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Effect of Quiet Zone Ripples on Antenna Pattern Measurement

Xiaoming Liu[1, *] and Junsheng Yu[2]

Abstract—Compact antenna test range (CATR) is one of the most commonly used antenna measurement techniques, particularly in the microwave/millimetre wave range. A conventional industry standard for the quiet zone of a CATR is $\pm 0.5\,\text{dB}$ amplitude variation and $\pm 5^\circ$ phase variation to conduct measurement with acceptable accuracy. Such a high standard, however, has not been rigorously verified in theory. And it is in contrast to 22.5° phase variation condition for the far-field method. Being inspired by many measurements, where the quiet zone is not up to the industry standard while satisfactory results are still obtained, this paper systematically investigates the effect of quiet zone performance on the radiation pattern measurement. It aims at searching for a guideline specifications for the construction of a CATR. Theoretical models have been built to predict the quiet zone performance on the antenna pattern measurement, particularly on the main beam. Many factors have been considered, such as amplitude and phase ripple, amplitude/phase taper, and electrical size. In coupling with experimental study, it is shown that a much more relaxed condition can be followed depending on the required measurement accuracy.

1. INTRODUCTION

There are many methods for antenna measurements, for instance, far-field method, near-field method, and compact antenna test range (CATR) [1]. The technique of CATR is suitable for microwave and millimetre wave antenna measurement due to its relative stable electromagnetic environment and full-weather capability. Even in the terahertz range, the CATR technique is still a preferential method for antenna measurement, particularly for electrically large aperture antenna. In a CATR system, reflectors/lenses are utilized to reshape the launching field of a horn antenna to a local area with ideal uniform phase and amplitude distribution. Such a local area used for antenna measurement is referred to as quiet zone (QZ), and is created in a relatively compact space, normally within tens of meters.

There is, however, no ideal quiet zone, where the field distribution is always with much variation in amplitude and phase, as illustrated in Fig. 1. Generally speaking, the amplitude ripple, amplitude taper, phase ripple and cross-polarization are characteristic parameters to the performance of the quiet zone of a CATR system. By an industry empirical standard [2], the amplitude and phase variations shall be within $\pm 0.5\,\text{dB}$ and $\pm 5^\circ$, respectively, to make a trustworthy measurement. Such a standard, though has not yet been proven rigorously, seems already accepted by many vendors, say *Airbus Defense & Space* [3], and *NSI-MI* [4].

Generally speaking, the CATR can be considered as an alternative method to the far-field measurement. To create a local area of approximate planar wave, the far-field measurement method requires that the distance L between the transmitting antenna and the antenna under test (AUT) is larger than $2D^2/\lambda$, with D being the aperture diameter of the AUT and λ the operating wavelength. Such criteria are dedicated by the rule of that the maximal phase difference of the electromagnetic

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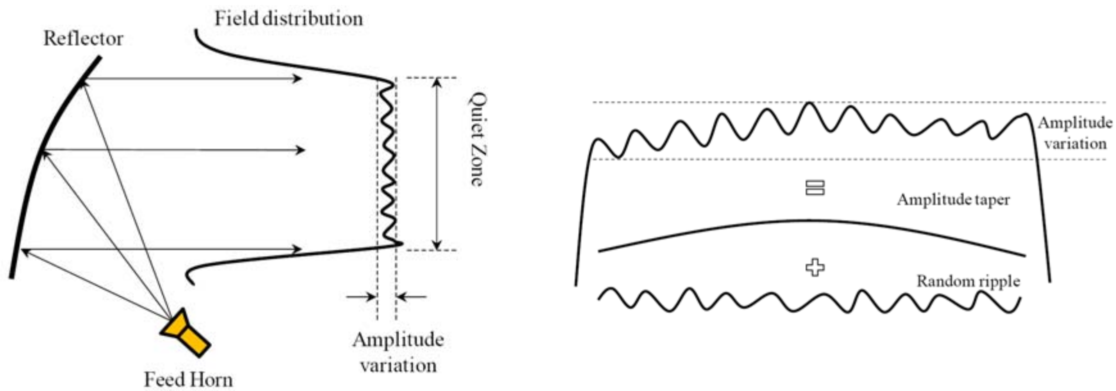
* Corresponding author: Xiaoming Liu (xiaoming.liu@ahnu.edu.cn).
1 Anhui Key Laboratory of Optoelectronic Materials Science and technology, Anhui Normal University, Wuhu 241002, China.
2 School of Electronic Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China.



(a) (b)

Figure 1. A simple illustration of a single-reflector CATR system and its field distribution. (a) The quiet zone of a CATR system. (b) Amplitude variation.

wave incident on the AUT is smaller than 22.5° [1] and that the first null of the antenna pattern can be recognized [5]. In this sense, the far-field method seems less stringent than a CATR system. Although larger distance may be used in practice, say $4D^2/\lambda$ [5], the increasing distance between the transmitting horn and the AUT is prohibited for electrically large antenna in the millimetre wave and THz range. This is very much because the atmospherical absorption in the millimetre wave range is very predominant, and building large dynamic range electronic systems in this frequency range is challenging. Nevertheless, by the far-field standard, antenna measurement is still acceptable. Therefore, one question that rises is that why a CATR system requires a much higher standard? Or in other words, is there any possibility that a CATR system of 22.5° phase variation still provides acceptable measurement?

Actually, a few publications show that even the quiet zone is not up to the industry standard, the measured results are still acceptable [6–8]. A space qualified antenna may be much more stringent in terms of gain measurement accuracy. For instance, from the published data by *Airbus Defense & Space* [3], the gain accuracy can be within ±0.25 dB. However, for a common ground-based antenna, for instance, microwave relay communication, the gain accuracy is less strict; for instance 1 dB gain deviation is satisfactory. It is therefore possible that a much relaxed condition may be adequate for antenna pattern measurement. Theoretically, Wayne et al. [9] presented a method to estimate antenna pattern parameter uncertainty from specified QZ metrics for a given ideal or expected antenna pattern. This method provides a worst case boundary condition that though technically correct, is over pessimistic in the typical compact range [9]. Unfortunately, this work did not suggest a quantitative standard of QZ to the community of antenna measurement. Gregson and Parini for the first time presented the work using a newly developed CATR computational electromagnetic method to examine the effect that specific QZ performance parameters have on antenna pattern measurement. It was found that the conventional specification produces an uncertainty of nearly ±1 dB on a −20 dB side-lobe level [10]. However, their effects on the main beam have not been fully addressed.

It is therefore the purpose of this work to investigate the far-field distortion to the main beam due to imperfect QZ comprehensively and try to build a link between the QZ performance and measurement accuracy. To address this issue, theoretical models are presented to mimic the measurement scenario. Two representative types of antennas, line antenna and aperture antenna are investigated. The QZ variations are set to random distribution, and the amplitude taper is set to parabolic distribution. As a special case, sinusoidal ripple is also studied since in many systems multi-path effect and edge scattering cause high-order harmonics. To experimentally verify the proposed concept, a corrugated horn is measured in the QZ of a tri-reflector compact antenna at 135 GHz, and 200 GHz. The QZ performance was worse than the current industry standard.

The following part of this paper is organized as follows: Section 2 is devoted to the general theory for the cases of line and aperture antennas, while Section 3 is for the calculation results based on Section 2; Section 4 discusses the general cases based on the numerical results; Section 5 summarizes this work.

2. THEORETICAL MODELS

2.1. Receiving Antenna in Non-Ideal Quiet Zone

The receiving process of an antenna is in essence the coupling of the incident field to the supportable mode. A generalised form can therefore be written as

$$I = \langle E_{\mathrm{in}}(x, y), M(x, y) \rangle, \tag{1}$$

where $\langle\rangle$ defines the operator calculating the coupling between the incident wave $E_{\mathrm{in}}(x, y)$ and the supporting mode $M(x, y)$.

Actually, it has been well understood that an amplitude variation of the illuminating field can produce an error in the measured pattern of the AUT, and this effect can be evaluated by recognising that the variation of illuminating field over the AUT on receive is analogous to the modification of the aperture illumination from its feed on transmit [5]. In other words, suppose that the AUT has an aperture illumination from its feed on transmit given by $M(x, y)$ and that the variation of the incident field is given by $E_v(x, y)$, the measured radiation pattern is essentially the same as that for the transmitting case with the feed modified to produce a distribution over the AUT given by $E_v(x, y) \cdot M(x, y)$ [5].

2.2. Variation Model of Amplitude and Phase

Basically, there are three types of variation, random ripple, taper variation, and slow sinusoidal variation. The random ripple in a QZ is seen in many systems, as shown in [11] and [12]. Such variation is normally contributed by many factors, such as random noises, residue reflections from absorption materials, and the imperfection of the reflectors. Particularly, the machining accuracy contributes much to the performance, usually requires an RSM less than $\lambda/50$, best $\lambda/100$. Amplitude or phase taper is another case in many CATR systems, for instance a single-reflector CATR system or other multi-reflector systems [13]. One possible source of taper variation is displacement of the feed from its idea position. Large-scale distortion due to fabrication may also cause amplitude and phase distortion. This is also an important source of asymmetric quiet zone. Apart from the previous types of variation, periodic ripple is also an important factor in a QZ, for instance, in [14]. This type of variation is probably due to stable scattering or structural imperfection, such as scattering from the supporting structure of reflector and edge diffraction. Edge diffracted rays coming to the QZ often undergo different path lengths and therefore have different phases, causing constructive and destructive field distributions in the QZ. Though there are many factors causing imperfect quiet-zone, we are going to focus on the following types as illustrated in Fig. 2.

The random ripple can be modelled as

$$I(z) \propto U(-a, a), \tag{2}$$

which indicates that the amplitude or phase ripple $I(z)$ conforms to a uniform distribution in the range of $(-a, a)$. An example of random amplitude ripple of ± 1 dB is shown in Fig. 2(a). The taper and sinusoidal variations can be modelled as

$$I(z) = -I\left(\frac{z}{l}\right)^2, \tag{3}$$

and

$$I(z) = I \sin\left(\frac{n\pi z}{\lambda}\right), \tag{4}$$

respectively. In Equations (3) and (4), I is the maximal amplitude/phase deviation, l the size of the QZ, n the order of sinusoidal ripple, and λ the wavelength of operation. Therefore, parameter n stands for how fast the local variation is in terms of one wavelength. Such a criterion is to make sure that the assessment is conducted in terms of electrical size rather than a physical one. Examples of taper variation and harmonic variation are shown in Figs. 2(b) and (c), respectively. A true QZ is very likely a combination of the three types of variation, as shown in Fig. 2(d). The calculation in this paper, however, will not consider the combination cases.

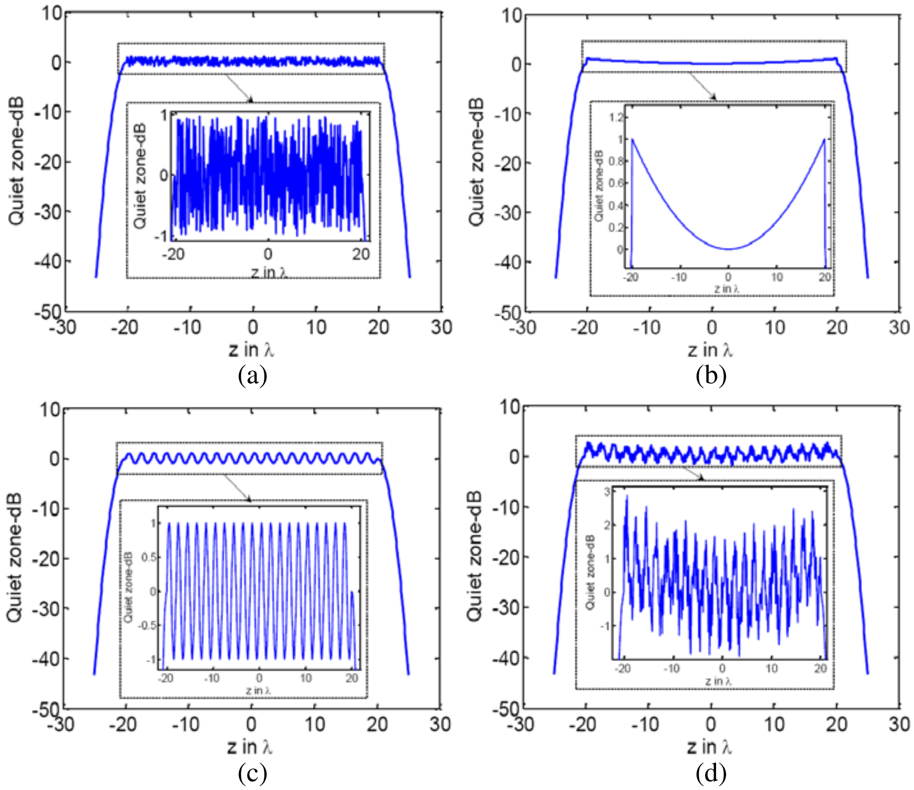


Figure 2. A quiet zone with amplitude ripple of ±1 dB. (a) Radom ripple. (b) Taper variation. (c) Sinusoidal variation. (d) Combined variation.

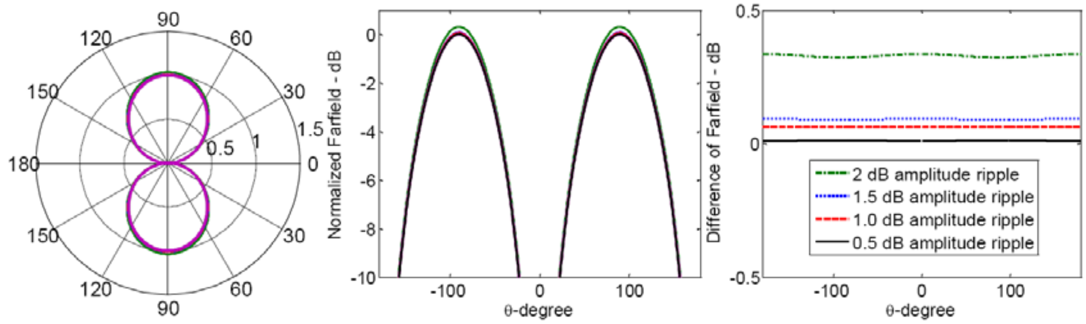
3. CALCULATION RESULTS

3.1. Random Ripple

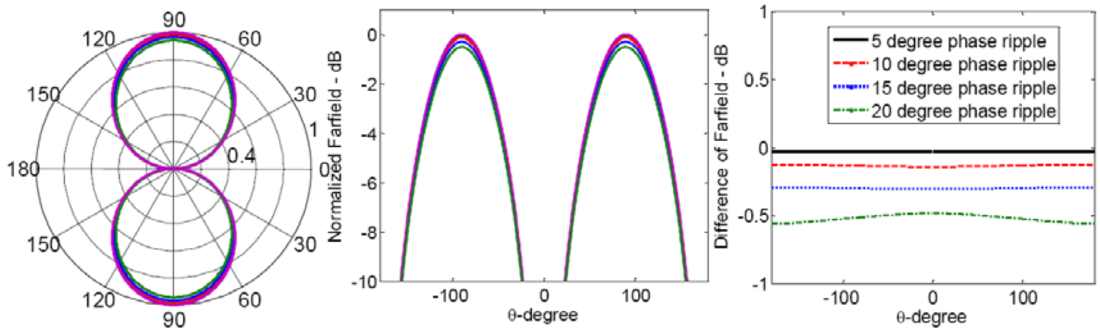
For the calculation of the influence of random ripple to antenna far-field, the ripple conforming to uniform distribution as Equation (2) is employed. A line antenna of 0.5λ is employed for the calculation. Two cases are considered. (1) The amplitude random ripples are set to $a = 0.5$ dB, 1.0 dB, 1.5 dB, and 2.0 dB with the phase ripple set to 0°; (2) The phase ripples are set to $a = 5°$, 10°, 15°, and 20° with the amplitude ripple set to 0 dB. The calculation results using Equation (1) are shown in Fig. 3(a) and Fig. 3(b), for different levels of amplitude and phase ripples, respectively. It is seen that for the amplitude variation, when $a = 0.5$ dB, the far-field deviation is less than 0.1 dB compared to that of an ideal QZ. For the phase ripple, when $a = 5°$, the far-field deviation is less than 0.1 dB compared to that of an ideal QZ. Even for much worse cases, for instance, 2 dB amplitude ripple and 20° phase ripple, the far-field deviation is less than 0.6 dB.

3.2. Taper Variation

By using Equation (3), the amplitude random ripple is set to $I = 0.5$ dB, 1.0 dB, 1.5 dB, and 2.0 dB, while the phase ripple is set to $I = 5°$, 10°, 15°, and 20°, respectively. As seen from Fig. 4(a), the far-field deviation can be as high as 1.8 dB for amplitude taper of 2 dB when the phase is set to be ideal. On the other hand, for phase taper, see Fig. 4(b), the radiation pattern does not change too much compared to that of an ideal QZ. The comparison indicates that amplitude taper distorts the radiation pattern much more serious than phase taper does.

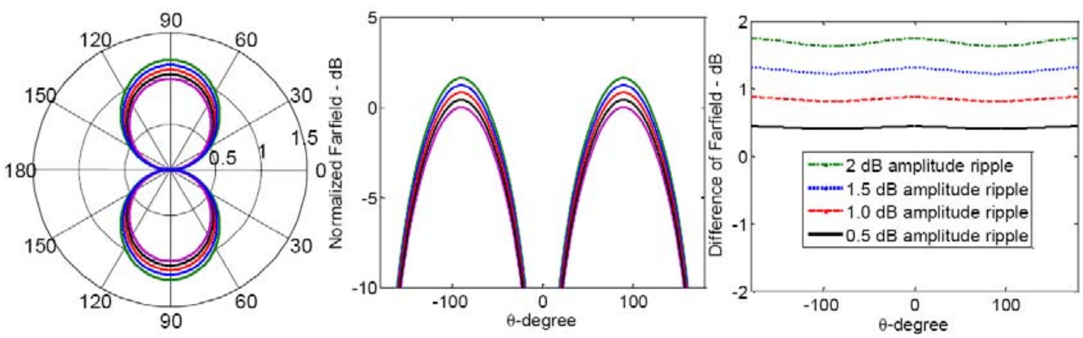


(a)

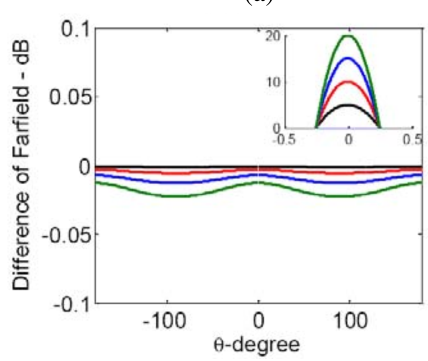


(b)

Figure 3. Radiation pattern of different level of random ripple. (a) Random amplitude ripple. (b) Random phase ripple.



(a)



(b)

Figure 4. Radiation pattern of different level of amplitude taper. (a) Amplitude taper. (b) Phase taper.

3.3. Sinusoidal Variation

The distortion on radiation pattern when the amplitude variation is set to 0.5, 1.0 1.5 and 2.0 dB is plotted in Fig. 5. While the phase variation of 5°, 10°, 15°, and 20° is shown in Fig. 6. Four values of n have been selected as examples, i.e., $n = 2, 5, 10, 20$. It has to be pointed out that $n = 2$ stands for

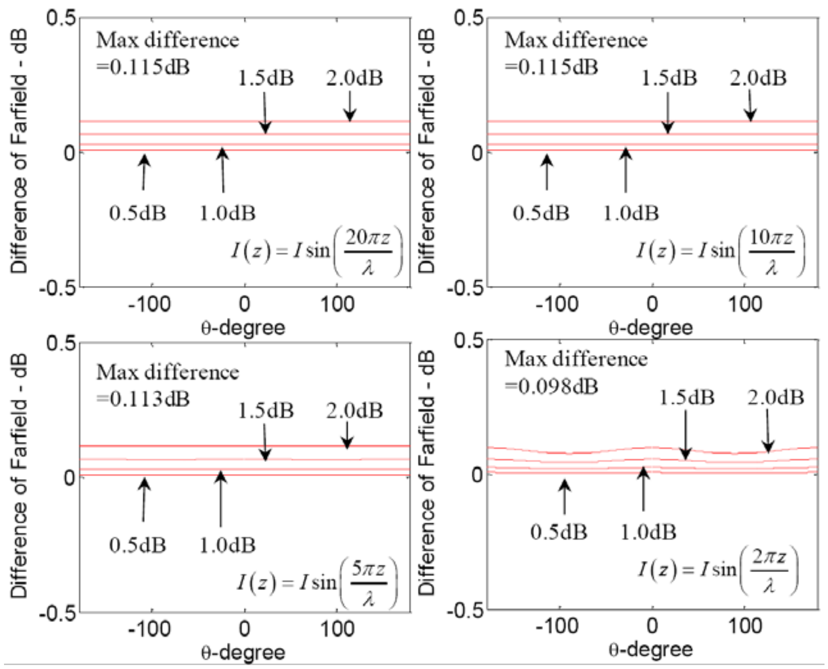


Figure 5. Distortion on radiation pattern of different level of sinusoidal amplitude variation.

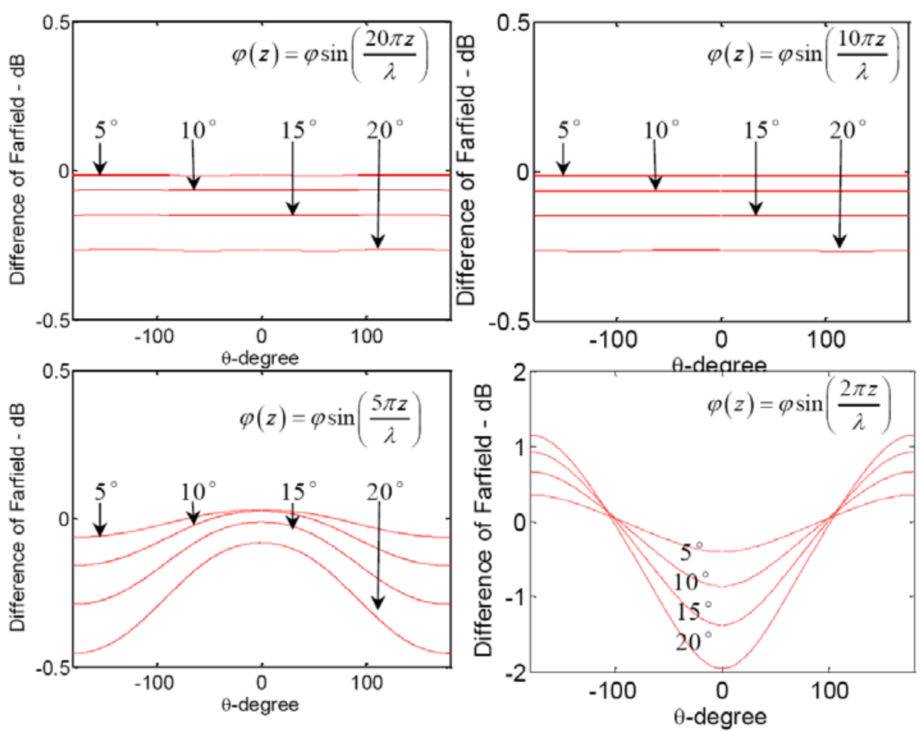


Figure 6. Distortion on radiation pattern of different level of sinusoidal phase variation.

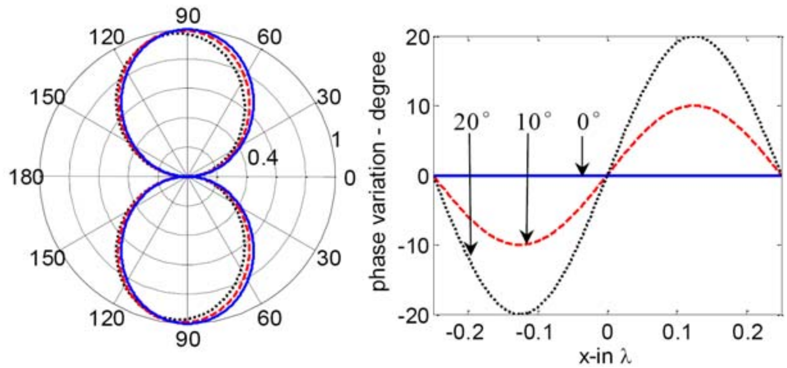


Figure 7. Radiation pattern of different level of periodic phase variation.

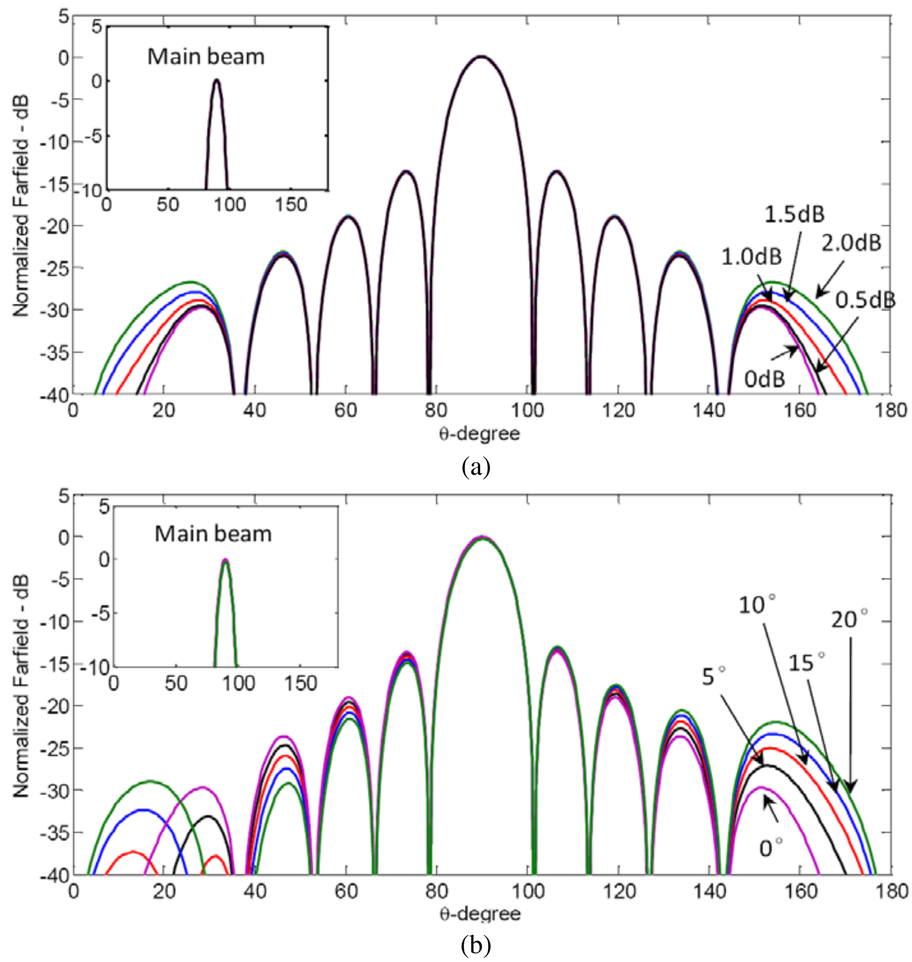


Figure 8. Radiation pattern of different level of variation for a 5λ line antenna with uniform distribution. (a) Amplitude variation. (b) Phase variation.

slow variation, while $n = 20$ is for fast variation. As it is mentioned that n stands for periodic variation in terms of a wavelength, one antenna working at different frequencies may suffer different distortions on radiation pattern if the variation remains unchanged in terms of physical size. From the plots, it is clearly seen that amplitude variation does not cause too much difference to the radiation pattern, maximally 0.115 dB, while for phase variation, the radiation pattern shows much significant change, particularly for small value of n. Seen from Fig. 7, the radiation pattern is actually distorted depending on the phase variation.

3.4. Effect of Electrical Length

To investigate the effect of electrical length, a line antenna of 5λ in length is considered. The predicted fields are presented in Fig. 8. From the results, it can be deduced that the main beam is not affected too much, even smaller than the electrically small case, while the far side lobes are much more affected, particularly for the case of large phase deviation. It seems that phase is easier to affect the radiation pattern than amplitude does. For instance, the third side lobe increases from -25 dB to roughly -20 dB, and the fourth side lobe increases from -30 dB to roughly -23 dB when the phase variation increases from $0°$ to $20°$. In comparison, when the amplitude variation increases from 0 dB to 2 dB, the third side lobe does not change too much, roughly a couple of dB, and the fourth side lobe increases from -30 dB to roughly -27 dB.

Therefore, for electrically-large antenna, side lobes are more affected by non-ideal QZ, and the phase seems to play a more important role.

3.5. Aperture Antenna

For the aperture antenna, only the E-plane is investigated. Assuming a uniformly distributed rectangular aperture of 5λ in width and the QZ of 0.5, 1.0 1.5, 2.0, 3.0, 4.0, 5.0, and 6.0 dB, the far-fields are plotted in Fig. 9(a). For the cases where the phase variation is 5°, 10°, 15°, 20°, 25°, 30°, 35°, and 40°, and the results are presented in Fig. 9(b). To reach 2 dB distortion on the boresight direction, 6 dB standard variation should be introduced, and 40° phase standard deviation should be introduced to reach 2 dB distortion. To reach 0.5 dB distortion, the standard deviations of amplitude and phase are 3 dB and 20°, respectively.

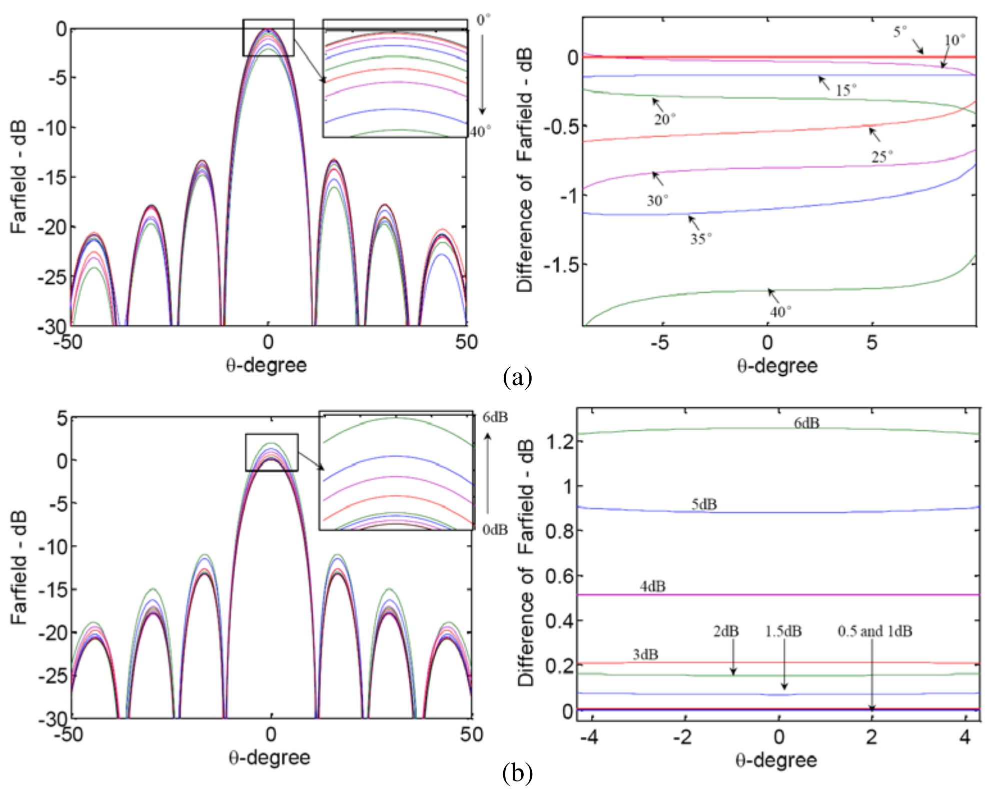


Figure 9. Far-fields of various ripple. (a) Amplitude. (b) Phase.

For the cases of amplitude/phase taper and sinusoidal variation, similar results to line antenna have been found. Therefore, these results were not presented.

4. DISCUSSION

Comparing the three kinds of variation, random ripple, taper variation, and sinusoidal variation, it is seen that the most harmful deviation is amplitude taper, see Figs. 3–9. In contrast, random variation and sinusoidal variation are much less influential to the radiation pattern. Lower order sinusoidal phase variations have more effects than higher order ones, see Fig. 6. For electrically large antenna, the main lobe is not affected appreciably by amplitude or phase variation, while side lobes are more prone to both variations, particularly phase variation. For aperture antennas, the same observations can be made.

Using a half-wavelength line antenna, more calculations were conducted, with the calculated results presented in Tables 1 and 2. Considering the worst situation, to achieve 0.5 dB accuracy, the amplitude variation should be within 0.5 dB, while the phase variation has to be within 5°, which is consistent with the industry standard. However, to achieve 1.0 dB accuracy, the standard can be relaxed to 1.0 dB amplitude variation and 15° phase variation. If 2.0 dB accuracy is acceptable, then the standard becomes 3 dB amplitude variation and 25° phase variation. In many cases, the amplitude taper is not present in a QZ, for instance, Fig. 9(a) in [15], Fig. 8(a) in [16], and Fig. 6-6 in [17]. In that case, the QZ standard can be much further relaxed. For instance, to achieve 0.5 dB accuracy, the amplitude variation can be 2 dB, and the phase variation can be 20°.

Table 1. Variation of the far-field in the boresight direction of various amplitude variations.

Unit-dB	0.5	1	1.5	2	3	4	5	6
Random	0.01	0.05	0.11	0.20	0.57	0.84	1.45	2.03
Taper	0.40	0.81	1.26	1.61	2.02	2.46	3.28	4.11
Sin ($n = 2$)	0.01	0.03	0.06	0.15	0.26	0.45	0.71	1.01

Table 2. Variation of the far-field in the boresight direction of various phase variations.

Unit-degree	5	10	15	20	25	30	35	40
Random	−0.04	−0.13	−0.28	−0.53	−0.83	−1.20	−1.67	−2.06
Taper	−0.002	−0.01	−0.03	−0.05	−0.07	−0.11	−0.14	−0.19
Sin ($n = 2$)	−0.03	−0.13	−0.30	−0.52	−0.81	−1.20	−1.62	−2.07

The theoretical results indicate much more relaxed conditions than the conventional standard. Indeed, many examples have demonstrated that the QZ ripple can be relaxed, while not degrading the radiation pattern measurement noticeably [6–8]. In addition, two horn antennas, as shown in Fig. 10(a), have been measured in a CATR system with 2 dB amplitude ripple and 30° phase ripple, see [4]. The aperture of each antenna is 5.3λ in diameter at the measured frequencies. Parameters are fed to commercial software *CHAMP* (*TICRA*) for simulation assessment. Also, it is predicted by using Equation (4) with $n = 5$ that the maximal difference between the distorted pattern and ideal pattern is within 1.0 dB for the main beam. It has to be pointed out that the reason for selecting $n = 5$ is that the ripple in the central region is more like a sinusoidal distribution fit to the model of Equation (4) with n approximately equal to 5. The measured results in comparison with the simulated ones are presented in Figs. 1(b) and (c). It is seen that the difference between the measured and simulated results are within 0.5 dB for 3 dB beamwidth. For a −8.686 dB beamwidth, a Gaussian beam representation [18], the difference is within 0.8 dB. The overall deviation in the range of [−20°, 20°] is within 1 dB, see Fig. 10(d). The comparison of the far-field phase between the simulation (solid line) and measurement (dotted line) is plotted in Fig. 10(e). Since absolute phase is position dependent, an obvious difference

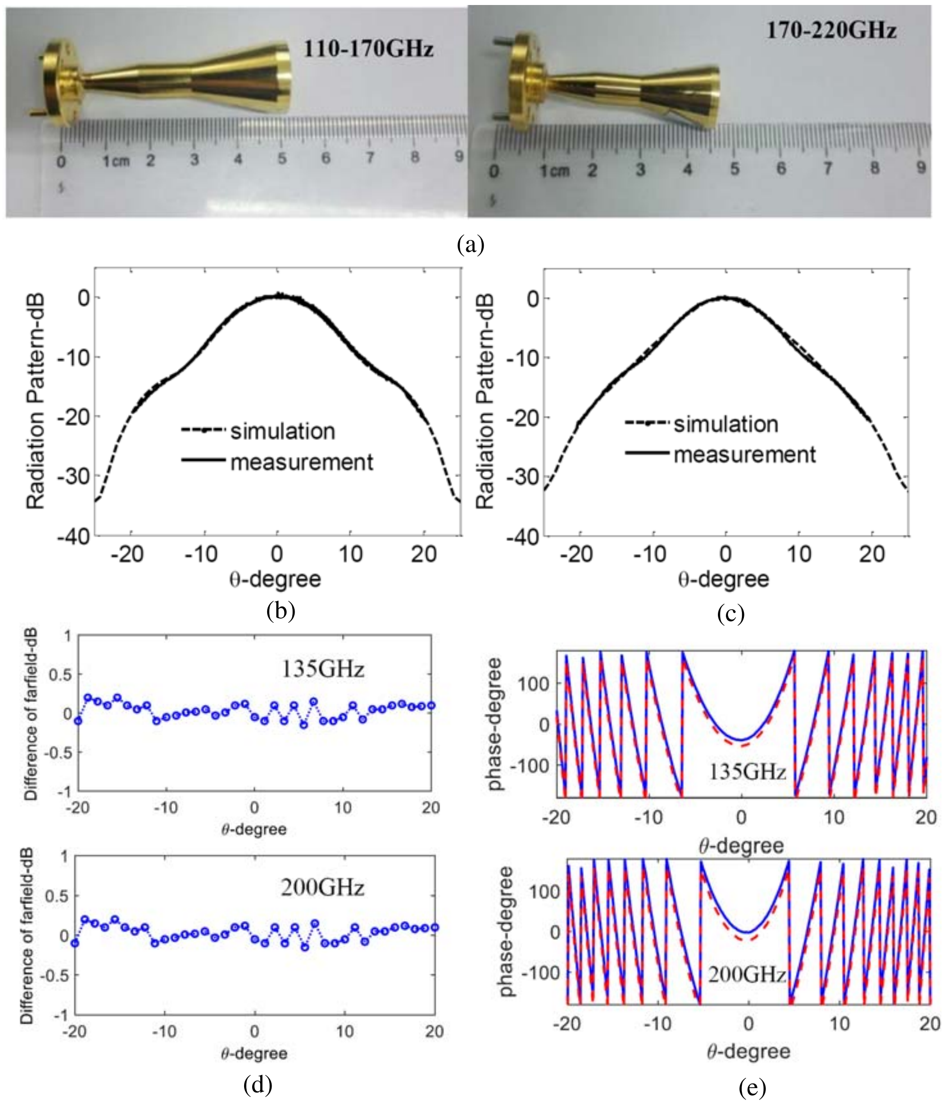


Figure 10. Comparison between simulated results and measured results in a non-ideal quiet zone of 2 dB amplitude ripple and 30° phase ripple. (a) Photograph of the horn antennas at 110–170 GHz, and 170–220 GHz. (b) 135 GHz. (c) 200 GHz. (d) Difference between measurement and simulation. (e) The comparison of the measured and simulated phases of the far-filed.

is observed in the main beam range. However, the difference between the simulation and measurement is almost a constant, about 10 degrees for 135 GHz and 14 degrees for 220 GHz.

As the experiment shows, a QZ of 2 dB amplitude ripple and 30° phase ripple can still give a much acceptable radiation pattern, see Fig. 10. Referring to the far-field condition, i.e., 22.5° phase ripple, the industry standard seems much higher than needed in most cases. To appreciate this phenomenon, one has to bear in mind of that the far field of an antenna is integration over its near field. In other words, it is a process of averaging or smoothing. The effect of fast variation over the near field, in most cases is screened by averaging. However, slow variation, particularly amplitude taper and slow phase variation, is much more harmful to the radiation pattern measurement, as can be seen from Figs. 5 and 6. This is because there are no enough integration elements to cancel each other in the case of slow variation, which is quite similar to fast fading and slow fading. Fast fading can be overcome using an integrator, while slow fading is much more complicated. Normally diversity techniques are required to offset the effects of slow fading.

Surely, if 0.5 dB accuracy is needed, then the conventional standard has to be employed. This is why the conventional standard is considered for most CATR systems, since many reflector antennas are for space-borne applications. However due to the coming millimetre wave communication [19, 20], such high precision gain measurement is not required. For instance, 1 dB accuracy is adequate, and the condition can consequently be relaxed. This is because many millimetre wave communications on the ground only require omnidirectional pattern, and coverage is superior to the gain accuracy.

In comparison, other error sources are much more influential than the QZ performance, such as the stability of the mechanical system, random noise in the electronic system, and stray signals coupling into the AUT. Many works have been published to reduce the measurement errors. A few examples can be listed as [8, 21–23].

5. CONCLUSION

Theoretical models have been built to predict the QZ effect on the antenna pattern measurement. It is found that to achieve 0.5 dB accuracy measurement, the conventional standard has to be employed, while for 1.0 dB accuracy measurement, the standard is much relaxed. The far-field condition of 22.5 degree phase variation is one boundary metrics, by using which the first lobe and first null can be distinguished, corresponding to a low-accuracy measurement. For higher accuracy measurement, the distance between the transmitting antenna and the AUT has to be increased to further reduce phase variation. In this sense, the compact range technique is very similar to the far-field range. Furthermore, it is found from the calculation that amplitude taper is the most harmful variation in antenna pattern measurement. In addition, it is found that for electrically large antenna, the sidelobes are much more affected by non-ideal QZ than the main beam is. Experiments suggest that QZ of 2 dB amplitude ripple and 30° phase ripple can still give 0.8 dB accuracy of measurement.

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