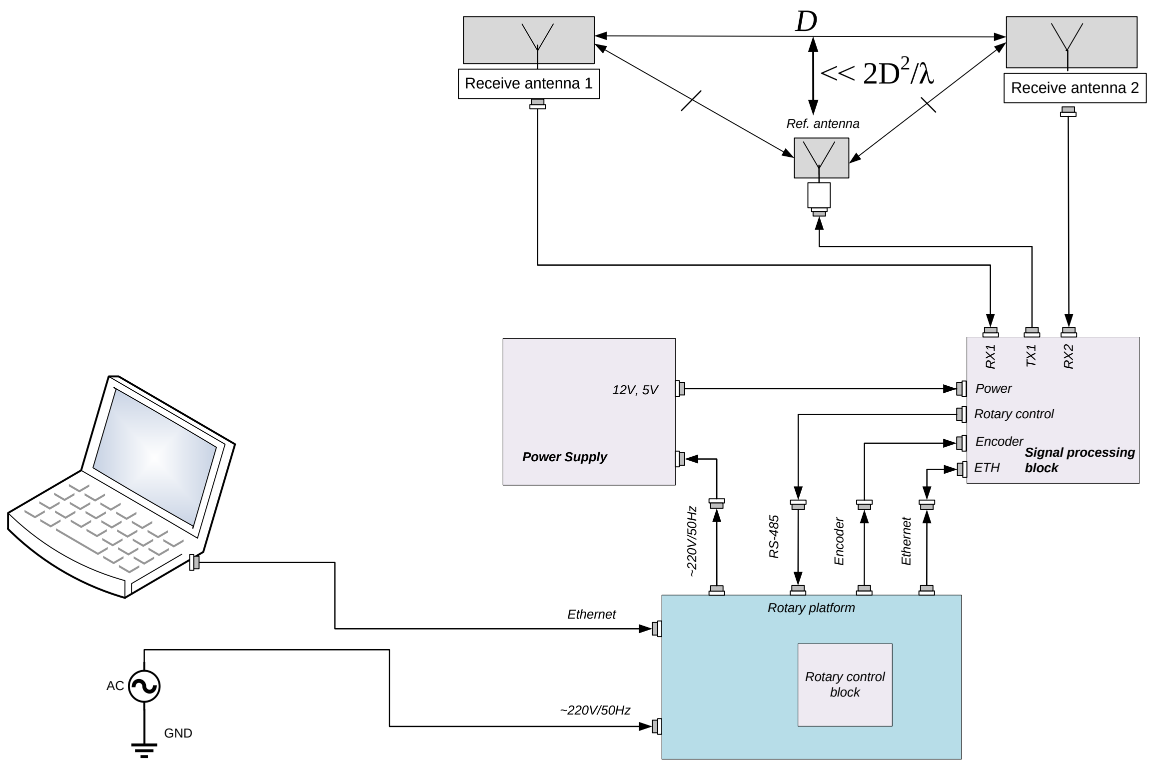


Figure 7. Calibration system diagram for determining the transmission characteristics S_{21} when using REVmax, REVmin, and non-calibration

Subsequently, let us set the following initial parameter values: the distance between two calibration receives antennas $D = 0.625\lambda$; the distance between the PAA under calibration and the reference antenna was 0.07 m, which satisfied the near-field criteria at 3 GHz. Figure 10 shows the outcomes of the proposed method in comparison with the traditional REV method. It is noteworthy that the REVmax approach could also be implemented by the proposed calibration system, identifying the maximum point instead. Based on the recorded data, the received magnitude dynamic range of the proposed and REV methods was approximately 35 dB and 1 dB, respectively. In addition, when the angle of incidence $\theta = 90^o$, the proposed calibration shows a maximum deviation of 5^0 while the REVmax method show a maximum deviation of 70^0.

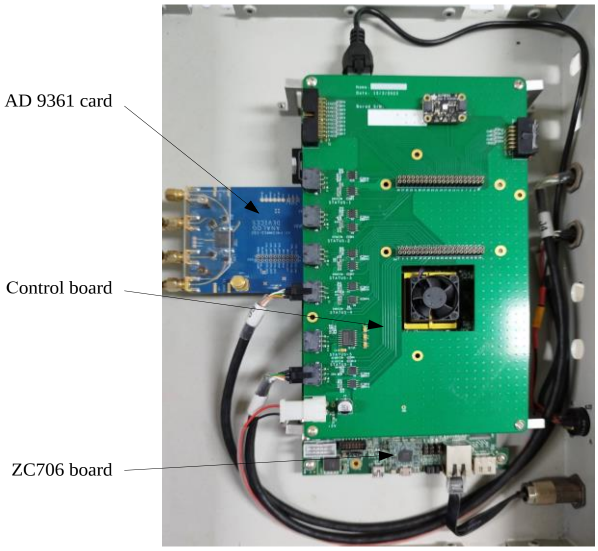


Figure 8. Signal processing block

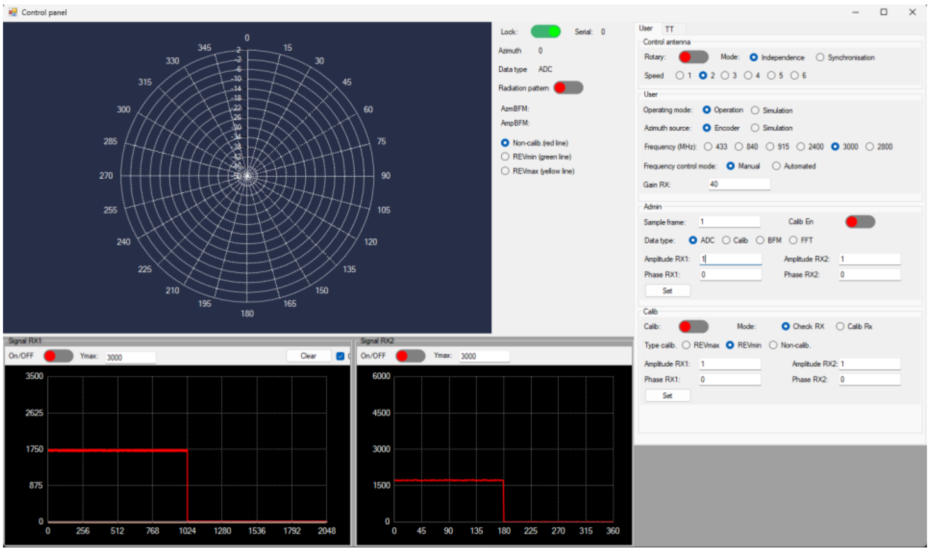


Figure 9. A software graphical user interface for automatic calibration control

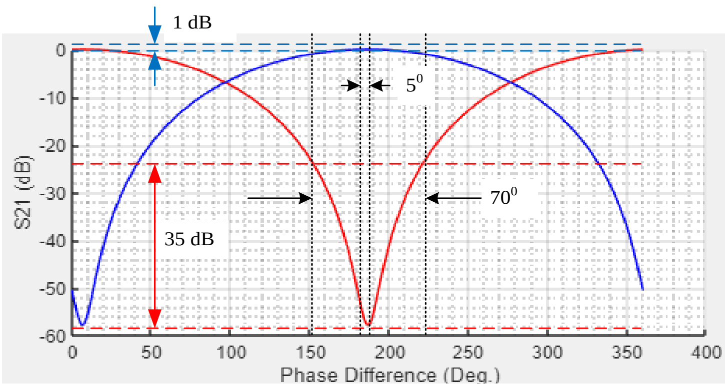


Figure 10. Mersurement results with each received power with regard to phase difference of antenna 1 and antenna 2 when using the REVmax and REVmin methods: Blue line – REVmax method; Red line – REVmin method

In the subsequent step, Figure 11 demonstrates the calibration system for drawing the radiation patterns of the proposed array after performing the phase shift of received signals by different methods. The system includes the following components: laptop with installed MATLAB 2022a; rotary control block and rotary platform; power supply 12V, 5V; the signal processing block, which is described in Figure 8, comprising AD9361 card, control board and a ZC706 Xilinx FPGA board; 02 calibration receive antennas and 01 transceiver antenna. The transceiver antenna and calibration antennas are distant from each other in the far-field region as shown in Figure 11. The transceiver antenna is aligned toward two calibration receive antennas. In the first step, we are using a transceiver antenna to transmit the signal. Then, digitizing the signal received from the 02 receiving antennas using the AD9361 card. The signal from the AD9361 card is transferred to the ZC706 card to draw the radiation pattern of the received signal on the laptop when using REVmax, REVmin methods, and non-calibration. Additionally, a graphical user interface for automated calibration control was developed using MATLAB as shown in Figure 9.

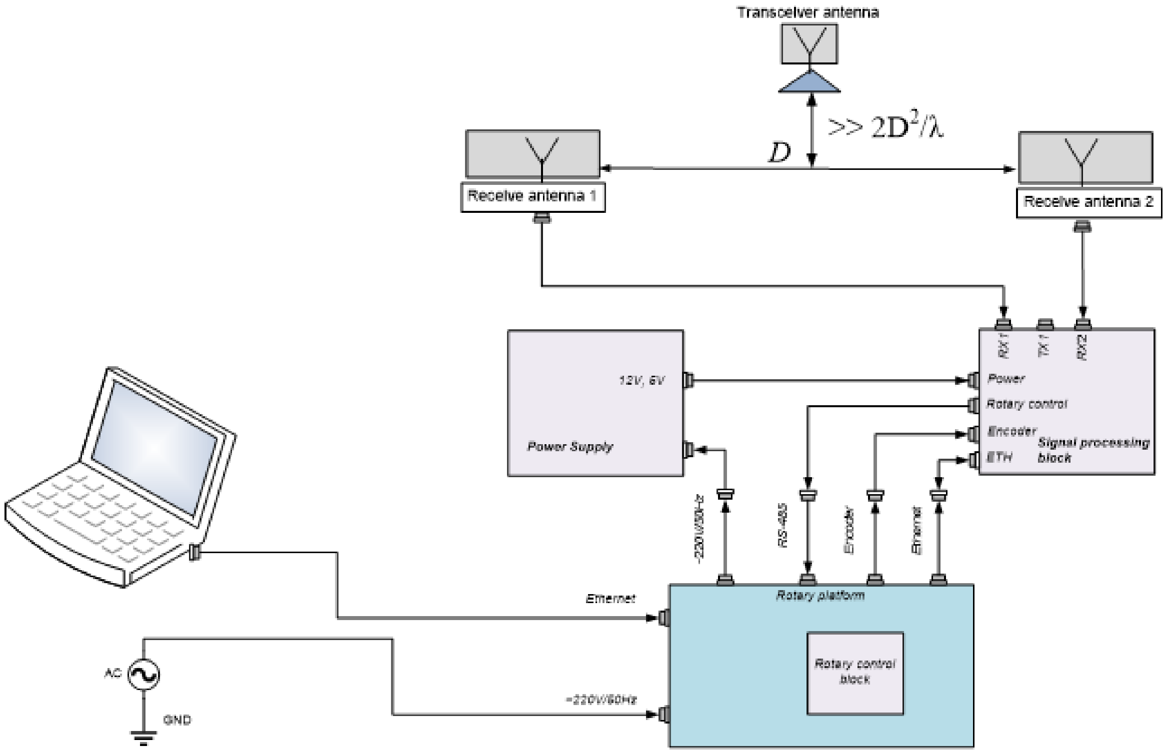
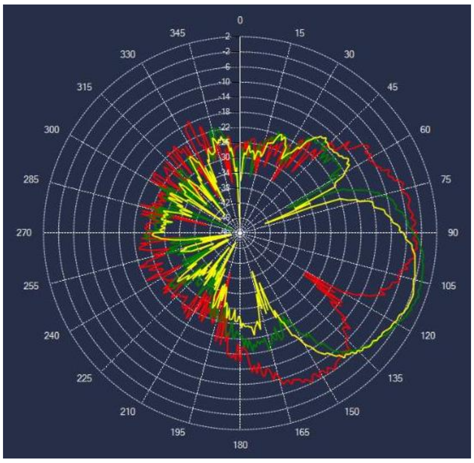
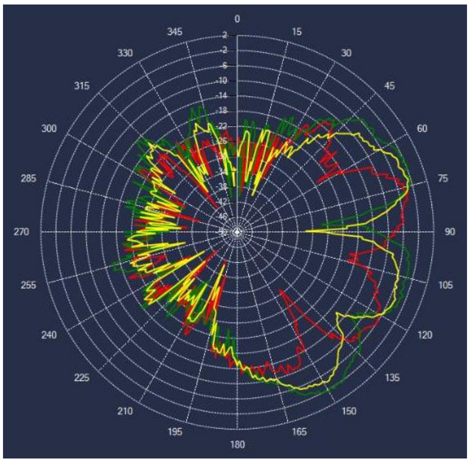


Figure 11. Calibration system diagram for drawing the radiation patterns after performing the phase shift of received signals by different methods

Figure 12 demonstrate the calibration results when using REVmax, REVmin methods, and non-calibration. Figures 12(a) and 12(b) show radiation pattern of the combined beam when using different calibration methods in the cases distance between elements of the array $D = 0{,}625\lambda$ and $D = 1{,}25\lambda$, respectively. Upon doubling the distance *D* between elements of the array, the peak and width of the side lobes also change. At that time, the REVmin method in PAA has better performance than the REV method. Table 1 show the measured peak gain in E-plane is improved by 8.4 … 8.8 dB and 3.7 … 4.1 dB, respectively, than without calibration and REVmax method. Different noise has a relatively large influence on the radiation pattern of the combined beam. The occurrence of these undesired phase shifts and amplitude attenuations can be attributed to a number of factors associated with RF hardware, including antennas, phase shifters, attenuators, amplifiers, dividers, combiners, switches, connectors, transmission lines, coaxial cables, and waveguides. It is crucial to emphasise that any RF component that is employed across all element channels cannot be the source of relative phase and amplitude shifts. The phase of the received signal is contingent upon not only the shift induced by the receiver channel but also the phase difference between the probe and local oscillator signal. However, REVmin method still ensures a better radiation pattern than REVmax method.



(a)



(b)

Figure 12. Radiation pattern of the combined beam in E-plane when using different calibration methods in the cases (a) $D = 0{,}625\lambda$ and (b) $D = 1{,}25\lambda$: non-calibration – red line; REVmax – yellow line; REVmin – green line

Table 1. The measured peak gain (dB) in the E-plane of the radiation pattern of the combined beam after calibration methods

Method	Number of measurements									
	1	2	3	4	5	6	7	8	9	10
Non-calib.	-9.8	-9.6	-9.5	-9.7	-9.8	-9.6	-9.7	-9.7	-9.6	-9.8
REVmax	-4.9	-4.8	-5.0	-4,1	-5.0	-4.9	-5.0	-5.1	-4.8	-4.9
REVmin	-1.0	-0.9	-1.1	-1.2	-1.0	-1.0	-0.9	-1.0	-1.1	-1.0

4. CONCLUSION

Phased array element excitation (both amplitude and phase) always deviates from the ideal values that would cause array performance degradation. It is therefore essential that such deviations are carefully calibrated and compensated to the greatest possible extent to ensure the accurate design of a practical phased array system. The paper proposes a new REV calibration method that can effectively improve both the accuracy and complexity of the system. The proposed method is distinguished from existing methods by using the minimum point finding method of the array factor. This method is based on a few straightforward mathematical operations and does not require any supplementary calibration components or additional hardware. Then, the proposed method was tested by implementing a phased array antenna calibration system consisting of two elements at a frequency of 3 GHz and compared with the conventional REV method. Experimental results show that the minimum point finding method provides higher accuracy than the maximum point finding method of the function AF_N when determining phase shift Υ_m. The proposed method showed a better detection range per phase change corresponding to a 35 dB higher resolution. To ascertain the reliability of the proposed system, a total of 10 trials were conducted. The deviation of the proposed system in each trial was 5^0, whereas the REV method exhibited a deviation of 70^0. The peak of the combined beam when using REVmin is higher than REVmax which is 3.7 ... 4.1 dB. REVmin still ensures a better radiation pattern than REVmax in relatively large external noise environments. Therefore, the proposed method can be considered an effective solution for large-scale phased array calibration systems at the production stage.

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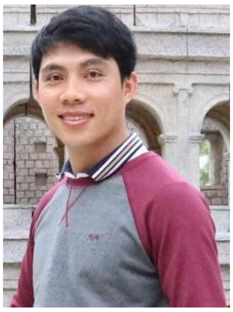

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