Fast Measurement Technique for Phased Array Calibration

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***Abstract*—A novel measurement method is proposed in order to measure the active electric fields of the individual antenna elements in a phased array antenna. Fast and accurate measurements can be realized by the proposed method because the electric fields of multiple elements can be obtained simultaneously and no phase measurements are required. Hence, it can be easily applied to the on-board diagnostics and re-calibration in the operating phased array antenna systems. In the first step with this method, the phases of multiple antenna elements are successively shifted with the specified phase intervals while the array power variations are measured. Next, the measured power variation is expanded into a Fourier series and the terms are rearranged to put them into the form of the rotating element electric field vector (REV) method. Finally, the REV solution is used to identify the electric fields of the individual elements. Additionally, a theoretical study is carried out on the accuracy of the proposed measurement method. Simple, closed-form equations have been successfully derived for the measurement errors and the calibration accuracy is theoretically estimated. The proposed measurement method is validated with experimental results and the measurement accuracy is compared with the theoretical prediction.**

***Index Terms*—Calibration, Fourier series, measurement, measurement errors, phased arrays.**

I. Introduction

A VARIETY OF measurement techniques have been proposed for phased array calibrations. In all cases, the objective is to obtain the complex electric fields (amplitude and phase) of the individual antenna elements and to compensate for the element-to-element variations. Unlike a single-element measurement, where the electric fields of the individual elements are determined with only a single element illuminated, the measurement techniques described in [1]–[6] measure the *in-situ* electric fields with the entire array radiating and include some error terms such as T/R module variations, feed-circuit variations, mutual coupling, and diffraction due to antenna structures etc.

One effective calibration procedure is the so-called the rotating element electric field vector (REV) method [1], in which power measurements are made to determine the electric fields of the individual elements [7]. Note that the REV procedure does not require any phase measurements. In particular, the sinusoidal array power variation is measured while the phase of a single element is successively shifted from 0 to 360 degrees. The complex electric field of the corresponding element can be obtained from three parameters in the measured power variation – the maximum power, the minimum power and the phase shift corresponding to the maximum power. Due to the simplicity of the measurement, the REV method has been generally applied to initial calibrations [8]–[11] and self-diagnostic systems [12], [13] for various phased array antennas. Other proposed applications of this technique include a phaseless near field measurement technique [14], and a beam-pointing technique [15]. However, since the measurements must be made as the phase of each element in the array is successively shifted from 0 to 360 degrees, the REV method requires a large number of measurements. Overcoming the large measurement times required for the REV method would allow for a fast and efficient measurement operation necessary for phased array calibrations.

Several other measurement techniques which are similar to the REV method but are faster and more efficient have been previously described [3]–[6]. In the toggling method [3], two array fields, where the phase of an element is switched to 0 degrees or 180 degrees, are measured and the electric field of the corresponding element can be obtained from the difference. In the multielement phase-toggle (MEP) method [4], the complex array field (not power but electric field amplitude and phase) variation is observed while the phases of multiple elements are simultaneously shifted with different intervals and the electric fields of the corresponding elements can be obtained by using an FFT for the measured field variation. In [5] and [6], the phase control with orthogonal code patterns is employed so that the electric fields of multiple elements can be measured simultaneously. These measurement techniques are considered to be faster and more efficient than the REV method, but they do require accurate phase measurements. Hence, it is not always easy to apply them for the operating phased array antenna systems.

In this paper, a novel measurement method is proposed to measure the active electric fields of the individual elements in a phased array antenna. Like the REV method, the proposed method requires no phase measurements, but by simultaneously measuring multiple elements, this method is faster than the REV method. The proposed method can be easily applied to the on-board diagnostics and re-calibration of the operating phased array antenna systems, where the accurate and stable phase measurements are sometimes difficult to obtain. For the first step in the proposed method, the phases of multiple elements are successively shifted with the different phase intervals while

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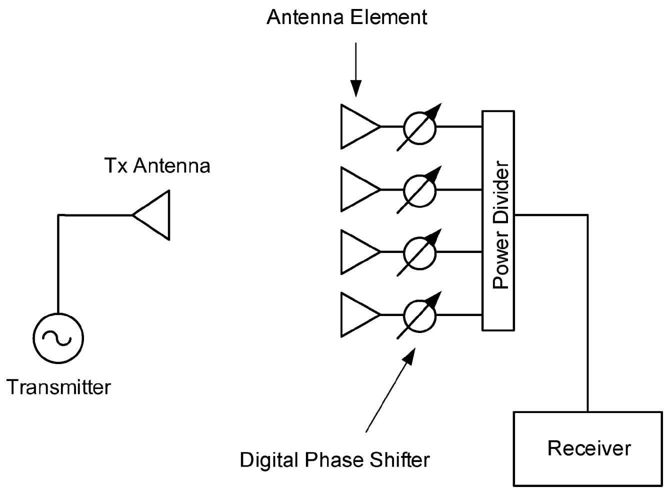

Fig. 1. Schematic measurement configuration for phased array calibration.

the total array power variation is measured. Although similar to the MEP method, it is important to note that this new method does not require any phase measurements. Next, the measured power variation is expanded into a Fourier series and after some rearrangement, the form of the expansion is found to be identical with the conventional REV method. Using the same techniques employed in the conventional REV method, the complex electric field of the corresponding elements can then be derived. Our proposed method is an extension of the conventional REV method, which can significantly reduce the measurement times to determine the complex electric fields of the individual elements in a phased array antenna.

However, the measurement error in the new method will increase as compared with the conventional REV method, i.e., the measurement time reduction is achieved at the expense of the increased measurement error. Therefore, the measurement error is theoretically clarified with a statistical analysis. Simple, closed-form equations are successfully derived to estimate the measurement accuracy.

Finally, the proposed measurement method is validated with some experiment results and it is confirmed that the measurement accuracy can be evaluated by the theoretical equations.

II. Measurement Theory

A. The Principle

In the proposed measurement method, some successive phase shifts are simultaneously carried out for multiple antenna elements. We will first derive a radiation power equation with the phase shifts applied to multiple elements. Fig. 1 shows a typical measurement configuration for a phased array calibration. Digital phase shifters are connected with all elements and the successive phase shifts are made with them. The array field is

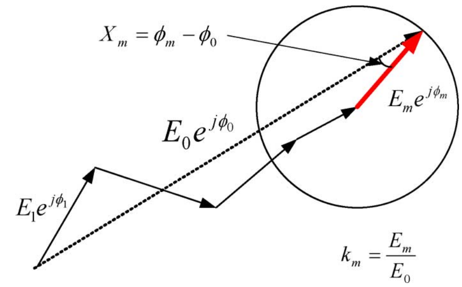

Fig. 2. Complex vector showing the array field is the vector sum of the electric field of the individual elements.

graphically displayed as a complex vector in Fig. 2 and it is just the vector sum of the electric field vectors of the individual elements. In Fig. 2, E_0 and ϕ_0 symbolize the amplitude and phase of the initial array field (i.e., before any element phase shifts are made). The amplitude and phase of the electric field due to the mth antenna element are symbolized by E_m and ϕ_m, respectively.

Now let us consider the array field where the phases of M elements are simultaneously shifted. The phase shift for the mth element can be expressed by $l_m\Delta\phi(m = 1\ldots M)$, where l_m is an unique integer (i.e., different for each m) and $\Delta\phi$ is the minimum phase shift of the digital phase shifters. The array field with these phase-shifted electric fields is given by

$$E = E_0 e^{j\phi_0} - \sum_{m=1}^{M} E_m e^{j\phi_m} + \sum_{m=1}^{M} E_m e^{j(\phi_m + l_m\Delta\phi)}. \quad (1)$$

Equation (1) shows an array field variation with the successive phase shifts in the proposed measurement method. Dividing (1) with the initial array field, we obtain

$$\begin{aligned}\hat{E} &= \frac{E}{E_0 e^{j\phi_0}}\\ &= 1 - \sum_{m=1}^{M} k_m \cos X_m + \sum_{m=1}^{M} k_m \cos(X_m + l_m\Delta\phi)\\ &\quad + j\left[-\sum_{m=1}^{M} k_m \sin X_m + \sum_{m=1}^{M} k_m \sin(X_m + l_m\Delta\phi)\right] \quad (2)\end{aligned}$$

$$k_m = \frac{E_m}{E_0} \qquad X_m = \phi_m - \phi_0 \quad (3)$$

where k_m and X_m are the electric field amplitude and phase of the mth element relative to the initial array field. The objective of the measurement is to uniquely determine k_m and X_m. From (2), the relative array power can be expressed in terms of the Fourier series. See (4), shown at the bottom of the page, where A is an average value and $XC_{mm'}$, $XS_{mm'}$, C_m, and S_m are Fourier series coefficients obtained by Fourier series expansion of a measured power variation. The detailed calculation of these parameters will be explained in the next subsection.

$$f = \left|\hat{E}\right|^2 = A + \sum_{m=1}^{M} \sum_{m'>m}^{M} \left[XC_{mm'} \cos(l_m - l_{m'})\Delta\phi + XS_{mm'} \sin(l_m - l_{m'})\Delta\phi\right] + \sum_{m=1}^{M} \left[C_m \cos l_m\Delta\phi + S_m \sin l_m\Delta\phi\right] \quad (4)$$

In (4), if we let $l_m = 0$ except when $m = n$, the electric field of the nth element can be obtained. In this case, the array power is expressed as

$$f = A + {\sum_{m=1}^{M}}' {\sum_{m}^{M}}' > m^M XC_{mm'} + {\sum_{m=1}^{B}}' C_m$$
$$+\left[C_n + {\sum_{m=1}^{B}}' XC_{nm}\right] \cos l_n \Delta\phi + \left[S_n + {\sum_{m=1}^{B}}' XS_{nm}\right] \sin l_n \Delta\phi \tag{5}$$

where $\sum'$ represents the summation over m excluding the case $m = n$.

Note that (5) must also represent the array power variation in the conventional REV method as all of the l_m's are zero except $m = n$ (i.e., only one element is having its phase shift). As shown in Appendix I, the array power variation in the conventional REV method can be expressed as

$$f_{i,n} = \frac{\alpha_n}{2} + c_n \cos l_n \Delta\phi + s_n \sin l_n \Delta\phi. \tag{6}$$

Therefore, our measurement method leads mathematically to the conventional REV method with the following identifications:

$$\alpha_n = 2\left[A + {\sum_{m=1}^{M}}' {\sum_{m'>m}^{M}}' XC_{mm'} + {\sum_{m=1}^{M}}' C_m\right] \tag{7}$$

$$c_n = C_n + \sum_{m=1}^{M'} XC_{nm} \tag{8}$$

$$s_n = S_n + \sum_{m=1}^{M'} XS_{nm}. \tag{9}$$

According to the expression above, the electric field amplitude k_n and phase X_n of the nth element can be obtained as

$$k_n = \frac{\Gamma_n}{\sqrt{1 + 2\Gamma_n \cos \Phi_{n,0} + \Gamma_n^2}} \tag{10}$$

$$\tan X_n = \frac{\sin \Phi_{n,0}}{\cos \Phi_{n,0} + \Gamma_n} \tag{11}$$

where the parameters on the right-hand sides are defined in Appendix I.

Note that the total power measurement times in the proposed method will be $1/M$ times less than the conventional REV method but the total phase-up times for each element are the same. If time for a phase-up is longer than the one for a power measurement, the measurement time reduction cannot be attained by the proposed method. However, time for a power measurement will be significantly longer than a phase control because the phase controls can be also carried out in parallel but the power measurements must be made in series. In a typical phased array system, measurement time will be in the order of milliseconds (ms) but phase control time will be in the order of microseconds (μs). Hence, the measurement time will be dominant. To reduce the number of measurements in the proposed method will lead to the significant time saving in the phased array calibrations.

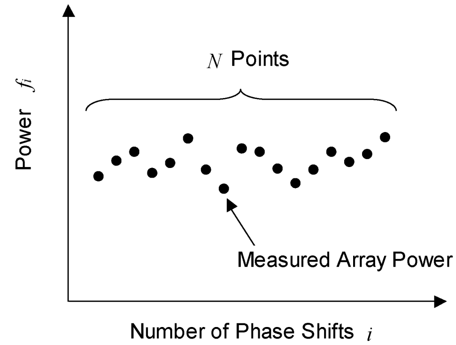

Fig. 3. Example of an array power variation measured with the successive phase shifts for multiple elements.

B. Fourier Coefficients

Equation (4) implies that the array power variation consists of the l_mth and $(l_m - l_{m'})$th order components $(m, m' = 1 \ldots M)$ of $\cos \Delta\phi$ or $\sin \Delta\phi$. The coefficients in (4) can be obtained by a Fourier series expansion of a measured array power variation.

In the proposed measurement method, the phases of multiple elements are successively shifted with the constant phase intervals $l_m \Delta\phi$ $(m = 1 \ldots M)$. For example, let us assume that the profile of a measured array power variation is as shown in Fig. 3, where the abscissa is the number of successive phase shifts and the ordinate is the corresponding array power. By expanding this measured variation into a Fourier series, the coefficients in (4) are found to be

$$XC_{mm'} = \frac{2}{N} \sum_{i=1}^{N} f_i \cos\left\{i\left(l_m - l_{m'}\right)\Delta\phi\right\} \tag{12}$$

$$XS_{mm'} = \frac{2}{N} \sum_{i=1}^{N} f_i \sin\left\{i\left(l_m - l_{m'}\right)\Delta\phi\right\} \tag{13}$$

$$C_m = \frac{2}{N} \sum_{i=1}^{N} f_i \cos\left\{i\, l_m \Delta\phi\right\} \tag{14}$$

$$S_m = \frac{2}{N} \sum_{i=1}^{N} f_i \sin\left\{i\, l_m \Delta\phi\right\} \tag{15}$$

$$A = \frac{1}{N} \sum_{i=1}^{N} f_i \tag{16}$$

where N is the maximum number of the successive phase shifts, which is set to the maximum number of phase states of the digital phase shifters. For example, N is equal to 2^{Nb} for an Nb-bit digital phase shifter. As an example, a 5-bit phase shifter will have $N = 32$ phase states.

C. Phase Shift Intervals

The phase shift intervals for each element cannot be determined independently. Equation (4) shows that the array power consists of the l_mth and $(l_m - l_{m'})$th order components $(m, m' = 1 \ldots M)$. To obtain the complex electric fields of the corresponding elements, these components must be completely extracted by Fourier series expansion and must be orthogonal to each other. This is the first necessary condition for the phase shift intervals in the proposed measurement method.

TABLE I
EXAMPLE OF THE AVAILABLE FOURIER SERIES TERMS FOR 5-BIT DIGITAL PHASE SHIFTER

m	m'	l_m	$l_{m'}$	$l_m - l_{m'}$
1	N/A	1	N/A	N/A
2	1	5	1	4
3	1	7	1	6
	2		5	2

TABLE II
EXAMPLE OF THE AVAILABLE FOURIER SERIES TERMS FOR 4-BIT DIGITAL PHASE SHIFTER

m	m'	l_m	$l_{m'}$	$l_m - l_{m'}$
1	N/A	1	N/A	N/A
2	1	5	1	4

From a statistical point of view, the smallest final error will be attained if all phase states of a digital phase shifter are utilized [7]. Repeatedly using some phase states will increase the measurement error due to the low correlation among some measured array powers. Therefore, the maximum number of the digital phase states and the l_m should not contain any common factors. This is the second condition that is desirable for more accurate measurements

The above two conditions should be satisfied in order to maximize the measurement accuracy. For a 5-bit digital phase shifter, the number of simultaneously measured elements should be less than or equal to three and the phase shift intervals can be selected for $l_m = 1$, 3, 7, or $l_m = 1$, 5, 7. For example, the available terms for $l_m = 1$, 5, 7 are listed in Table I. For a 4-bit digital phase shifter, the number of simultaneously measured elements should be less than or equal to two and the phase shift intervals can be selected for $l_m = 1$, 3, or $l_m = 1$, 5. For example, the available terms for $l_m = 1$, 5 are listed in Table II.

III. MEASUREMENT ACCURACY

In this section, the measurement accuracy of the proposed measurement method will be theoretically discussed.

A. Measurement Error Factors and Assumptions

The following items can be considered as the measurement error factors in the proposed method.

1) Complex electric field variation due to the digital phase shifter connected with each antenna element;
2) Antenna noise figure;
3) Receiver noise figure;
4) Other unexpected and impulsive noise.

Item 1), the variation of the digital phase shifter, is the primary error factor because it is an essential and reappearing error. Items 2) and 3) can be reduced by appropriate setting of the receiving dynamic range or by averaging. Item 4) also includes the thermal drift etc but they are neglected in this study. The detailed discussion of their effects is out of the scope in this paper. Hence, only the error factor in item 1) is discussed in this paper.

In the theoretical study of the measurement accuracy, the following assumptions are introduced [7], which are almost the same as in the statistical field analysis with random errors [16].

A) Complex electric field variations, i.e., the amplitude and phase variations are known for each antenna element;
B) Amplitude and phase variations for each antenna element are mutually independent random errors, which follow Gaussian distributions. Their means are zero and the standard deviations are given by amplitude standard deviation: 8.68 δ [dB] and phase standard deviation: Φ [rad], where δ is the standard deviation in volts;
C) Amplitude variations are of the same order as the phase variations;
D) The array field is sufficiently larger than the electric field variation of each antenna element;
E) The array field is sufficiently larger than the electric fields of all antenna elements.

Generally speaking, the maximum electric field variation of each antenna element will be specified in phased array systems because they cause gain reduction, sidelobe degradation, beam pointing errors, etc [16]. Therefore, the assumption A) is acceptable and the variation will be specified with the standard deviations as given in the assumption B). The assumption B) is not strictly true and the amplitude and phase errors depend on one another in general. It is introduced to simplify the statistical analysis. However, if the dependence is not so great, this assumption can be acceptable. In the next section, it will be found that this assumption is supported by the experiment results and the simplified analysis is also valid. Also, the assumption C) is not completely true. But if the amplitude and phase errors are not so large, this can be also acceptable. This assumption will be supported by the measured amplitude and phase variations of digital phase shifters. The assumption D) is acceptable, where the first order approximation is effective. The assumption E) is required to determine a unique solution in the conventional REV method [1].

B. Array Power Error Due to the Electric Field Variations of the Individual Elements

Under the above assumptions, the probability density can be derived for the array power with some electric field variations in the measured elements. When the electric fields of the individual elements have some amplitude and phase variations, the electric field of the mth element in (2) can be replaced as follows:

$$k_m \rightarrow k_m(1+\Delta_m) \tag{17}$$

$$l_m\Delta\phi \rightarrow l_m\Delta\phi + \Delta\Phi_m \tag{18}$$

where Δ_m and $\Delta\Phi_m$ is the amplitude and phase variations, respectively. Their standard deviations are given in the assumption B). After shifting the phase reference of (2) as described in [7], we can obtain the first approximation for an array field with some electric field variations as follows:

$$\hat{E} \approx \left(\hat{E}_r + A\right) + j\left(\hat{E}_i + B\right) \tag{19}$$

$$\hat{E}_r = 1 + \sum_{m=1}^{M}\left[-k_m \cos X_m + k_m \cos(X_m + l_m\Delta\phi)\right] \tag{20}$$

$$\hat{E}_i = \sum_{m=1}^{M}\left[-k_m \sin X_m + k_m \sin(X_m + l_m\Delta\phi)\right] \tag{21}$$

$$A=\sum_{m=1}^{M}[k_m\Delta_m\cos(X_m+l_m\Delta\phi)-k_m\Delta\Phi_m\sin(X_m+l_m\Delta\phi)] \tag{22}$$

$$B=\sum_{m=1}^{M}[k_m\Delta_m\sin(X_m+l_m\Delta\phi)+k_m\Delta\Phi_m\cos(X_m+l_m\Delta\phi)] \tag{23}$$

where $\hat{E}_r$ and $\hat{E}_i$ are the real and imaginary parts of the array field without any electric field variations. The A and B are the real and imaginary parts of the variation field components. From (19), the probability density can be derived for the array field amplitude as follows [7]:

$$P(\rho)=\frac{\rho}{\sigma^2}e^{-(1/2\sigma^2)\{\rho^2+f_0\}}I_0\left[\frac{\rho\sqrt{f_0}}{\sigma^2}\right] \tag{24}$$

$$\sigma^2=\frac{\delta^2+\Phi^2}{2}\sum_{m=1}^{M}k_m^2 \tag{25}$$

where ρ is the array field amplitude, $I_0[z]$ is the 0th order Inflected Bessel function and f_0 is the array power without any electric field variations. The probability density leads to Ricean distribution, which is similar with the one of the radiation field with random errors [17], [18].

From (24), we can obtain the probability density for array power $f=\rho^2$ as follows [6]:

$$P(f)=\frac{1}{2\sigma^2}e^{-(1/2\sigma^2)\{f+f_0\}}I_0\left[\frac{\sqrt{ff_0}}{\sigma^2}\right]. \tag{26}$$

Therefore, the average f_{average} and the standard deviation σ_f of the array power with some electric field variations of the individual elements are approximately given by

$$f_{\text{average}}\approx f_0 \tag{27}$$

$$\sigma_f^2\approx 4\sigma^2 f_0. \tag{28}$$

According to (28), the standard deviation of the array power can be obtained from the ideal array power without any variations, the electric field amplitudes of the measured elements, and the standard deviations of some electric field variations. In the proposed method, σ given by (25) is greater than the conventional REV method.

C. Measurement Accuracy for Electric Field Amplitude

The electric field amplitude k_n derived by (10) will contain some errors because the array power have some errors whose standard deviation is given by (28). Considering the assumption E), the electric field amplitude of the nth elements contains the following measurement error [7] shown in (29)–(31) at the bottom of the page, where Δk_n is the amplitude measurement error for the nth element, Δf_i is the array power error whose standard deviation is given by (28), and the other parameters are defined in Appendix I.

Although (29) is the same as the conventional REV method [7], α_n, c_n and s_n are given by (7)–(9) in the proposed method. Therefore, (32) can be obtained, and is shown at the bottom of the page.

From (32), the standard deviation σ_k of the measured element amplitude is given by (33), shown at the bottom of the next page.

Since $\Gamma_n \ll 1$, i.e., under the assumption D), we obtain the following equations from the relationships described in Appendix– II

$$-Q\frac{\partial P}{\partial\alpha_n}+P\frac{\partial Q}{\partial\alpha_n}\approx 0 \tag{34}$$

$$-Q\frac{\partial P}{\partial c_n}+P\frac{\partial Q}{\partial c_n}\approx \frac{\cos\Phi_{n,0}}{N} \tag{35}$$

$$-Q\frac{\partial P}{\partial s_n}+P\frac{\partial Q}{\partial s_n}\approx -\frac{\sin\Phi_{n,0}}{N}. \tag{36}$$

If the amplitudes of all elements are assumed to be almost the same, σ, which is given by (25), is approximated as follows:

$$\sigma^2=\frac{\delta^2+\Phi^2}{2}\sum_{m=1}^{M}k_m^2\approx\frac{\delta^2+\Phi^2}{2}M\,k_n^2. \tag{37}$$

$$\Delta k_n=\frac{1}{k_nP^2}\sum_{i=1}^{N}\left[-Q\left\{\frac{\partial P}{\partial\alpha_n}\frac{\partial\alpha_n}{\partial f_i}+\frac{\partial P}{\partial c_n}\frac{\partial c_n}{\partial f_i}+\frac{\partial P}{\partial s_n}\frac{\partial s_n}{\partial f_i}\right\}+P\left\{\frac{\partial Q}{\partial\alpha_n}\frac{\partial\alpha_n}{\partial f_i}+\frac{\partial Q}{\partial c_n}\frac{\partial c_n}{\partial f_i}+\frac{\partial Q}{\partial s_n}\frac{\partial s_n}{\partial f_i}\right\}\right]\Delta f_i \tag{29}$$

$$P=\sqrt{1+2\Gamma_n\cos\Phi_{n,0}+\Gamma_n^2} \tag{30}$$

$$Q=\Gamma_n \tag{31}$$

$$\begin{aligned}\Delta k_n=\frac{1}{k_nP^2}{\sum_{i=1}^{N}}{}'\Bigg[&\left(-Q\frac{\partial P}{\partial\alpha_n}+P\frac{\partial Q}{\partial\alpha_n}\right)\times\left\{1+2{\sum_{m=1}^{M}}{}'{\sum_{m'>m}^{M}}{}'\cos(l_m-l_{m'})i\Delta\phi+2{\sum_{m=1}^{M}}{}'\cos l_m i\Delta\phi\right\}\\&+\left(-Q\frac{\partial P}{\partial c_n}+P\frac{\partial Q}{\partial c_n}\right)\left\{\cos l_n i\Delta\phi+{\sum_{m=1}^{M}}{}'\cos(l_n-l_m)i\Delta\phi\right\}\\&+\left(-Q\frac{\partial P}{\partial s_n}+P\frac{\partial Q}{\partial s_n}\right)\left\{\sin l_n i\Delta\phi+{\sum_{m=1}^{M}}{}'\sin(l_n-l_m)i\Delta\phi\right\}\Bigg]\Delta f_i.\end{aligned} \tag{32}$$

After substituting (34)–(37) into (33), then from the assumption D), the standard deviation σ_k can be expressed as

$$\sigma_k^2 \approx \frac{M^2}{N}(\delta^2 + \Phi^2). \tag{38}$$

Converting (38) into dB, the standard deviation σ_k results in:

$$\sigma_k \approx 8.68M\sqrt{\frac{\delta^2+\Phi^2}{N}} \quad [\text{dB}]. \tag{39}$$

Equation (39) implies the standard deviation for the amplitude error of the electric field measured by the proposed method. For $M = 1$, (39) shows the standard deviation for the conventional REV method, which corresponds with the result in [7]. It is theoretically found that the amplitude error in the proposed method is M times as large as the one in the conventional REV method.

D. Measurement Accuracy for Electric Field Phase

The electric field phase derived by (11) will also contain some errors. Using the assumption E), the electric field phase contains the following measurement error [7], see (40)–(42) at the bottom of the page.

By substituting (7)–(9) and (12)–(16) into (40), the standard deviation σ_X of the derived element phase is given by (43) at the bottom of the page.

Since $\Gamma_n \ll 1$, i.e., from the assumption D), we obtain the following equations from the relationships described in Appendix II

$$-V\frac{\partial U}{\partial \alpha_n} + U\frac{\partial V}{\partial \alpha_n} \approx 0 \tag{44}$$

$$-V\frac{\partial U}{\partial c_n} + U\frac{\partial V}{\partial c_n} \approx -\frac{\sin\Phi_{n,0}}{\sqrt{c_n^2+s_n^2}} = -\frac{\sin\Phi_{n,0}}{k_n N Y_n} \tag{45}$$

$$-V\frac{\partial U}{\partial s_n} + U\frac{\partial V}{\partial s_n} \approx -\frac{\cos\Phi_{n,0}}{\sqrt{c_n^2+s_n^2}} = -\frac{\cos\Phi_{n,0}}{k_n N Y_n}. \tag{46}$$

Furthermore, if we assume $\Gamma_n \ll 1$, then

$$(U^2+V^2)^2 \approx 1 \tag{47}$$

$$Y_n^2 \approx 1. \tag{48}$$

By substituting (44)–(48) into (43) and using the assumption D), the standard deviation σ_X can be obtained as

$$\sigma_X^2 \approx \frac{M^2}{N}(\delta^2 + \Phi^2). \tag{49}$$

$$\begin{aligned}\sigma_k^2 = \frac{1}{k_n^2 P^4}\sum_{i=1}^{N}{}' \Bigg[&\left(-Q\frac{\partial P}{\partial \alpha_n} + P\frac{\partial Q}{\partial \alpha_n}\right) \times \left\{1 + 2\sum_{m=1}^{M}{}'\sum_{m'>m}^{M}{}' \cos(l_m - l_{m'})i\Delta\phi + 2\sum_{m=1}^{M}{}' \cos l_m i\Delta\phi\right\}\\
&+\left(-Q\frac{\partial P}{\partial c_n} + P\frac{\partial Q}{\partial c_n}\right)\left\{\cos l_n i\Delta\phi + \sum_{m=1}^{M}{}' \cos(l_n - l_m)i\Delta\phi\right\}\\
&+\left(-Q\frac{\partial P}{\partial s_n} + P\frac{\partial Q}{\partial s_n}\right)\left\{\sin l_n i\Delta\phi + \sum_{m=1}^{M}{}' \sin(l_n - l_m)i\Delta\phi\right\}\Bigg]^2 \sigma_f^2.\end{aligned} \tag{33}$$

$$\Delta X_n = \frac{1}{U^2+V^2}\sum_{i=1}^{N}\left[-V\left\{\frac{\partial U}{\partial \alpha_n}\frac{\partial \alpha_n}{\partial f_i} + \frac{\partial U}{\partial c_n}\frac{\partial c_n}{\partial f_i} + \frac{\partial U}{\partial s_n}\frac{\partial s_n}{\partial f_i}\right\} + U\left\{\frac{\partial V}{\partial \alpha_n}\frac{\partial \alpha_n}{\partial f_i} + \frac{\partial V}{\partial c_n}\frac{\partial c_n}{\partial f_i} + \frac{\partial V}{\partial s_n}\frac{\partial s_n}{\partial f_i}\right\}\right]\Delta f_i \tag{40}$$

$$U = \cos\Phi_{n,0} + \Gamma_n \tag{41}$$

$$V = \sin\Phi_{m,0}. \tag{42}$$

$$\begin{aligned}\sigma_X^2 = \frac{1}{(U^2+V^2)^2}\sum_{i=1}^{N}{}' \Bigg[&\left(-V\frac{\partial U}{\partial \alpha_n} + U\frac{\partial V}{\partial \alpha_n}\right) \times \left\{1 + 2\sum_{m=1}^{M}{}'\sum_{m'>m}^{M}{}' \cos(\Phi_{m,i} - \Phi_{m',i}) + 2\sum_{m=1}^{M}{}' \cos\Phi_{m,i}\right\}\\
&+\left(-V\frac{\partial U}{\partial c_n} + U\frac{\partial V}{\partial c_n}\right)\left\{\cos\Phi_{n,i} + \sum_{m=1}^{M}{}' \cos(\Phi_{n,i} - \Phi_{m,i})\right\}\\
&+\left(-V\frac{\partial U}{\partial s_n} + U\frac{\partial V}{\partial s_n}\right)\left\{\sin\Phi_{n,i} + \sum_{m=1}^{M}{}' \sin(\Phi_{n,i} - \Phi_{m,i})\right\}\Bigg]^2 \sigma_f^2.\end{aligned} \tag{43}$$

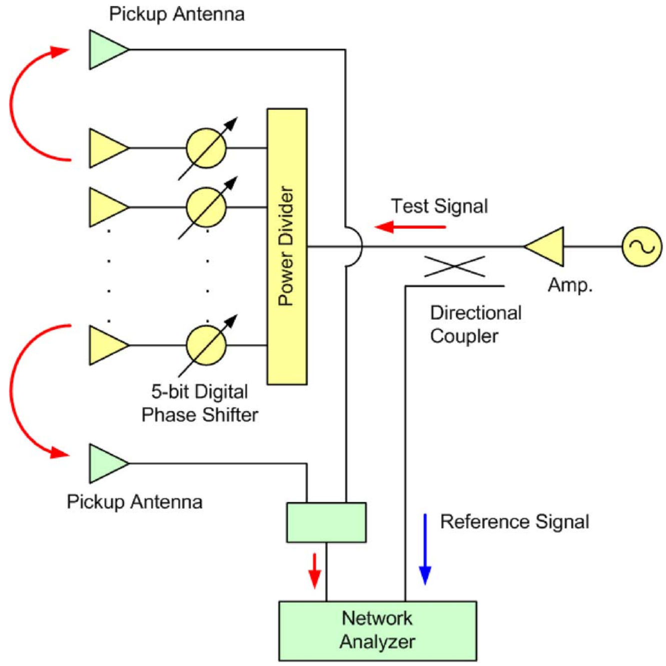

Fig. 4. Schematic diagram of the measured phased array antenna system.

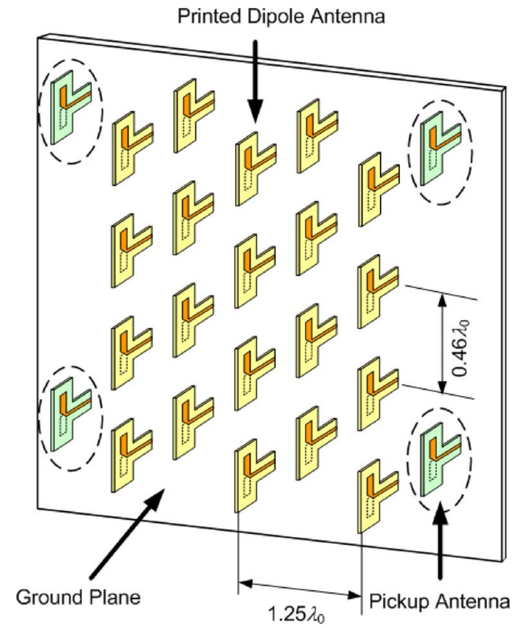

Fig. 5. Antenna aperture configuration under testing.

Converting (49) from radians into degrees, the standard deviation σ_X results in

$$\sigma_X \approx \frac{180M}{\pi}\sqrt{\frac{\delta^2+\Phi^2}{N}} \quad [\text{deg.}]. \tag{50}$$

Equation (50) implies the standard deviation for the phase error of the electric field measured by the proposed method. For $M=1$, (50) shows the standard deviation for the conventional REV method, which corresponds with the result in [7]. This is the same as the amplitude and it is theoretically found that phase error in the proposed method is M times as large as the one in the conventional REV method.

E. Discussion

According to the above theoretical study, the measurement error in the proposed method will increase as compared with the conventional REV method. For example, in the case of measuring M elements simultaneously, the measurement error will become M times as large as the conventional REV method. Therefore, a trade-off between the measurement time reduction and the measurement error increase can be made. It will depend on the system requirement whether this trade is allowable. However, the trade-off can be quantitatively discussed with the above theory.

IV. Experiment Results

The proposed measurement method is validated by some experiment results. Also, the measurement accuracies are evaluated for the electric fields of all antenna elements.

A. Measurement Configuration

Fig. 4 shows the measurement configuration. Antenna under testing (AUT) is a phased array antenna consisting of 20 printed dipole antenna elements as shown in Fig. 5. 5-bit digital phase shifters are connected with all antenna elements. Pick-up antennas are also arranged on the same aperture as AUT. This configuration is supposed to be a self-diagnostic system for the on-board calibration [12], [13]. The electric field of the individual elements can be obtained from the array power variation measured by the pick-up antennas.

B. Reference Electric Fields of the Individual Elements

In order to validate the proposed method, the reference electric fields are required for all elements. They are directly measured with a vector network analyzer (VNA) for element by element. In the direct measurement, only the objective antenna element is excited and the others are terminated with dummy loads. However, the measured electric fields have some errors because the digital phase shifters have some transmitting variations. Also, the transmitting variation at a specified phase state is different from the others. Hence, the electric fields measured for all phase state must be averaged as follows:

$$E_{m,ref} = \frac{1}{N}\sum_{i=1}^{N} E_{m,i}e^{+ji\Delta\phi} \tag{51}$$

where $E_{m,ref}$ is the reference electric field (complex), $E_{m,i}$ is the directly-measured electric field (complex) with the ith successive phase delay, N is the maximum number of the phase states, and $\Delta\phi$ is the minimum phase shift.

The averaged electric fields will be referred to validate the proposed measurement method and estimate the measurement accuracy.

C. Measured Array Power Variation and Fourier Expansions

Since 5-bit digital phase shifters are connected, the three elements can be simultaneously measured by the proposed method.

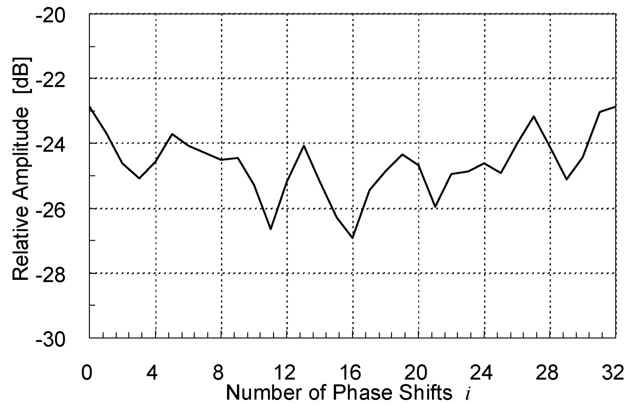

Fig. 6. Example of an array power variation with the successive phase shifts for three elements.

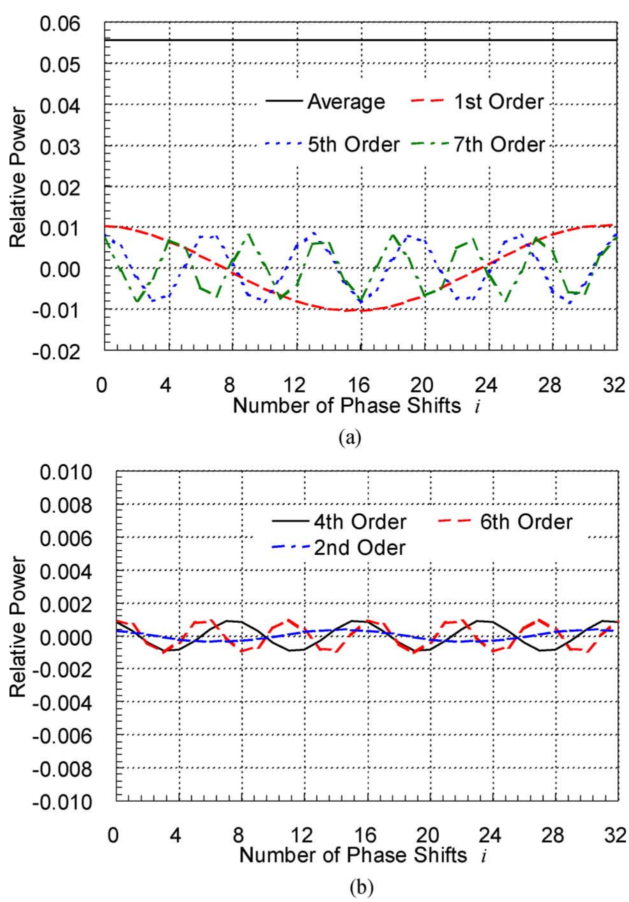

Fig. 7. Fourier series expansions of the measured array power variation in Fig. 6. (a) Average and dominant components. (b) Higher order components.

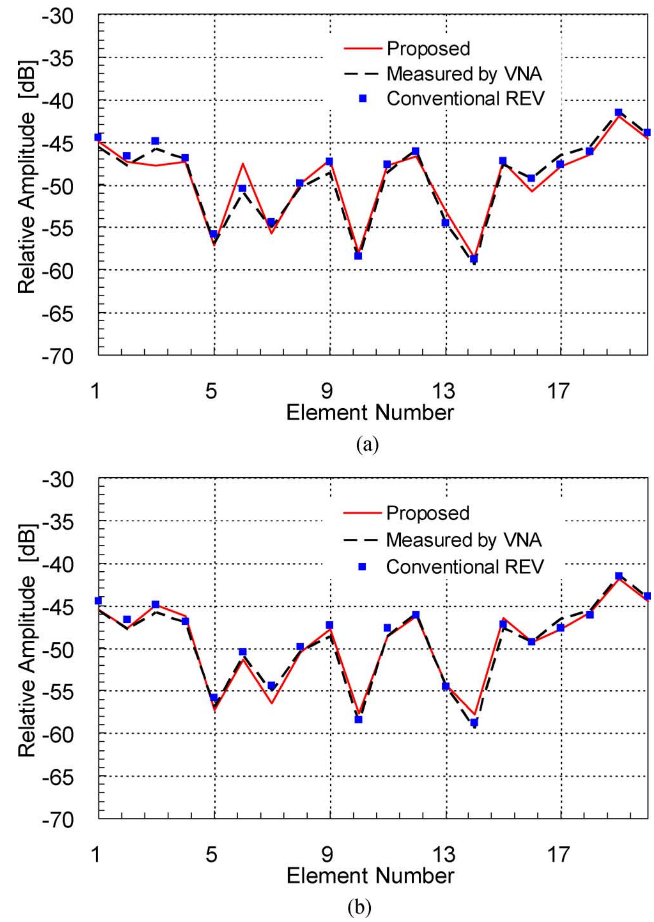

Fig. 8. Measured electric field amplitudes. (a) Three element phases are simultaneously shifted with the intervals of $1\Delta\phi$, $5\Delta\phi$, $7\Delta\phi$. (b) Two element phases are simultaneously shifted with the intervals of $1\Delta\phi$, $5\Delta\phi$.

And the successive phase intervals, $1\Delta\phi, 5\Delta\phi, 7\Delta\phi$, can be selected for three antenna elements, where $\Delta\phi$ is the minimum phase shift of the connected digital phase shifters, i.e., 11.25 degrees. Fig. 6 shows an example of an array power variation measured with the above successive phase shifts. In Fig. 6, the abscissa is the number of the successive phase shifts and the ordinate is the corresponding array power.

In the proposed method, Fourier series coefficients of the measured array power variation (Fig. 6) must be calculated not only for the 1st, 5th, 7th orders but also for the 2nd, 4th, 6th ones as shown in Table I. The Fourier series components obtained from Fig. 6 are shown in Fig. 7. These Fourier series coefficients give the left-hand side of (12)–(16). The electric field amplitudes and phases of the corresponding elements can be derived by (10) and (11).

D. Measured Electric Fields of the Individual Elements

Figs. 8 and 9 show the measured electric field amplitudes and phases of all antenna elements. In this paper, two kinds of measurements were carried out. In one measurement, three antenna elements are simultaneously measured and the successive phase shift intervals, $1\Delta\phi$, $5\Delta\phi$, and $7\Delta\phi$, are selected for them. In this case, one element was measured twice because the total element number 20 is not divisible by three. The electric field of the corresponding element was obtained by averaging the two measured results. In the other measurement, two antenna elements are simultaneously measured and the successive phase shift intervals, $1\Delta\phi$ and $5\Delta\phi$, are selected for them. In Figs. 8 and 9, the directly measured electric fields are referred for comparisons. Both are in good agreements and our proposed measurement method is experimentally validated. Also, the comparisons with the conventional REV method are shown in these figures and the measurement accuracies will be discussed later.

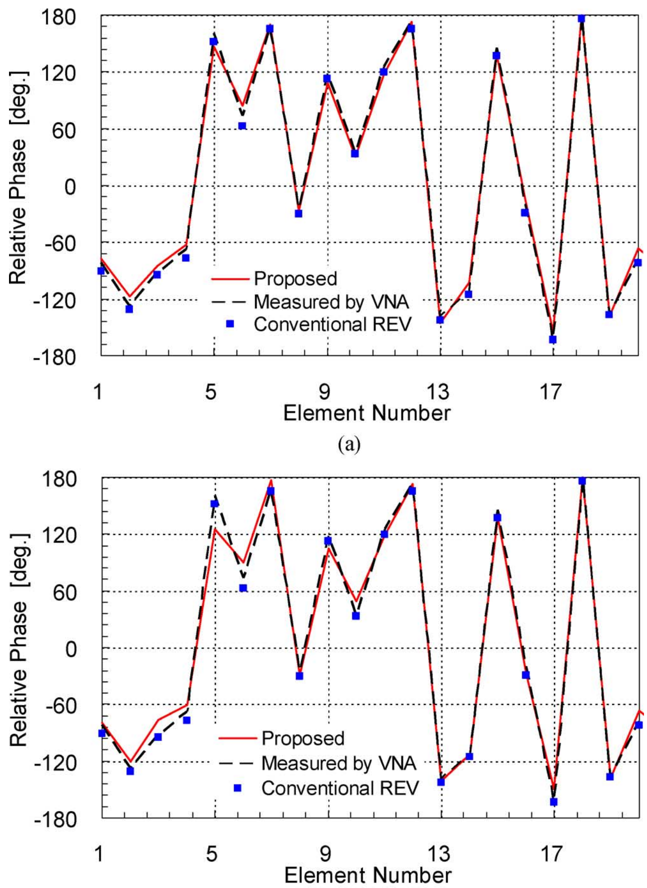

Fig. 9. Measured electric field phases. (a) Three element phases are simultaneously shifted with the intervals of $1\Delta\phi, 5\Delta\phi, 7\Delta\phi$. (b) Two element phases are simultaneously shifted with the intervals of $1\Delta\phi, 5\Delta\phi$.

TABLE III
TOTAL NUMBER OF MEASUREMENTS

M	Number of Measurements
1	640
2	320
3	224

Total numbers of the power measurements are listed in Table III. In this table, M is the number of simultaneously measured elements. The case $M = 1$, therefore, corresponds with the conventional REV method. It is found that the significant measurement time reduction can be attained by the proposed method.

E. Measurement Accuracy

For a theoretical prediction of the measurement accuracy, the electric field variation of each element must be preliminarily specified. In a usual phased array development, the measurement and calibration accuracy can be investigated because the electric field variation of each element should be specified. In this paper, the electric field variation, i.e., the transmitting variations of the digital phase shifters are directly measured in order to evaluate the measurement accuracy exactly.

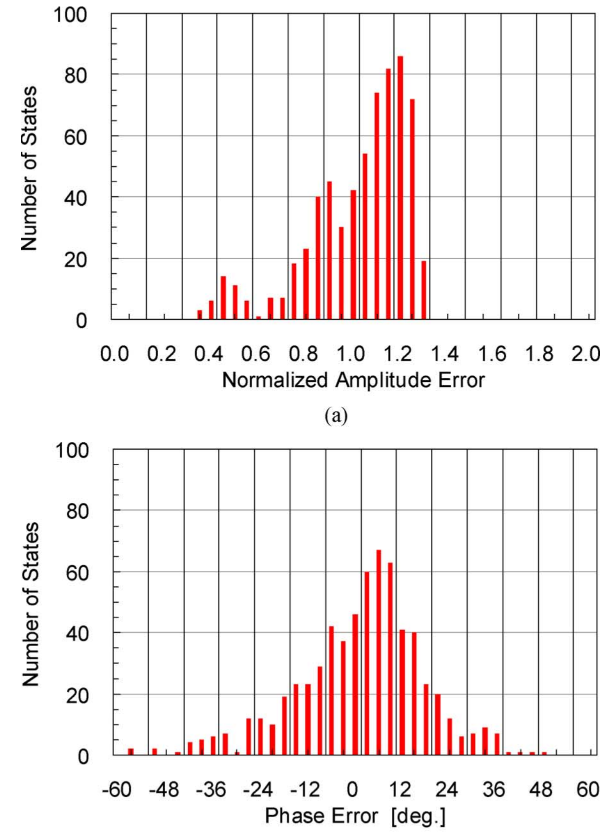

Fig. 10. Histogram of the transmitting variations of the used digital phase shifters. (a) Amplitude. (b) Phase.

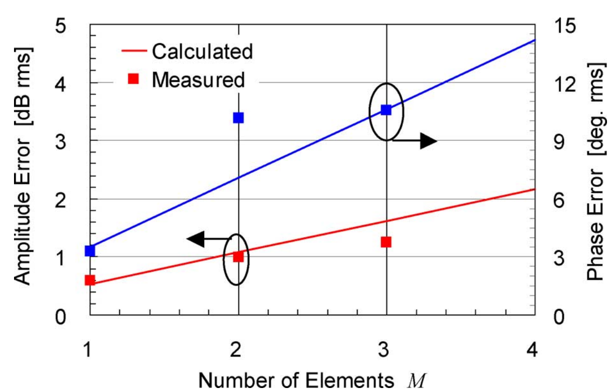

Fig. 11. Measurement errors of the electric fields in the proposed method.

Fig. 10 shows the histograms for the measured transmitting variations of all 5-bit digital phase shifters. From these measured results, the standard deviations of the electric field variations for all elements can be regarded as 1.81 dB for amplitude and 16.1 degrees for phase. These deviations were used for the theoretical predictions of the measurement errors in the proposed method. Equation (39) and (50) can be utilized for the predictions.

Fig. 11 shows the calculated and measured errors of the individual electric fields in the proposed method and they are numerically summarized in Table IV. In Fig. 11, the abscissa is the number of simultaneously measured antenna elements and

TABLE IV
SUMMARY OF THE CALCULATED AND MEASURED ERRORS

Number of Measured Elements	Amplitude Error [dB]			Phase Error [deg.]		
	Calculated	Measured	Difference	Calculated	Measured	Difference
1	0.54	0.60	0.06	3.54	3.27	-0.27
2	1.08	0.99	-0.09	7.08	10.14	3.06
3	1.62	1.25	-0.37	10.62	10.56	-0.06

the ordinate is the electric field error. The calculated errors are the theoretically predicted ones according to (39) and (50). The measured errors are obtained by comparing two kinds of measurement results as shown in Figs. 8 and 9, where the one is made by the proposed method and the other is directly measured by VNA. The amplitude differences between the calculated and measured ones are less than 0.37 dB and the phase differences are less than 3.06 degrees. The calculated and measured errors are in good agreement. Hence, the measurement accuracy can be theoretically estimated by (39) and (50).

Also, it is observed in Fig. 11 that the measurement error increases as the number of simultaneously measured antenna elements becomes greater. The case $M = 1$ corresponds with the conventional REV method. The proposed method, hence, has greater measurement errors than the conventional REV method. This measurement error increase will be tradeoff for the measurement time reduction as shown in Table III.

V. CONCLUSION

A novel measurement method was proposed for phased array calibration and experimentally validated. In the proposed method, the phases of multiple antenna elements are successively shifted with some different phase intervals while the array power variation is measured. The complex electric field of the corresponding elements can be simultaneously derived by identifying the measured power variation with the conventional REV method. The proposed method can significantly reduce the measurement times in phased array calibrations. For example, the proposed method using 5-bit digital phase shifters will take a third as many measurement times as the conventional REV method.

However, the proposed method will cause greater errors for the measured element fields. The theoretical study was carried out to estimate the increased errors and the theoretical predictions were validated in experiments. The measurement errors using 5-bit digital phase shifters, for example, will be three times as much as the conventional REV method.

The proposed measurement method can be easily applied to the operating phased array antenna systems because no phase measurements are required. The significant measurement time reduction can be achieved at the expense of the increased measurement error. The trade-off can be quantitatively discussed with the developed theory.

APPENDIX I

The measurement theory of the conventional REV method is summarized. The sinusoidal array power variation is measured

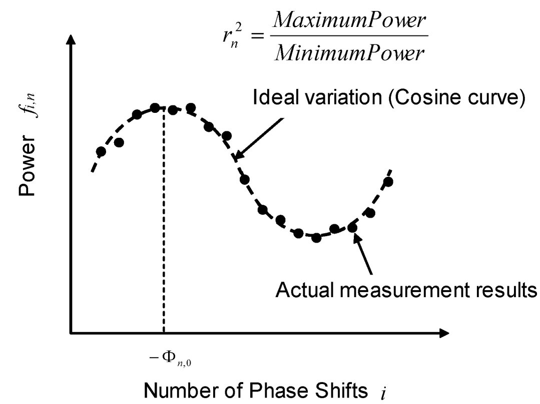

Fig. 12. Sinusoidal array power variation measured in the REV method.

as shown in Fig. 12 when the phase of the nth element is successively shifted from 0 to 360 degrees. According to the theory of the REV method, the electric field amplitude k_n and phase X_n of the corresponding element can be obtained as follows:

$$k_n = \frac{\Gamma_n}{\sqrt{1 + 2\Gamma_n \cos\Phi_{n,0} + \Gamma_n^2}} \tag{52}$$

$$\tan X_n = \frac{\sin\Phi_{n,0}}{\cos\Phi_{n,0} + \Gamma_n} \tag{53}$$

$$\Gamma_n = \frac{r_n - 1}{r_n + 1} \tag{54}$$

$$\tan\Phi_{m,0} = -\frac{s_n}{c_n} \tag{55}$$

$$r_n^2 = \frac{\alpha_n + 2\sqrt{c_n^2 + s_n^2}}{\alpha_n - 2\sqrt{c_n^2 + s_n^2}} \tag{56}$$

$$\alpha_n = \frac{2}{N}\sum_{i=1}^{N} f_{i,n} \tag{57}$$

$$c_n = \frac{2}{N}\sum_{i=1}^{N} f_{i,n}\cos\Phi_{n,i} \tag{58}$$

$$s_n = \frac{2}{N}\sum_{i=1}^{N} f_{i,n}\sin\Phi_{n,i}. \tag{59}$$

By using these parameters, the array power $f_{i,n}$ with the phase shift $\Phi_{n,i}$ for the nth antenna element can be also expressed as follows:

$$f_{i,n} = (Y_n^2 + k_n^2) + 2k_nY_n\cos(\Phi_{n,i} + \Phi_{n,0}) \tag{60}$$

$$Y_n^2 = (\cos X_n - k_n)^2 + \sin^2 X_n. \tag{61}$$

APPENDIX II

In regard with the parameters defined by (30) and (31), the following equations can be obtained [7]:

$$-Q\frac{\partial P}{\partial \alpha_n} + P\frac{\partial Q}{\partial \alpha_n} = -\frac{k_m(\Gamma_n \cos\Phi_{m,0}+1)}{4r_n\sqrt{c_{n2}+s_n^2}}(r_n^2-1) \quad (62)$$

$$\begin{aligned}-Q\frac{\partial P}{\partial s_n} + P\frac{\partial Q}{\partial s_n} &= +(\Gamma_n \cos\Phi_{m,0}+1)\frac{k_m\cos\Phi_{m,0}}{2r\sqrt{c_n^2+s_n^2}}(r_n^2+1)\\ &\quad -\frac{k_m\Gamma_n \sin^2\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}} \quad (63)\end{aligned}$$

$$\begin{aligned}-Q\frac{\partial P}{\partial s_n} + P\frac{\partial Q}{\partial s_n} &= -(\Gamma_n \cos\Phi_{m,0}+1)\frac{k_m\sin\Phi_{m,0}}{2r\sqrt{c_n^2+s_n^2}}(r_n^2+1)\\ &\quad -\frac{k_m\Gamma_n \sin\Phi_{m,0}\cos\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}}. \quad (64)\end{aligned}$$

Furthermore, we can also derive the following equations about the parameters defined by (41) and (42) [7]:

$$\begin{aligned}&(U^2+V^2)^2\\ &\quad=(1+2\Gamma_n\cos\Phi_{m,0}+\Gamma_n^2)^2=\frac{\Gamma_n^4}{k_m^4} \quad (65)\end{aligned}$$

$$\begin{aligned}&-V\frac{\partial U}{\partial \alpha_n}+U\frac{\partial V}{\partial \alpha_n}\\ &\quad=+\frac{\sin\Phi_{m,0}}{r_n\sqrt{c_n^2+s_n^2}}\left(\frac{r_n-1}{2}\right)^2 \quad (66)\end{aligned}$$

$$\begin{aligned}-V\frac{\partial U}{\partial s_n}+U\frac{\partial V}{\partial s_n} &= -\frac{\sin\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}}-\frac{\sin\Phi_{m,0}\cos\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}}R\\ &\quad-\frac{\Gamma_n\sin\Phi_{m,0}\cos\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}} \quad (67)\end{aligned}$$

$$-V\frac{\partial U}{\partial s_n}+U\frac{\partial V}{\partial s_n} = -\frac{\cos\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}}-\frac{\sin^2\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}}R-\frac{\Gamma_n\cos^2\Phi_{m,0}}{\sqrt{c_n^2+s_n^2}} \quad (68)$$

$$R=\frac{(r_n^2+1)(r_n-1)}{2r_n(r_n+1)}. \quad (69)$$

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