A phase-matching method for antenna phase center determination basing upon site insertion loss measurement in OATS

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***Abstract*-The phase center of directional antennas, such as log-periodic dipole array (LPDA), varies with frequencies and is easily influenced by surroundings. This forms a dominant error for antenna calibration due to an undefined actual distance between the radiation and reception points. This paper concentrates on the phase center determination for broadband wire-element EMC antenna. A novel method named as phase-matching is developed, which uses the measurement data of site insertion loss (SIL) between an antenna under test (AUT) and a reference antenna with a definite phase center in an open area test site (OATS). Precise broadband calculable dipole antennas are utilized in this work. Both the theoretical derivation and validations are presented in this paper. The determination error based upon usages of measurement data is about 60 mm around 250 MHz, and is reduced to 15 mm around 900 MHz.**

I. INTRODUCTION

Antenna phase center (PC) is defined as a location from which radiation is considered to emanate. In general, the phase center of a dipole antenna is the center point of radiating elements. A bi-conical antenna has a similar radiation pattern with dipoles, and thus its PC locates at the geometrical center; however, active elements of a log-periodic dipole array (LPDA) antenna shift during a frequency sweep, which causes PCs to change with frequencies. This results in an undefined actual distance between the radiation and reception points, and thus forms a dominant error for LPDA antenna calibration [1-3]. This paper concentrates on the phase center determination for broadband EMC antenna, such as LPDA and bi-log antennas.

Over the decades, a lot of previous work has been focused on phase center determination for antenna calibration purpose. The analytical formula firstly proposed by NPL (National Physical Laboratory, UK)[1] and later appears in a CISPR draft document[3] assumes that phase centers of LPDAs locate exactly at resonant elements and moves linearly with frequencies along its boresight. Such linear interpolation is an approximation within about 50 mm around 200 MHz, and 30 mm around 1 GHz. ETS-Lindgren proposed a CFNSA model [4, 5] for LPDAs; nevertheless, a representation of LPDA pattern with cosine and higher order polynomial functions may not sufficient at high frequencies. In another hand, both the analytical calculation and the CFNSA model are only suitable for commonly-used LPDA antennas. Universal methods which are with no limitation of antenna shape are based on either numerical simulations [6] or phase pattern measurements[7], which are quite time-consuming and not practical for regular antenna calibration.

A novel phase center determination method is developed. Different from the fore-mentioned solutions, the proposed method has no limitation of antenna shape and the phase center variation in multiple dimensions can be considered. Moreover, the site insertion loss (SIL) measurement between an antenna under test (AUT) and a reference antenna can be easily conducted in an Open Area Test Site (OATS).

This paper is organized as follows. A novel phase center determination model including its essential theoretical derivation is presented in Section II. Simulation and measurement validations are discussed in Section III. Section IV ends with conclusions.

II. PHASE-MATCHING METHOD

A theoretical model for transmission between broadband antennas over an infinite conducting ground plane was proposed by Smith [8] and later became the base of Standard Site Method (SSM) for OATS antenna calibration. The proposed phase center determination method is based on site insertion loss measurements in an OATS. Fig.1 illustrates the measurement model.

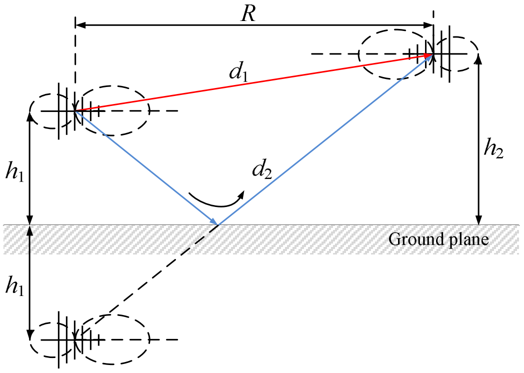

Figure 1. Site Insertion Loss measurement

Basing on the geometrical optics (GO) approximation principle, (1) gives the received electric filed strength by the receiving antenna in condition of horizontal polarization.

$$E_H = \sqrt{30 P_T D}\left[\frac{e^{-j\beta d_1}}{d_1} + \frac{|\rho_h|\, e^{-j\beta d_2} e^{j\phi_h}}{d_2}\right] \quad (\text{mV/m}) , \qquad (1)$$

where, P_T and D are the radiation power and the gain of transmitting antenna, respectively. The complex quantity $|\rho_h| e^{j\phi_h}$ is a reflection coefficient of the ground plane, and

β=2π/λ is the wave number in free space. The antenna height, h_1 and h_2 are defined as heights of antenna phase centers above the ground plane. The quantity R is the separation distance between phase centers of the antennas as they projected on the ground plane. d_1 and d_2 are the propagation distance of direct ray and ground-reflected ray from the transmitting antenna to the receiving antenna, respectively.

SIL is transmission loss between two polarization matched antennas when a direct electrical connection via cables and attenuators between the signal generator output and the measuring receiver input is replaced by transmitting and receiving antennas placed at specified positions on a calibration site[3]. The measurement of SIL is common to all radiated field methods of antenna calibration. The SIL measurement procedures, and measurement uncertainty components, are described in [2]. Equation (2) represents a quantitative relationship between SIL and received electric filed strength, where f_M is the frequencies in mega Hertz; AF_T and AF_R are respectively the free-space antenna factor of the transmitting antenna and the receiving antenna [8].

$$SIL = \frac{79.58\sqrt{30P_T D}AF_T AF_R}{2f_M E_H}\,. \qquad (2)$$

Substituting (1) in (2) gives (3), where the scalar quantity C equals $39.79AF_T AF_R / f_M$.

$$SIL = C\left[\frac{e^{-j\beta d_1}}{d_1} + \frac{|\rho_h| e^{-j\beta d_2} e^{j\phi_h}}{d_2}\right]^{-1}. \qquad (3)$$

It is clear in (3) that, two factors contribute phase variations between the transmitting antenna and the receiving antenna when conducting SIL measurement in an OATS. From a phase point of view, the first right hand side term of (1) denotes the phase shifting due to the propagation of direct ray d_1, while the second RHS term implies the phase shifting due to the propagation of ground-reflected ray d_2. The vector superposition of the two terms makes great complexity of the phase of receiving field strength, which also results in difficulties of solving phase center information directly from conventional SIL measurements.

A novel phase center determination model is shown in Fig.2. O_1 and O_2 denote reference points for measuring antenna separation, i.e., pseudo phase centers. The actual phase center P_1 and P_2 can be described by relative coordinate parameters (Δx_1, Δz_1) and (Δx_2,Δz_2), respectively. The coordinate axes of local coordinates O_1-$x_1 z_1$ and O_2-$x_2 z_2$ are collinear with which of the global coordinate O-xz. Since an OATS can represent a half free space, and the measurement model shown in Fig.2 is symmetrical in y direction, the phase center variation in y direction is neglectable.

In the proposed method, heights of two antennas are adjusted in opposite directions, but with same variations, i.e.,

$$h_1' = h_1 - \Delta h\,,\ h_2' = h_2 + \Delta h\,, \qquad (4)$$

where Δh is the height adjustment.

Such specific procedure is developed by intention of the following two aspects.

(1) to keep ground-reflected waves (ray-lengths) constant. The ground-reflected ray can be calculated by (5), with the measurement manner as (4), we can obtain $d_2' = d_2$.

$$d_2' = \sqrt{R^2 + (h_1' + h_2')^2} = \sqrt{R^2 + (h_1 + h_2)^2} = d_2\,; \qquad (5)$$

(2) to keep the reflection coefficient unchanged.
The reflect angle γ in Fig.2 keeps unchanged in this height adjustment manner, according to the reflection coefficient calculation (5), this procedure can keep the reflection coefficient unchanged.

$$\boldsymbol{\rho}_h = |\rho_h| e^{j\phi_h} = \frac{\sin\gamma - (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}}{\sin\gamma + (K - j60\lambda\sigma - \cos^2\gamma)^{1/2}}\,, \qquad (6)$$

where K is relative dielectric constant, and σ is the conductivity.

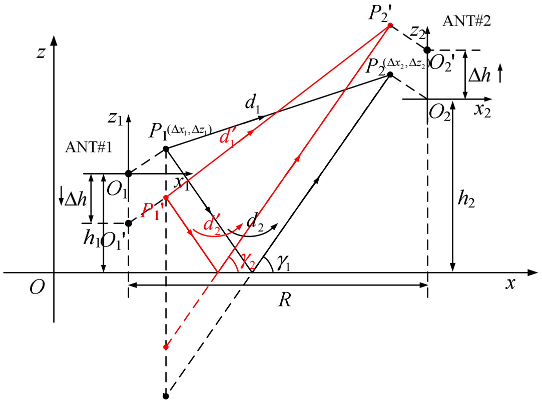

Figure 2. Principle of phase center determination

In this case, equation (7) can be deduced from the theoretical site attenuation model, where C is a constant at a given frequency. With measured SILs of different height configurations, independent equations as (8) can be formed from (7) by matching phases of two sides where the measured SILs are described as $SIL = Ae^{j\varphi}$ and $SIL' = A'e^{j\varphi'}$. The left hand side of (8) can be calculated by the measured SIL magnitude and phase, and in the right hand side , the unknowns d_1 and d_1' are the corresponding direct wave-paths, which are also functions of phase center parameters, Δx_1, Δz_1, Δx_2 and Δz_2. The name of phase matching is given to this method.

$$\frac{1}{SIL'} - \frac{1}{SIL} = C\left[\frac{e^{-j\beta d_1'}}{d_1'} - \frac{e^{-j\beta d_1}}{d_1}\right]. \qquad (7)$$

$$\frac{A_2\sin\varphi_1 - A_1\sin\varphi_2}{A_1\cos\varphi_2 - A_2\cos\varphi_1} = \frac{d_1'\sin\beta d_1 - d_1\sin\beta d_1'}{d_1\cos\beta d_1' - d_1'\cos\beta d_1}\,, \qquad (8)$$

where $d_1 = \sqrt{(R + \Delta x_1 - \Delta x_2)^2 + (h_2 - h_1 + \Delta z_1 - \Delta z_2)^2}$

$$d_1' = \sqrt{(R + \Delta x_1 - \Delta x_2)^2 + (h_2 - h_1 + \Delta z_1 - \Delta z_2 + 2\Delta h)^2}$$

To simply the calculation, a reference antenna with a definite phase center position is used. High-precision standard broadband calculable dipoles are recommended in this method for their phase centers are exactly located at the centers of radiation elements.

Setting the phase center of a dipole at O_2 in Fig.2, Equation (8) can be simplified by Δx_2=Δz_2=0. SIL measurement in cases of several height configuration results in a certain amount of equations by substituting the measurement data in (8). Theoretically, the left two unknowns of phase center deviation respect to the reference point, i.e., Δx_1 and Δz_1 can be solved by using any two equations as (8). The transcendental equation (8) is difficult to be directly solved by using conventional numerical methods. A specific genetic algorithm is utilized to solve this optimization problem in this work.

With the knowledge of phase center at given frequencies, the antenna factor can be corrected by correction of electric field strength accounting for phase center as (9).

$$\Delta E = 20\log(\frac{R_{phase}}{R}), \qquad (9)$$

where R_{phase} is the separation distance between actual phase centers of the antennas as they projected on the ground plane. For a given frequency, the correction ΔE in dB, is added to the measured field strength.

III. SIMULATION AND MEASUREMENT VALIDATION

A. Validation principle

Theoretically, phase center of a resonant dipole is located in its geometrical center. In order to validate the proposed phase-matching method, the SIL simulation and measurement of pairs of resonant dipoles are presented in this section. Fig.3 demonstrates the validation principle, where the pseudo phase center P_1' of AUT has deviations of Δx and Δz with respect to the actual phase center P_1, and observation point of reference antenna is exactly its phase center P_2. Since the separation distance R and the height h_1 are measured from AUT's geometrical center, the theoretical value of Δx and Δy are zero.

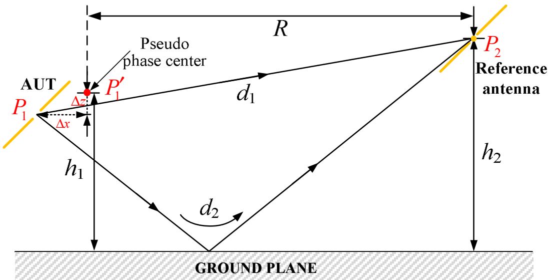

Figure 3. The validation model

B. Simulation and measurement

The antenna heights are adjusted keeping h_1+h_2=8m in the validation. The height configuration indicated in Table 1 results in six sets of SIL data including the magnitude and phase information. 15 different equations can be formed by using any combination of two *SIL*s, and finally average values of Δx and Δz can be obtained.

TABLE I
ANTENNA HEIGHT CONFIGURATIONS

	R (m)	h_1 (m)	h_2 (m)
SIL1	5	4	4
SIL2	5	3.8	4.2
SIL3	5	3.6	4.4
SIL4	5	3.4	4.6
SIL5	5	3.2	4.8
SIL6	5	3	5

Simulation experiments using an infinite ground plane and ideal half-wave 250MHz resonant dipoles were performed by Method of Moment (MoM) calculator NEC2. Fig.4 shows the simulated SIL data.

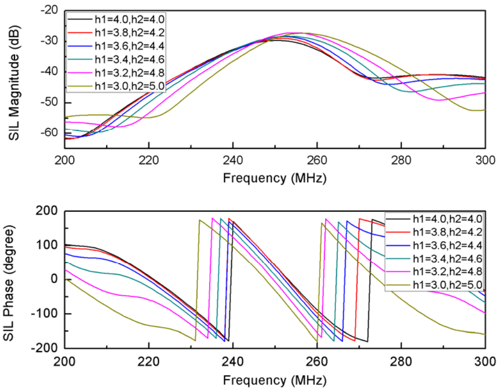

Figure 4. Simulated SIL data of 250MHz resonant dipoles

Corresponding measurement were carried out in a standard OATS of NIM (National Institute of Metrology) in Beijing. The steel ground plane has the dimensions of 60 m by 40 m, and the central (25m by 25m) flatness is within 4 mm.

Fig.5 illustrates the measurement system. Two antenna masts capable of stepping height in small increments (minimum one centimeter) stand over the ground plane. A vector network analyzer (VNA), a motor control unit and other auxiliary device are installed in an underground control room. A serial of NPL broadband calculable dipole antennas (CRD series) which has fixed element lengths are used in the measurement. Fig.6 demonstrates the measurement data of a pair of 250MHz resonant dipoles.

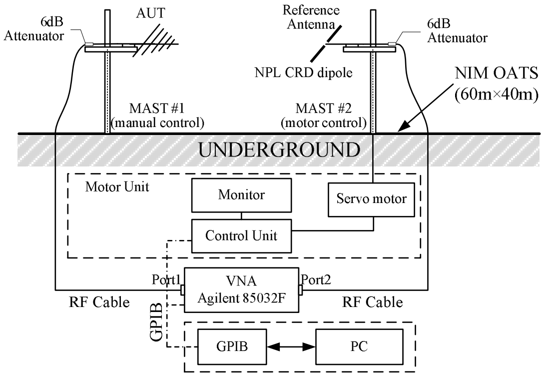

Figure 5. NIM OATS measurement system

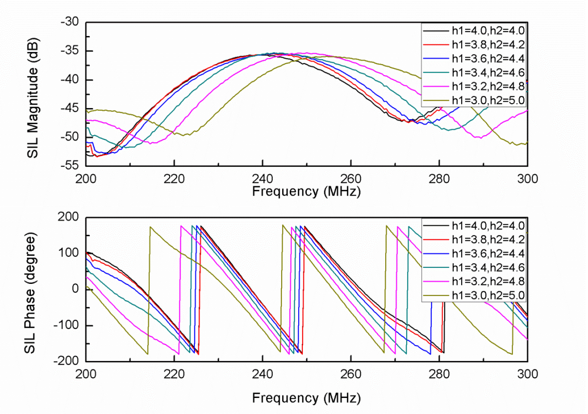

Figure 6. Measured SIL data of 250MHz resonant dipoles

More validations are conducted with 600MHz and 900MHz resonant dipoles.

C. *Phase center determination*

Using the proposed phase matching method, AUT's phase center derivation with respect to the pseudos' can be calculated. Fig.7-9 present the results for 250MHz, 600MHz and 900MHz resonant dipoles, respectively. The phase center determination are based upon the use of simulated *SIL* and measured SIL data for each configration.

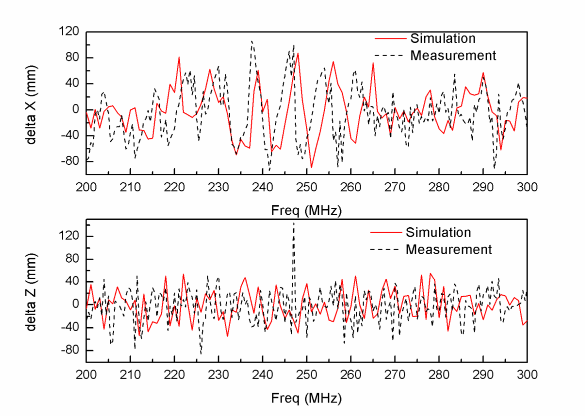

Figure 7. Phase center determination around 250MHz

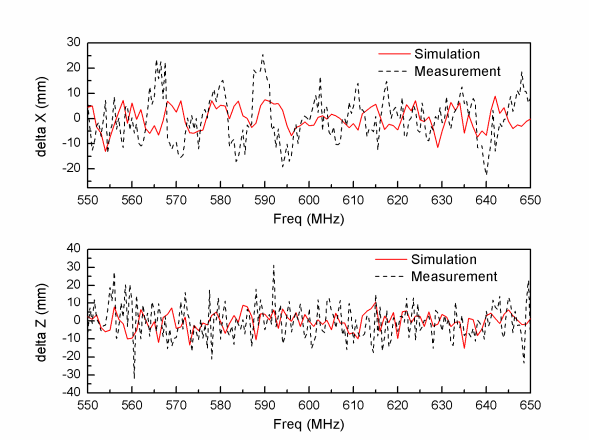

Figure 8. Phase center determination around 600MHz

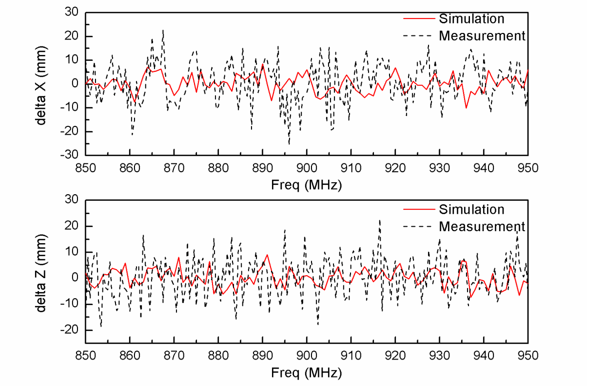

Figure 9. Phase center determination around 900MHz

The determination results based upon the simulated SILs are better than that based upon the measured SILs, due to the measurement uncertainty and system errors. Table 2 gives the detail results. Overall, using the measured SIL data, the determination error is about 60 mm around 250 MHz, and is reduced to 15 mm around 900 MHz.

TABLE II
VALIDATION RESULTS

Frequency (MHz)	By measured SIL		By simulated SIL	
	Δx, mm	Δz, mm	Δx, mm	Δz, mm
200 - 300	± 60	±60	±60	±60
550 - 650	±20	±20	±10	±10
850 - 950	±15	±15	±10	±10

IV. CONCLUSION

This paper presents a novel phase matching method to determine phase centers of broadband wire-element EMC antenna, and it is based upon site insertion loss measurements in OATS. The main advantages respect to conventional methods are as following, this method can determine the phase center derivation from any reference point in two orthogonal dimensions, and it has no limitation of antenna shape. It is based upon actual SIL measurement, so the effect of ground coupling, antenna coupling, and antenna mast can be considered in the phase center determination; meanwhile, the SIL measurement is more easily conducted than other precision phase measurement. As an application of this method, phase center determination of a commonly used LPDA (VUSLP 9111) and the antenna factor correction will be carried out in the future.

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