

# Numerical Simulation of Far-Field Gain Determination at Reduced Distances Using Phase Center

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**SUMMARY** This paper describes numerical analyses of the distance-dependent gain variation that exists in gain measurements based on the Friis transmission formula for typical broadband antennas, including double-ridged guide horn and log-periodic dipole array antennas. The analyses are performed by simulating gain measurements using the method of moments with higher-order basis functions and the finite integration method. In addition, we propose approximate techniques to determine the antenna phase center by exploiting the distance dependence of the gain. Simulation and experimental results show the effectiveness of using the location of the phase center to accurately determine the far-field gain at reduced antenna separation distances.

**key words:** gain measurement, Friis transmission formula, method of moments, finite integration method, phase center

## 1. Introduction

The three-antenna method, which is based on the Friis transmission formula [1], is widely used to determine the far-field gain of antennas. However, even if the separation distance between two antennas satisfies the usual far-field criterion, the measured gain of many broadband antennas varies with the separation distance. For pyramidal horn antennas, the measured gain is reduced by approximately 1 dB at distances satisfying the well-known far-field criterion of  $2D^2/\lambda$  (where  $D$  is the maximum aperture size and  $\lambda$  is the wavelength). To use the far-field Friis formula in the Fresnel region, the gain reduction factor has been studied as a means of correcting the proximity effect between two closely spaced antennas [2]–[5]. Specifically, Chu and Sempak [3] derived a correction factor for the gain reduction as a function of the antenna dimensions and the distance between the apertures of two horns. The separation distance required for accurate measurement, i.e., to obtain a gain reduction of within 0.05 dB, is approximately  $32D^2/\lambda$  [3]. Newell et al. [6] developed an extrapolation technique for reducing the distance required for conventional gain measurements. Another approach with the same purpose is to use the phase center of the antenna [7]–[12]. This is because the phase center can be treated as an equivalent point source — i.e., the “true” reference point of the antenna — under a far-field condition. Muehldorf [13] theoretically determined the phase center of rectangular and diagonal horn antennas. However, for other broadband antennas with com-

plex structures, it is difficult to calculate the phase center using the same theoretical approach as that used for horn antennas. In addition, phase center measurements are generally costly and require significant effort because there is a requirement for precise phase measurement with an antenna-scanning and positioning system in the far-field region [14].

In this paper, we first present the effect of the separation distance between antennas on gain measurement based on the Friis transmission formula. We perform numerical simulations for typical broadband antennas using the method of moments for pyramidal horn and double-ridged guide horn antennas and the finite integration method for a log-periodic dipole array antenna. We then propose approximate techniques, namely, the gain-fitting and gain two-distance methods [15], [16], for determining the phase center by exploiting the distance-dependent gain variation. Finally, a numerical simulation and experiment are performed to verify the effectiveness of using the phase center to accurately determine the far-field gain, specifically, to reduce separation distances.

## 2. Gain Determination

The Friis transmission formula is often used for gain measurements in the far-field region [1]. For a two-antenna system in free space, as shown in Fig. 1, the power received at a conjugate matched load connected to the receiving antenna is given by

$$P_R = P_T G_T G_R \left( \frac{\lambda}{4\pi r} \right)^2. \quad (1)$$

Here,  $G_T$  is the gain of the transmitting antenna,  $G_R$  is the gain of the receiving antenna,  $P_T$  is the power input to the transmitting antenna,  $P_R$  is the power received by the receiving antenna, and  $r$  is the distance between the two antennas.

The absolute gain can be determined by solving three equations, shown in Eq. (1), which are obtained by using all pair combinations of the three antennas. That is, from the

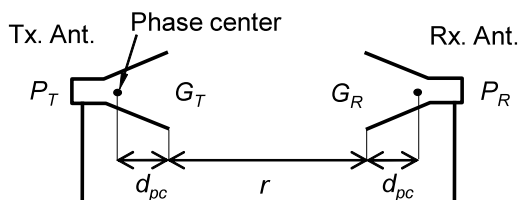


Fig. 1 Friis transmission formula.

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measurements of the antenna insertion loss  $IL(= P_R/P_T)$ , the gains of antennas #1, #2, and #3 are expressed as follows:

$$G_1 = \frac{4\pi r}{\lambda} \sqrt{\frac{IL_{(12)}IL_{(13)}}{IL_{(23)}}}, \quad (2)$$

$$G_2 = \frac{4\pi r}{\lambda} \sqrt{\frac{IL_{(12)}IL_{(23)}}{IL_{(13)}}}, \quad (3)$$

$$G_3 = \frac{4\pi r}{\lambda} \sqrt{\frac{IL_{(13)}IL_{(23)}}{IL_{(12)}}}, \quad (4)$$

where the subscripts (12), (13), and (23) indicate the antenna combinations 1–2, 1–3, and 2–3, respectively. If two antennas are identical, the gain is represented by

$$G = \frac{4\pi r}{\lambda} \sqrt{IL}. \quad (5)$$

These methods are referred to as the three- and two-antenna methods, respectively [14]. In antenna measurements, the antennas are separated such that the far-field criterion is satisfied. The minimum far-field criterion  $r \geq 2D^2/\lambda_{min}$ , where  $\lambda_{min}$  is the minimum wavelength, is widely used for aperture antennas [17]. When the transmitting and receiving antennas have a comparable aperture size, the far-field criterion  $r \geq 2(D_t + D_r)^2/\lambda_{min}$ , where  $D_t$  and  $D_r$  are the maximum dimensions of the transmitting and receiving antennas, respectively, is generally applied [18]–[20].

### 3. Simulation of Gain Measurement

When measuring the far-field gain of antennas, the distance between given reference points (e.g., aperture, tip, or mid-point of antenna) is treated as the separation distance in the Friis transmission formula. From Eq. (5), using the  $S_{21}$  parameter between both antenna ports for the antenna insertion loss and the  $S_{11}$  parameter for the impedance mismatch loss, the absolute gain  $G_{(r)}$  determined at the distance  $r$  is represented by

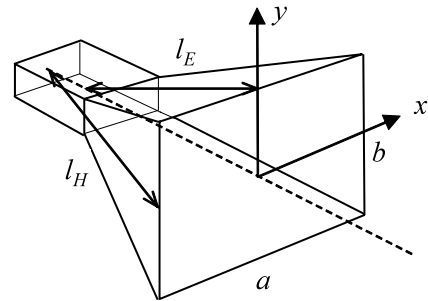
$$G_{(r)} = \frac{4\pi r}{\lambda} \frac{|S_{21}|}{1 - |S_{11}|^2}, \quad (6)$$

where the subscript  $(r)$  indicates the distance between given points.

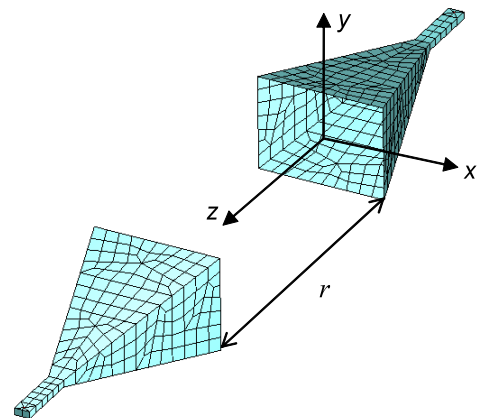
We numerically estimate the effect of the separation distance on gain measurement, based on the two-antenna method, using Eq. (6). In Secs. 3.1 and 3.2, we analyze and discuss the case of pyramidal horn and double ridged-guide horn antennas using a WIPL-D solver [21] based on the method of moments (MoM) with higher-order basis functions. In Sect. 3.3, we discuss the case of a log-periodic dipole array antenna using a CST MW-studio solver [22] based on the finite integration method (FIM).

#### 3.1 Pyramidal Horn Antenna

A pyramidal horn antenna is often used as a reference antenna in gain measurements. The geometry of a typical



**Fig. 2** Pyramidal horn antenna. For a C-band horn, the dimensions are  $a = 288$  mm,  $b = 213$  mm,  $l_E = 481.9$  mm, and  $l_H = 515.4$  mm.

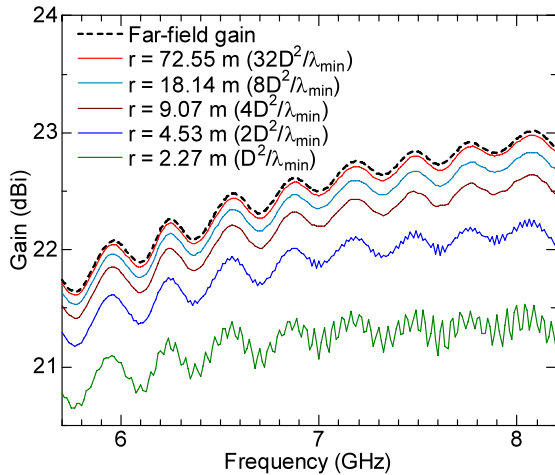


**Fig. 3** MoM simulation model of gain measurement for the C-band pyramidal horn antenna [15].

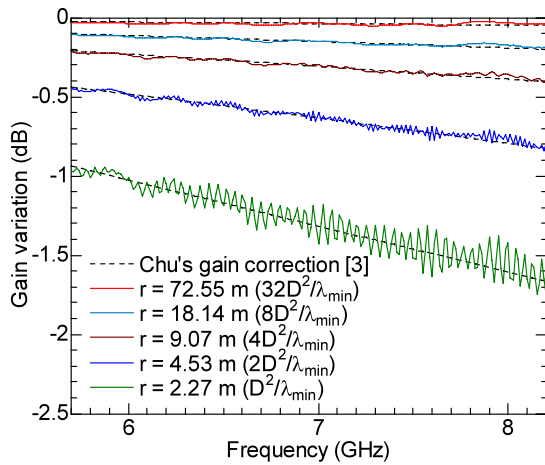
pyramidal horn antenna is shown in Fig. 2. The numerical simulation of gain measurement for the horn antenna is performed using the MoM [15]. A C-band (5.85–8.2 GHz) horn antenna is used for this simulation. The simulation model for gain measurement using the two-antenna method is shown in Fig. 3. Two identical horn antennas are arranged with a distance  $r$  between the apertures of both antennas. In the calculation model, the horn antenna is assumed to be a perfect conductor and is excited in the  $TE_{10}$  mode in a rectangular waveguide. As shown in Fig. 3, the simulation model is composed of quadrilateral surface patches with fourth-order basis functions, where the maximum size is one minimum wavelength  $\lambda_{min}$ . The total number of unknown coefficients is 7,901, exploiting the symmetry of the antenna structure.

Figure 4 shows the gain determined using the MoM simulation for antenna separations ranging from  $D^2/\lambda_{min}$  (2.27 m) to  $32D^2/\lambda_{min}$  (72.55 m). This result indicates that in the gain measurement based on the Friis transmission formula, the determined gain depends on the separation distance. A sufficient distance is required to accurately determine the far-field gain.

The gain variation factor is defined as the ratio of the gain determined at distance  $r$  to the far-field gain ( $G_{FAR}$ ) as follows:



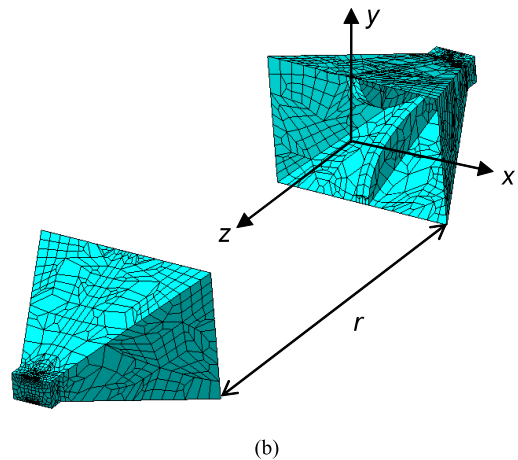
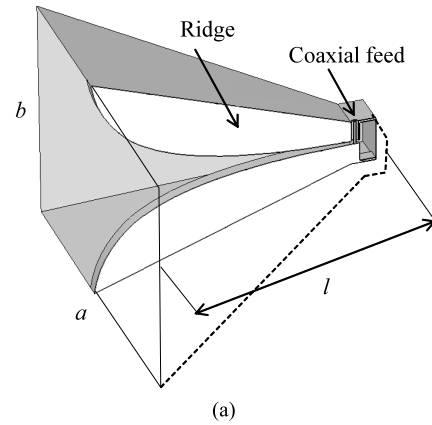
**Fig. 4** Gain of the C-band pyramidal horn antenna determined at several separation distances by MoM simulation [15].



**Fig. 5** Gain variation of the C-band pyramidal horn antenna due to antenna separation distance.

$$dG = \frac{G(r)}{G_{FAR}} \tag{7}$$

For pyramidal horn antennas, the tangential electric field in the aperture is assumed to have a cosine distribution. From this assumption, Chu and SEMPLAK [3] derived a correction factor for gain reduction, which is equivalent to the reciprocal of  $dG$ , as a function of the antenna dimensions and the distance between the apertures of the two horns. The gain variation obtained by the MoM simulation is plotted in Fig. 5 along with Chu's gain correction. Chu's correction is in good agreement with the simulated result, with the exception of the effect of multiple reflections between antennas caused at small separation distances, such as  $D^2/\lambda_{min}$  and  $2D^2/\lambda_{min}$ , because these reflections are neglected in the correction factor. These results also show that the gain variation is approximately 0.8 dB, even if the separation distance satisfies the usual far-field criterion of  $2D^2/\lambda_{min}$ , and the distance required to obtain a gain variation of less than 0.05 dB is greater than  $32D^2/\lambda_{min}$ .



**Fig. 6** (a) Calculation model of a DRGH antenna ( $a = 200$  mm,  $b = 140$  mm, and  $l = 188.4$  mm) for the operating frequency range 1–12 GHz. (b) MoM simulation model of gain measurement.

### 3.2 Double-Ridged Guide Horn Antenna

Double-ridged guide horn (DRGH) antennas are widely used as broadband antennas in radiated electromagnetic compatibility (EMC) testing. For the DRGH antenna, in the same manner as described in the previous section, the distance characteristics of gain are evaluated using the MoM. A calculation model of a DRGH antenna is shown in Fig. 6(a). The DRGH antenna is designed for a frequency range of 1 to 12 GHz with a perfect conductor and is excited by a coaxial feed. The simulation model for gain measurement is shown in Fig. 6(b), in which two identical ridged horn antennas are set up with a distance  $r$  between the apertures of both antennas. The simulation model consists of quadrilateral surface patches with fourth-order basis functions, where the maximum size is one minimum wavelength, and the total number of unknowns, exploiting the symmetry of the antenna structure, is 17,595. The gain is determined from Eq. (6) by calculating the  $S$ -parameters at both antenna ports for several separation distances.

Figure 7 shows the gain determined by the MoM simulation for antenna separations ranging from 0.5 to 15 m. The simulated gain is compared with the far-field gain di-

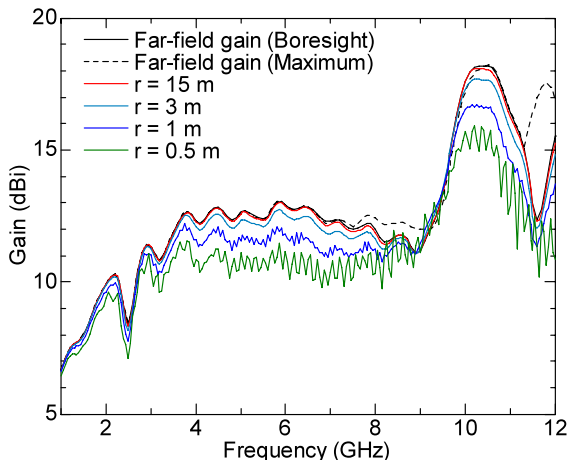


Fig. 7 Gain of the DRGH antenna determined at several separation distances by MoM simulation.

rectly calculated using the MoM solver. It is found that the gain depends on the separation distance in gain measurement based on the Friis transmission formula. A sufficient separation distance (e.g., 15 m) is required to accurately determine the far-field gain. Furthermore, the direction of the maximum gain of the DRGH antenna differed from the boresight direction in the 8 and 11 GHz bands. These characteristics are often observed in similar types of DRGH antennas [23], [24].

### 3.3 Log-Periodic Dipole Array Antenna

Log-periodic dipole array (LPDA) antennas are also commonly used as wideband antennas. The numerical simulation of gain measurement for an LPDA antenna is performed using a CST FIM solver [16]. The LPDA antenna model used for this evaluation is shown in Fig. 8(a). The geometric parameters of the antenna are a scaling factor  $\tau (= L_{n+1}/L_n)$  of 0.9153, a spacing factor  $\sigma (= S_n/2L_n)$  of 0.0568, and 27 ( $= N$ ) dipole elements, with the lengths of the longest and shortest dipole elements ( $L_1$  and  $L_N$ ) corresponding to an operating frequency range of 1 to 10 GHz [25]. The simulation model for gain measurement is shown in Fig. 8(b). For aperture antennas, such as horn antennas, the distance between the apertures of the two antennas is used as the separation distance  $r$ . For LPDA antennas, the distance between the reference points is used—generally the midpoint along their longitudinal axis [26], [27]. Two LPDA antennas separated by a distance  $r$  face each other in the analytical region. The region is composed of nonuniform cells with a maximum cell size of  $\lambda_{min}/20$ . The antenna is assumed to be a perfect conductor and is excited by a coaxial feed. A perfectly matched layer (PML) [28] with eight layers is used as the absorbing boundary condition at the boundaries of the analytical region. The gain is determined from Eq. (6) by computing the  $S$ -parameters at both antenna ports.

Figure 9 shows the gain determined at separation distances of 0.5, 1, and 1.5 m using the FIM simulation and the

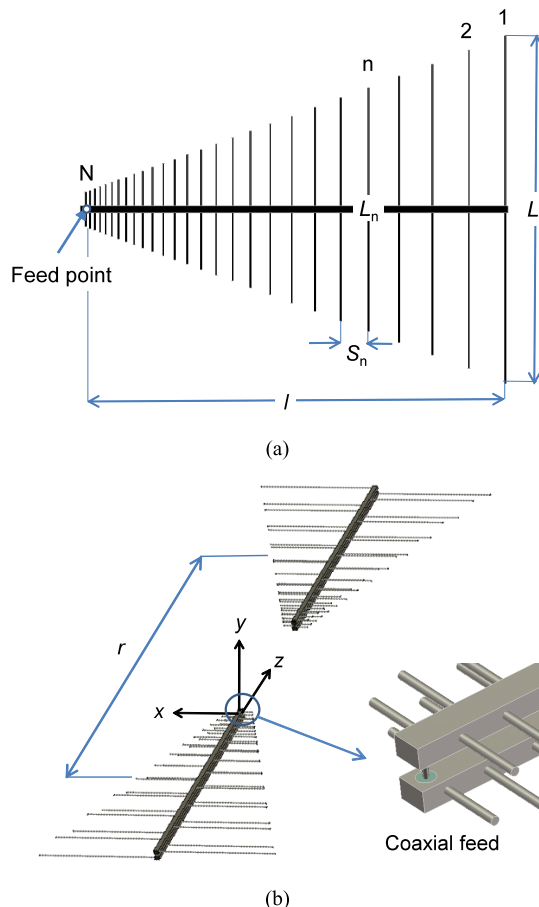


Fig. 8 (a) Calculation model of a LPDA antenna. The dimensions are  $\tau = L_{n+1}/L_n = 0.9153$ ,  $\sigma = S_n/2L_n = 0.0568$ ,  $l = 18.1$  cm, and 27 dipole elements ( $= N$ ) with an operating frequency range 1–10 GHz. (b) FIM simulation model of gain measurement [16].

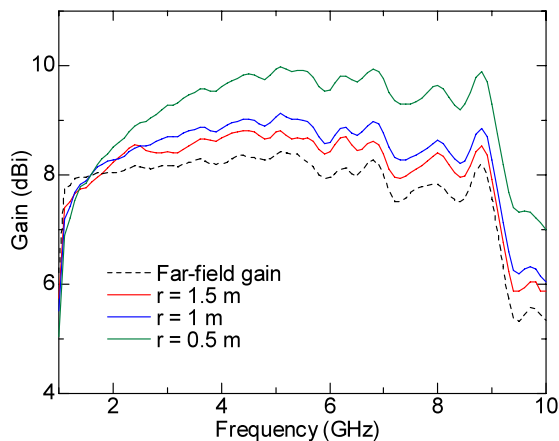


Fig. 9 Gain of the LPDA antenna determined at several separation distances by FIM simulation [16].

far-field gain. The gain determined using the fixed reference point depends on the separation distance. This is because the position of the resonant element of the LPDA antenna moves from the back end to the tip of the antenna with changes in the operating frequency. The FIM simulation for gain mea-

surement is effective for evaluating the proximity effects in the near field between antennas. However, in the case of a large distance between the antennas, the use of finite difference methods such as the FIM in the simulations is difficult because of CPU time and memory limitations.

#### 4. Relation between Gain Variation and Phase Center

The phase center of an antenna is defined as the center of curvature of a far-field equiphase front. The phase center is generally difficult to measure because it requires precise phase measurement with an antenna-scanning and positioning system in the far-field region [14]. Meanwhile, in the numerical approach, the phase center can be computed from the equiphase pattern by adjusting the origin of the near- to far-field transformation. The CST MW-studio solver has such a postprocessing capability for determining of the phase center. The phase center of the C-band horn antenna shown in Fig. 2 is computed using this FIM solver. The phase center locations  $d_H$  and  $d_E$  of the H- and E-planes, respectively, are defined as the distance from a given reference point (e.g., the aperture for the horn antenna) into the antenna on the boresight axis. The FIM model of the horn antenna is shown in Fig. 10. The analytical region is composed of 15,763,986 ( $= 183 \times 147 \times 586$ ) nonuniform cells and the maximum cell size is  $\lambda_{min}/20$ . A PML with eight layers is used as the absorbing boundary condition of the analytical region. The antenna is assumed to be a perfect conductor and is excited by the TE<sub>10</sub> mode in a rectangular waveguide.

The phase patterns calculated at 6 GHz at the phase center and its anteroposterior locations are shown in Fig. 11. When the angular region is within approximately  $\pm 2^\circ$  ( $= \theta$ ), which is less than approximately half of the 3 dB beamwidth of the horn antenna, the variation in the phase pattern at the phase center is nearly constant. Hence, the phase center is calculated for the angular region of  $\pm 2^\circ$  from 5.8 to 8.2 GHz. The numerical results of the phase center obtained by the FIM are shown in Fig. 12. The phase center depends on

the frequency; as the frequency increases, the phase center moves from the vicinity of the center of the horn antenna toward the waveguide port. The phase center determined by Muehldorf [13] is also shown in this figure. The results calculated by the FIM are almost in agreement with the theoretical results. The slight difference may be due to the effect of internal reflections from the discontinuities in the antenna such as from the edges of the aperture.

The phase center of an antenna differs for the E- and H-planes. To determine the gain, the mean of the phase centers of both planes,  $d_{pc} = (d_E + d_H)/2$ , is considered because it coincides with the location of the amplitude center [29]. In other words, the average phase center  $d_{pc}$  is treated as an equivalent point source (see Fig. 1). The phase center is strongly related to the gain variation resulting from the separation distance [11]. The distance ratio of the two apertures to the two phase centers,  $\Delta = r/(r + 2d_{pc})$ , of commercial C- to W-band pyramidal horn antennas is shown in Fig. 13 along with the reciprocal of Chu's correction factor, i.e., the gain variation factor. The location of the phase center  $d_{pc}$  for each horn is computed by FIM. This result indicates that the

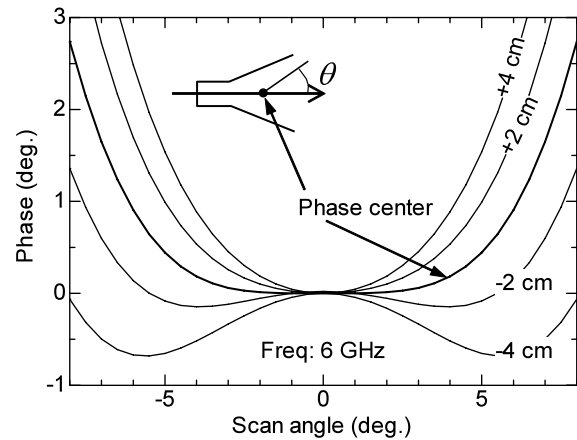


Fig. 11 H-plane phase patterns of the C-band pyramidal horn antenna calculated by FIM.

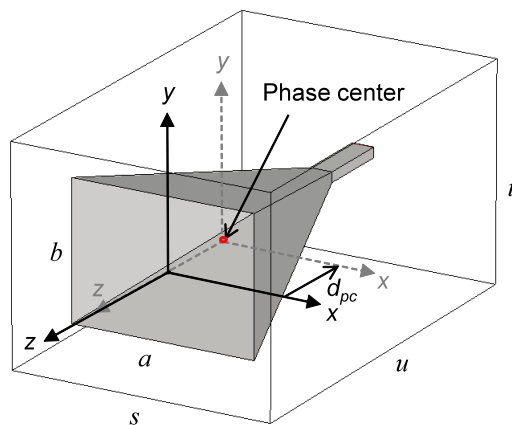


Fig. 10 FIM model of the C-band pyramidal horn antenna ( $s = 408$  mm,  $t = 333$  mm, and  $u = 628$  mm).

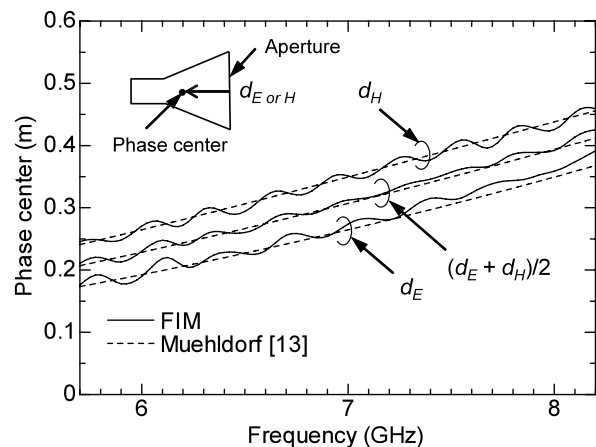
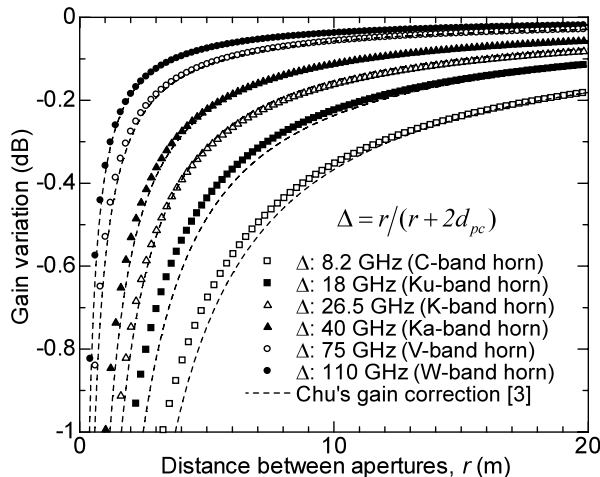


Fig. 12 Phase center location relative to the aperture of the C-band pyramidal horn antenna calculated by FIM.



**Fig. 13** Relation between gain variation and ratio of distance between apertures to distance between phase centers for pyramidal horns.

distance ratio is very close to the gain variation, for example, at a separation distance of greater than approximately 9 m ( $4D^2/\lambda_{min}$ ) for the C-band horn antenna. Hence, when the gain is determined on the basis of the location of the aperture, gain variation due to the separation distance corresponds to the ratio of the distance between the apertures to the distance between the phase centers.

## 5. Approximate Techniques for Determining the Phase Center

The phase center can be estimated by exploiting the distance dependence of the gain, i.e., using the relationship between the gain variation and the phase center. Two approximate methods, the gain-fitting method [15] and the gain two-distance method [16], which are based on numerical simulations of the two-antenna method, are described in this section.

### 5.1 Gain-Fitting Method

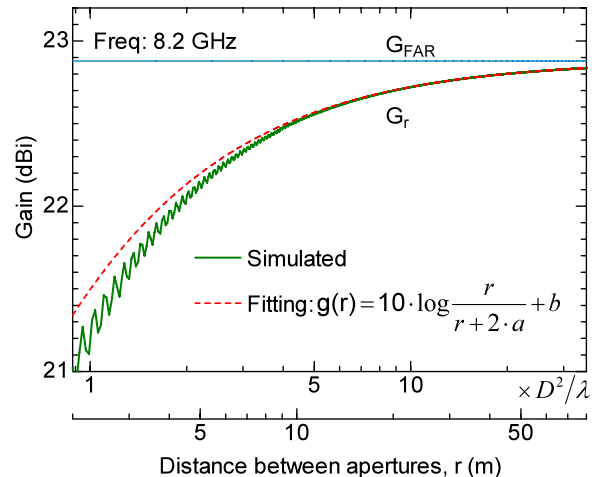
According to the Friis transmission formula, when the two antennas in Fig. 1 are identical, the ratio of the gain ( $G_{(r)}$ ) determined from the distance between the given points (e.g., apertures) to the gain ( $G_{(r+2d_{pc})}$ ) determined from the distance between the phase centers is expressed as follows (from Eq. (6)):

$$\frac{G_{(r)}}{G_{(r+2d_{pc})}} = \frac{r}{r + 2 \cdot d_{PC}}. \quad (8)$$

As mentioned in Sect. 4, assuming that the gain variation caused in gain measurement is equal to the ratio of the distance between the given points to the distance between the phase centers, the gain variation can be expressed by

$$dG = \frac{G_{(r)}}{G_{FAR}} \approx \frac{r}{r + 2 \cdot d_{PC}}, \quad (9)$$

where  $r \geq 4D^2/\lambda_{min}$  for horns. In addition, for typical



**Fig. 14** Gain characteristics of the C-band pyramidal horn antenna obtained from distance between apertures by MoM simulation [15].

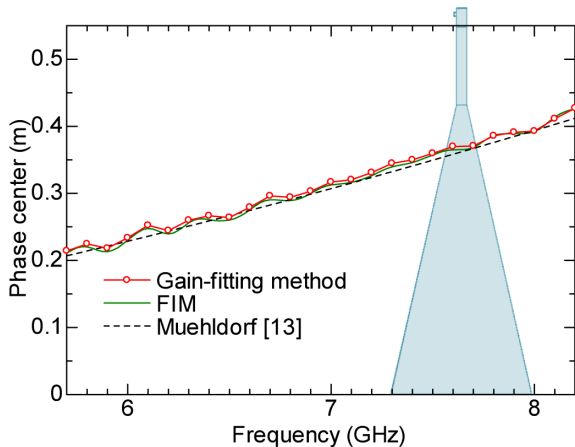
broadband antennas used in EMC testing, several investigations [10], [16] of the phase center have shown that the gain determined from the distance between the phase centers is very close to the far-field gain (i.e.,  $G_{(r+2d_{pc})} \approx G_{FAR}$ ).

Figure 14 shows the simulation result for the gain variation of the C-band horn antenna for a separation distance at 8.2 GHz. The gain is determined at separation distances  $r$  of 0 to 80 m in steps of 0.05 m using the MoM model, as shown in Fig. 3, of the two-antenna method. The phase center is estimated from these gain variations using the gain-fitting method [15]. That is, from Eq. (9), the phase center  $a$  and far-field gain  $b$  are obtained by curve fitting in the far-field range using the least-squares method with the following equation based on the distance ratio:

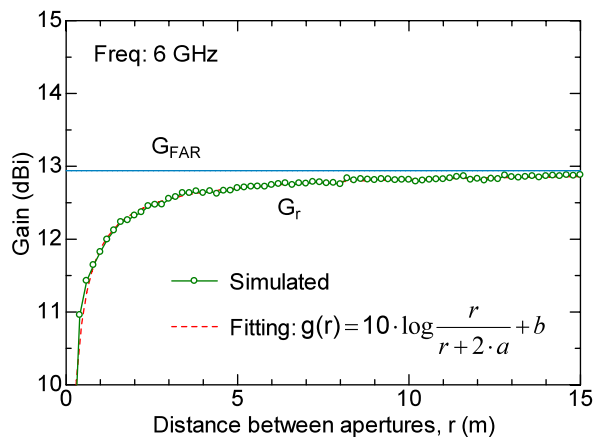
$$g(r), \text{ dB} = 10 \cdot \log \frac{r}{r + 2 \cdot a} + b. \quad (10)$$

A curve fitted using this function is plotted in Fig. 14. The curve fitting is performed with the Levenberg–Marquardt algorithm using 126 data points in the range from 30 to 80 m, which satisfy the far-field criterion, in steps of 0.4 m. The phase center and estimated gain at 8.2 GHz obtained from the curve fitting are 0.426 m ( $a$ ) and 22.88 dBi ( $b$ ), respectively. Additionally, from a different viewpoint, the fitted curve also corresponds to the correction factor for gain variation. In other words, we have shown that for antenna calibration, the use of the phase center is effective for correcting the gain variation due to the separation distance, although the proximity effects in the near field and the multiple reflections between the two antennas are not eliminated at small separation distances such as  $2D^2/\lambda$ .

Figure 15 shows the phase center of the C-band horn antenna at each frequency evaluated from the distance characteristics of the gain using the gain-fitting technique. To confirm the validity of this result, the phase centers obtained by applying the Muehldorf formula and by computation using the CST FIM solver are plotted in the same figure. The phase center determined by the proposed technique is in



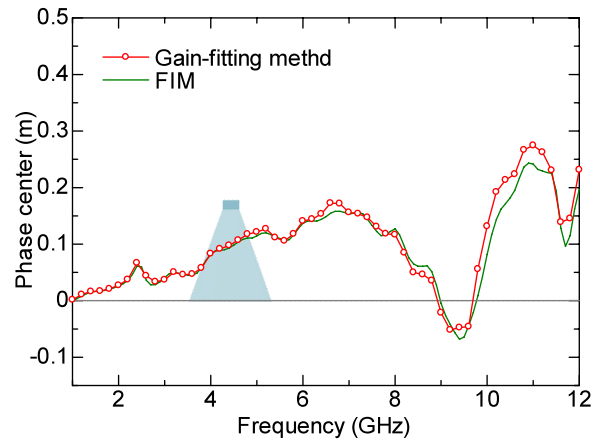
**Fig. 15** Phase center location relative to the aperture of the C-band pyramidal horn antenna determined by the gain-fitting method [15].



**Fig. 16** Gain characteristics of the DRGH antenna obtained from distance between apertures by MoM simulation.

agreement with the FIM result when the fitting range satisfies the far-field criterion (e.g., from  $12D^2/\lambda$  to  $32D^2/\lambda$ ).

Next, the gain-fitting method is applied to the model of the DRGH antenna shown in Fig. 6. The simulation result for the gain variation of the ridged horn antenna at 6 GHz due to the separation distance is shown in Fig. 16. The gain is determined at separation distances  $r$  of 0 to 15 m in steps of 0.2 m using the MoM model of the two-antenna method, as shown in Fig. 6. The phase center of the DRGH antenna at each frequency evaluated from the gain variation using the gain-fitting technique is shown in Fig. 17. The phase center is determined by this technique with a fitting range of 3 to 15 m satisfy the far-field condition, and is in agreement with the value computed using the CST FIM solver. The phase center of the DRGH antenna is more sensitive to the frequency than that of the pyramidal horn antenna, and is located outside the antenna at some frequencies above 9 GHz. This is due to the difference in the maximum beam and bore-sight directions (see Fig. 7).



**Fig. 17** Phase center location relative to the aperture of the DRGH antenna determined by the gain-fitting method.

## 5.2 Gain Two-Distance Method

The gain two-distance method [16] is also a technique used for determining the phase center from the distance-dependent gain variation resulting from applying the Friis transmission formula. In other words, the phase center can be estimated from gains determined at two different distances using the two-antenna method. Some similar approaches have been proposed for gain measurement [8], [9] and its numerical simulation based on theoretical investigations regarding the amplitude center [30], which involve the near-field region. However, we use the gain variation in the far-field region. The ratio between each gain at two different distances ( $r_1$  and  $r_2$ ) is obtained from Eq. (9) as follows:

$$\Delta G = \frac{G_{(r_1)}}{G_{(r_2)}} = \frac{r_1}{r_1 + 2 \cdot d_{PC}} \cdot \frac{r_2 + 2 \cdot d_{PC}}{r_2}. \quad (11)$$

Therefore, the phase center is obtained from Eq. (11) as

$$d_{PC} = \frac{r_1 \cdot r_2 \cdot (1 - \Delta G)}{2(\Delta G \cdot r_2 - r_1)}. \quad (12)$$

Figure 18 shows the phase center of an LPDA antenna estimated from the FIM simulation model (see Fig. 8) using this technique. The location of the phase center is calculated from the gains determined at distances of 0.5 m ( $r_1$ ) and 1 m ( $r_2$ ), as shown in Fig. 9. The location of the phase center is often approximated as that of the resonant dipole element, and the location is given by

$$d_{resonant} = \frac{1/f_{max} - 1/f}{1/f_{max} - 1/f_{min}} l, \quad (13)$$

where  $f_{max}$  and  $f_{min}$  are the maximum and minimum frequencies, respectively, and  $f$  is the operating frequency. As the frequency increases, the phase center moves from the vicinity of the end of the LPDA antenna toward the tip. However, below 6 GHz, the location of the phase center differs from that of the resonant dipoles. To compare these results, the phase center computed using the CST FIM solver

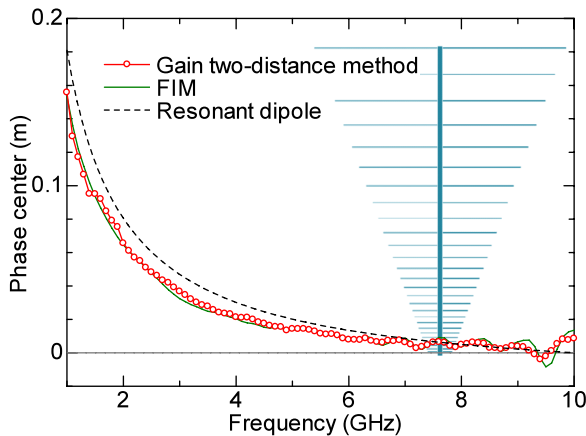


Fig. 18 Phase center location relative to the tip of the LPDA antenna determined by the gain two-distance method [16].

is also plotted in the same figure. The phase center determined by the gain two-distance technique is in good agreement with that obtained from the FIM calculation.

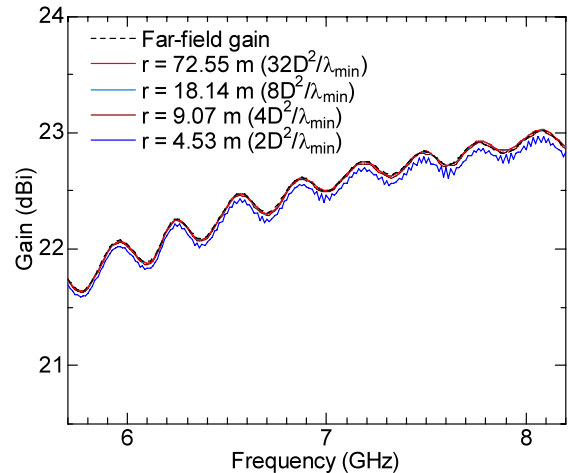
### 5.3 Gain Determination Using the Phase Center

The gain variation due to the separation distance between antennas in far-field gain measurement is caused by the difference between the given reference point and the phase center of an antenna. This means that the gain variation can be corrected using the phase center, as shown in Fig. 14, at a distance where the proximity effects in the near field and multiple reflections between the two antennas are negligible.

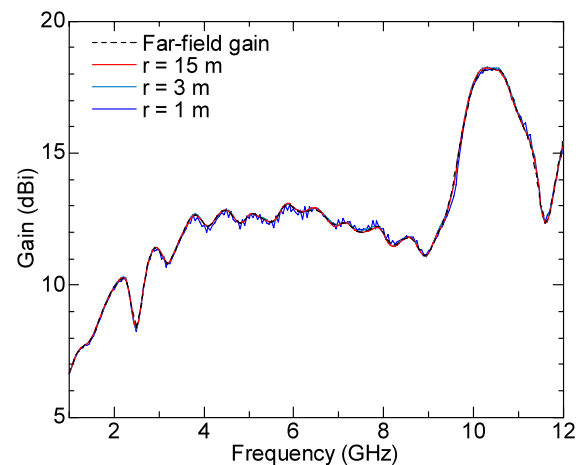
Simulation results of the gains obtained for the pyramidal horn, DRGH, and LPDA antennas using the phase center are shown in Fig. 19. The gain is determined by using the distance between the phase centers as the separation distance in Eq. (6). The plots of antenna gain exhibit good agreement with the far-field gain, regardless of the separation distance. This result indicates that for gain measurement, taking the location of the phase center into consideration does not result in the gain variation due to distance (as shown in Figs. 4, 7, and 9), even at relatively small separation distances (e.g.,  $r = 4D^2/\lambda_{min}$  for the horn,  $r = 1$  m for the ridged horn, and  $r = 0.5$  m for the LPDA). In other words, when the phase center is considered in the gain determination, accurate gain measurements can be performed at reduced distances as compared with the conventional method, in which the given location (e.g., the aperture for the horn or the midpoint of the antenna for the LPDA) is used.

## 6. Experimental Verification

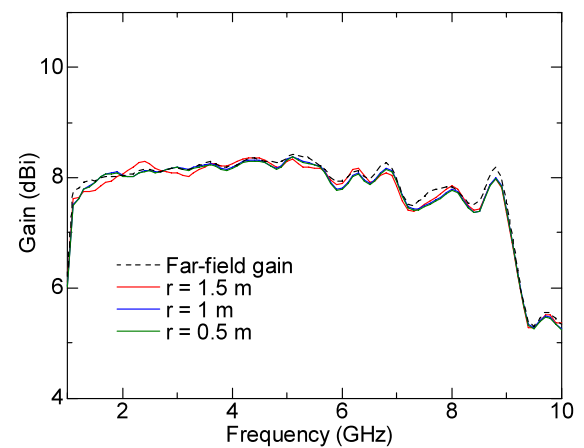
Two different types of commercial antenna were used to evaluate the proposed technique using the phase center. For a commercial V-band pyramidal horn antenna, the far-field gain was determined using the three-antenna method [31].



(a)



(b)

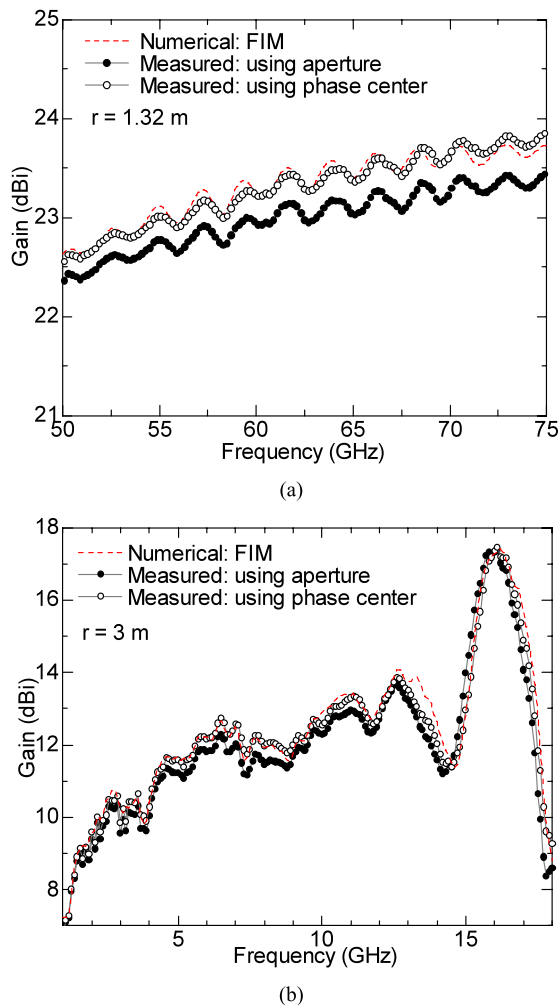


(c)

Fig. 19 Simulation results of gains of (a) pyramidal horn, (b) DRGH, and (c) LPDA [16] antennas determined at several separation distances using the phase center.

Two horn antennas were placed opposite each other in a full anechoic chamber with a distance  $r$  of 1.32 m ( $4D^2/\lambda_{min}$ ) between the apertures of the horn antennas. Both antennas were connected to a vector network analyzer. We mea-





**Fig. 20** Measured far-field gain of (a) V-band pyramidal horn ( $a = 36.42$  mm,  $b = 27.67$  mm,  $l_E = 67.42$  mm, and  $l_H = 70.96$  mm) and (b) DRGH ( $a = 240$  mm,  $b = 140$  mm, and  $l = 197$  mm) [32] antennas using the three-antenna method.

sured the antenna insertion ( $S_{21}$  parameter) and impedance mismatch ( $S_{11}$  parameter) losses in the 50 to 75 GHz frequency range for the three pairs of antennas and determined the far-field gains using Eqs. (2)–(4). For another commercial DRGH antenna with an operating frequency range of 1 to 18 GHz, the far-field gain was determined in the same manner with a distance  $r$  of 3 m between the apertures [32]. The phase centers of these antennas were computed by post-processing using the FIM solver, that is, from the calculation of equiphase patterns.

Figure 20 shows the far-field gains of the pyramidal horn and DRGH antennas determined using the three-antenna method. The theoretical values obtained by the FIM are shown in the same figure for comparison. The measured result for the horn obtained from the distance between the apertures is approximately 0.4 dB less than that the theoretical far-field gain, as shown in Fig. 20(a); however, that of obtained from the distance between the phase centers is in good agreement with the theoretical value. The gain of the

DRGH corrected using the location of the phase center at the relatively small separation distance of 3 m is also in good agreement with the far-field gain, as shown in Fig. 20(b). These results show the effectiveness of correcting the fixed reference point to the phase center location to accurately determine the far-field gain at reduced separation distances.

## 7. Conclusion

In this study, we presented numerical simulations of the distance-dependent gain variation that exists in conventional gain measurements for several broadband antennas. The analyses were performed using the method of moments with higher-order basis functions and the finite integration method. The simulation results indicate the following: (1) the gain variation corresponds to the ratio of the distances between two given reference points, such as between the apertures, to the distance between the phase centers of two antennas. (2) The phase center can be approximated by exploiting the gain variation due to the distance, that is, by the curve fitting considering the function based on the distance ratio, namely, the gain-fitting method, or from gains determined at two different distances, namely, the gain two-distance method. (3) An accurate far-field gain is obtained at reduced distances using the phase center. For example, for horn antennas, the separation distance is reduced to  $4D^2/\lambda$  from  $32D^2/\lambda$ , which is required in conventional measurements. The experimental results also confirm the usefulness of using the phase center.

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