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A Feed Scanning Based APC Technique for Compact Antenna Test Ranges

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Abstract—The measurement accuracy of a compact antenna test range (CATR) depends on the level of spurious signals. To improve the measurement accuracy, several error compensation methods have been developed, but most of them are not feasible at submillimeter wavelengths. This paper introduces an error compensation technique for compact antenna test ranges, which is especially suitable at submillimeter wavelengths. The method is based on antenna pattern comparison (APC). In the original APC technique the antenna pattern is recorded several times at different positions of the quiet-zone field, and the corrected pattern is obtained by averaging the measured patterns. In the proposed method, the lightweight transmitter is moved instead of moving the heavy combination of the antenna under test (AUT) and the rotation stage. The feasibility of the method is studied and the method is tested with measurements in a hologram based compact antenna test range at 310 GHz. The accuracy provided by the proposed method is compared to the accuracy provided by the conventional APC. The accuracies provided by both methods are practically equal.

Index Terms—Antenna measurements, compact range, error compensation, submillimeter wave measurements.

I. INTRODUCTION

THE measurement accuracy of a compact antenna test range (CATR) depends on the level of spurious signals. The level of any spurious signal should be about 10 dB below the side lobe level of the antenna under test (AUT), in order to measure the antenna pattern with an uncertainty of better than 3 dB. When measuring low side lobe levels, this condition is extremely difficult to fulfill. Possible sources of the spurious signals are for example diffraction from the edges of the focusing element and reflections in the range. The surface accuracy requirements of the focusing element (usually a reflector, but can be a hologram [1]) tighten with the frequency, and in the submillimeter wavelengths also the surface inaccuracies may cause field distortions in the quiet-zone.

To overcome these challenges, several error compensation methods have been introduced, such as time gating [2], antenna pattern comparison (APC) [3], test zone field compensation [4], virtual array [5], and deconvolution [6]. However, most of them are very laborious to implement and only few are suitable at submillimeter wavelengths. Time gating and antenna pattern

comparison are possible correction techniques at submillimeter wavelengths. Because the signal path of the spurious signal is longer than that of the straight signal, the spurious signal arrives later to the AUT than the desired plane wave. In the time gating, the spurious signals are cancelled out from the data by using a fast switch. The gating system can be soft or hard. In the soft gating, the pattern is measured point by point sweeping the measurement frequency in each point. The time domain data are then obtained via inverse Fourier transformation. The time domain gate is finally implemented numerically. In the hard gating, a fast RF switch is used to gate the spurious signals out. In a soft gating system, there must be a possibility to sweep the frequency. At submillimeter wavelengths this may be problematic. Moreover, only spurious signals, whose path length is much longer than the path length of the straight signal, can be cancelled out. Therefore, spurious signals originating from the focusing element can not be cancelled out. In submillimeter ranges this usually enables pattern correction only far from the main beam. In the APC technique, the antenna pattern is measured several times at different positions in the quiet-zone. The APC technique is more laborious than gating, but it allows pattern correction relatively close to main lobe region. A translation stage for moving the combination of the AUT and the rotation stage is needed for implementing the APC method. In the proposed feed scanning APC method (first introduced in [7]), the antenna pattern is measured several times using different transmitter positions. The corrected antenna pattern is obtained by averaging the measured patterns. The proposed method has same benefits as the conventional APC, but it is easier to implement at submillimeter waves, because the relatively small transmitter is moved instead of the potentially very large AUT.

In Section II, we introduce the principle of our proposed method and we discuss its applicability. In Section III we show the test procedure with the method. Section IV discusses the measurement setup. Section V contains the experimental results. The conclusions are presented in Section VI.

II. PROPOSED METHOD

A. Principle of the Method

The proposed method is based on antenna pattern comparison. In the APC method, the antenna pattern of the AUT is recorded several times at different locations in the quiet-zone. Because the spurious signal arrives from different direction than the desired plane wave, the relative phase difference between the spurious signal and the desired plane wave is different at each measurement position. The effect of the spurious signal

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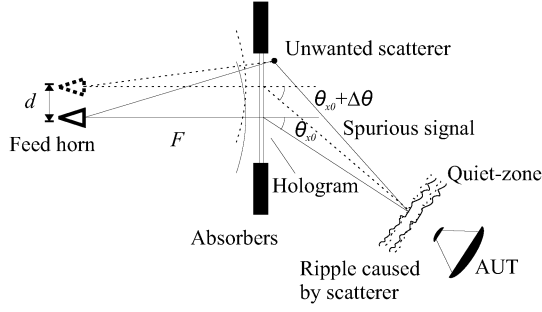


Fig. 1. Different phase change of the desired plane wave and spurious signal in the feed scanning based APC method. In this figure the CATR focusing element is a hologram, but the same principle applies also in case of a reflector as the focusing element.

can be compensated by averaging all the measured antenna patterns or by using an algorithm introduced in [8]. We assume in our proposed method that all the spurious signals originate from the feed antenna, i.e., no external signal sources are present. In that case, it is possible to cause a phase difference to the spurious signal by moving the transmitter instead of moving the AUT (Fig. 1). This is usually more convenient as transmitters are lighter and smaller than the combination of the AUT and the rotation stage. In addition, extra equipment is not needed, because the transmitter is usually placed on a scanner for optimizing the quiet-zone field by moving the feed.

This principle can be used to compensate the errors caused by standing waves between the transmitter and focusing element as well as errors caused by other spurious signals. The emphasis of this paper is on the compensation of the errors caused by spurious signals other than multiple reflections.

B. Optimal Feed Displacement Interval and Range

In order to effectively compensate all spurious signals originating from the transmitter, the optimal feed displacements must be calculated. For this, we need to know the range geometry. The angular range of the AUT, Ψ_{AUT} , in which the correction is performed, is first defined. The angular range is then reflected to the feed via range walls and objects, in order to define the most harmful directions of the scatterers seen from the feed antenna (Fig. 2). The optimal feed displacements can be finally calculated from the range reflected to the feed Ψ_{feed} . The transversal interference period d of two plane waves is

$$d = \frac{\lambda}{\sin \alpha} \quad (1)$$

where λ is the wavelength and α is the angle between plane waves. In this case the angle α is the angle reflected to the feed antenna. The plane wave condition is assumed in (1), i.e., the antenna is in the far-field of the scatterer. However, (1) is approximately valid also in near-field conditions, because a spherical wave front can be represented as a sum of the plane waves. In the near-field conditions, the size of the aperture of the AUT must be taken into account. In the following, the far-field condition is assumed for simplicity. Basically, the largest angle ($\max |\Psi_{feed}|$) defines the displacement interval and the smallest angle ($\min |\Psi_{feed}|$) defines the displacement range.

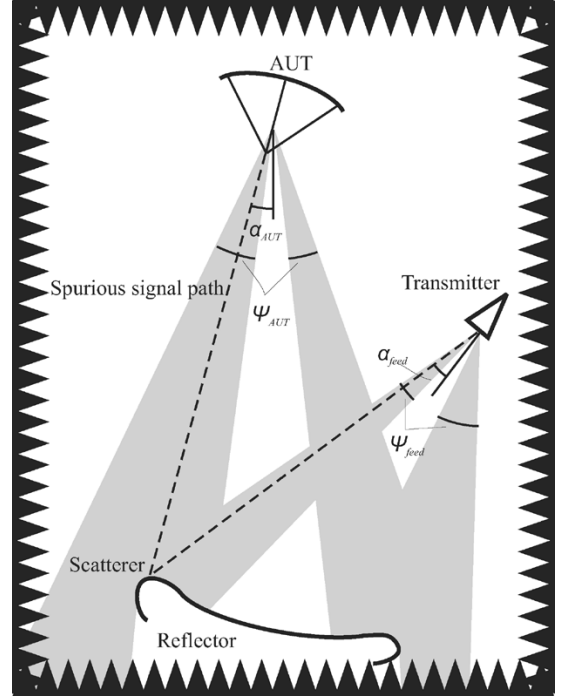


Fig. 2. Angular range of the antenna pattern, where the correction is performed, is projected to the transmitter. The optimal feed displacements are calculated from the projected range.

According to the Nyquist sampling theorem, the displacement interval should be less than one half of the smallest interference period. The displacement range depends on how many periods one wants to capture. Theoretically one period is enough to compensate the effect of the spurious signal. The displacement interval can be calculated from

$$d_{\text{interval}} = \frac{\lambda}{2 \sin(\max |\Psi_{feed}|)}. \quad (2)$$

Similarly the number of measurements needed can be calculated from

$$N = \frac{2 \sin(\max |\Psi_{feed}|)}{\sin(\min |\Psi_{feed}|)} + 1. \quad (3)$$

The needed displacement range is $(N - 1)d_{\text{interval}}$. Basically, the wider is the angular range, the larger number of measurements is needed. The critical factor here is usually the minimum of the angular range. When the correction is performed at small angles, the required displacement range may be huge. However, the correction range does not need to cover the main beam, because the effect of the stray signals on the main beam measurement is small.

C. Limitations to the Feed Displacement

Next we study what happens to the quiet-zone field when the feed is moved outside from the focus of the collimating element. We discuss a hologram based CATR, where the quiet-zone field is generated with a hologram [1], [9], but same principles apply for reflector and lens based CATRs as well. Let us first consider a hologram, which at each point causes a certain phase difference to the transmitted wave at a given frequency. Assume that

the hologram generates an ideal plane wave field propagating to the θ_{x0} -direction, when illuminated with a spherical wave front. If d is a transversal displacement of the feed antenna, the geometrically derived phase change in the illumination of the hologram is

$$\Delta\psi_{\text{inc}}(x, d) = \left(\sqrt{F^2 + (d+x)^2} - \sqrt{F^2 + x^2} \right) \cdot \frac{2\pi}{\lambda} \quad (4)$$

where F is the focal length of the hologram and x is the horizontal coordinate on the hologram surface (the vertical coordinate is omitted for simplicity). This is also the phase change in the transmitted field, since the hologram causes a constant phase change to the transmitted wave at a given place and at a given frequency. The phase of the transmitted field is

$$\begin{aligned} \psi'_{\text{trans}} &= \psi_{\text{trans}} + \Delta\psi_{\text{inc}} \\ &= 2\pi x\nu \\ &\quad + \frac{2\pi}{\lambda} \left(\sqrt{F^2 + (d+x)^2} - \sqrt{F^2 + x^2} \right) \end{aligned} \quad (5)$$

where ψ_{trans} is the original phase of the transmitted field and ν is the spatial frequency defined as

$$\nu = \frac{\sin \theta_{x0}}{\lambda} = \frac{\psi_{\text{trans}}}{2\pi x}. \quad (6)$$

Let us solve the steered direction $\Delta\theta$ of the plane wave. When $x + d \ll F$, (5) can be approximated using the first order Taylor expansion as

$$\psi'_{\text{trans}} \approx 2\pi x\nu + \frac{\pi}{\lambda F} (d^2 + 2xd). \quad (7)$$

The term d^2 is the phase shift of the plane wave with respect to the center of the hologram. Because it has no effect to the direction of the plane wave, it can be omitted. By substituting (7) to (6) we get

$$\sin(\theta_{x0} + \Delta\theta) = \nu'\lambda = \nu\lambda + \frac{d}{F} \quad (8)$$

where ν is the original spatial frequency and ν' is the spatial frequency when the feed is displaced. The steered direction can be solved using the first order Taylor expansion as

$$\begin{aligned} \sin(\theta_{x0} + \Delta\theta) &\approx \sin(\theta_{x0}) + \cos(\theta_{x0}) \cdot \Delta\theta \\ \Rightarrow \Delta\theta &\approx \frac{d}{F \cos \theta_{x0}}. \end{aligned} \quad (9)$$

Depending on the frequency and the range geometry, there is a limit how much the feed antenna can be displaced. First of all, the whole aperture of the AUT must remain in the quiet-zone field when the feed is displaced. Another limitation comes from the fact that moving the feed antenna degrades the quiet-zone quality. In general, the more accurate are the measurements the better should be the quiet-zone quality. When implementing the proposed method we can accept some degradation of the quiet-zone, because the method is still able to compensate the

unwanted effects. However, at certain point it is no longer beneficial to move the feed antenna more since moving the feed antenna causes more distortions to the quiet-zone field than what the method can compensate. The feed displacement limit depends on the AUT and the level of the spurious signals, and therefore no simple formula can be presented for determining the largest reasonable displacement. We decided to limit the displacement to the range, in which the quiet-zone criterion for the phase ($\pm 5^\circ$) is fulfilled. The phase variation from the linear phase slope behind the hologram caused by moving the feed can be solved by subtracting (7) from (5)

$$\Delta\phi = \frac{2\pi}{\lambda} \left(\sqrt{F^2 + (d+x)^2} - \sqrt{F^2 + x^2} - \frac{d^2 + 2dx}{2F} \right). \quad (10)$$

The largest variation occurs at the edges of the quiet-zone. Equation (10) can be used to determine the largest allowed feed displacement. In general, the maximum allowed displacement depends on the frequency and the range geometry.

Let us next consider the quiet-zone amplitude. Transversal movement of the feed changes the hologram illumination. This results into a quiet-zone field with a slope in the amplitude. However, the change in illumination can be mostly compensated by redirecting the feed toward the hologram (or reflector) center. Usually, this is not needed as the displacements are so small, that the illumination remains practically unchanged.

III. TEST PROCEDURE

The method is tested by two ways: by measuring antenna patterns of a real test antenna and a virtual antenna in quiet-zone fields using the feed scanning APC and the conventional APC. A test with the real antenna is made to verify the proposed method. However, the test does not define how well the method operates, because the true antenna pattern is not exactly known. The simulated measurements with the virtual antenna are made in order to compare the accuracy provided by the proposed method to the accuracy provided by the original APC. The comparison is easy since the true antenna pattern (of the virtual antenna) can be analytically calculated.

In addition to normal measurements, the tests are carried out in a situation where the quiet-zone field is intentionally degraded by adding scatterers behind the hologram. The antenna pattern of the test antenna is measured by rotating the AUT in azimuth direction in the quiet-zone. The virtual antenna is tested with a combination of measurements and simulations. First, the two-dimensional quiet-zone fields incident to the AUT aperture are measured using different feed antenna positions. Then, the antenna pattern measurements are simulated by calculating the measured pattern with the equation

$$\mathbf{P}_{\text{meas}}(k_x, k_y) = \iint \mathbf{E}_{qz} \cdot \mathbf{E}_{\text{aper}} \cdot e^{-j(k_x x + k_y y)} dx \cdot dy \quad (11)$$

where \mathbf{E}_{qz} is the measured electrical field of the quiet-zone, \mathbf{E}_{aper} is the aperture field of the virtual antenna, k_x and k_y

are x - and y -components of the wave vector. In both cases, the corrected antenna pattern is obtained by averaging the measured complex antenna patterns. The main lobe peaks of the patterns are normalized to 0 dB in amplitude and 0° in phase and shifted to 0° in angular space. The feed displacement interval is chosen to be 5 mm and the displacement range 50 mm. This enables the most efficient correction approximately in the range of $\pm 1.1^\circ \dots \pm 5.5^\circ$. The positions are located symmetrically on both sides of the center position of the feed antenna. Altogether, the antenna pattern (or the quiet-zone field in the case of the virtual antenna) is measured 11 times. For verification purposes, the conventional APC technique is tested. The displacement interval of the AUT is chosen to be the same 5 mm and the range 50 mm. The corrected antenna pattern is obtained similarly by averaging the measured patterns.

IV. MEASUREMENT SETUP

The method is tested in a hologram based compact antenna test range at 310 GHz. The focal length of the hologram is 1.8 m and the hologram diameter is 600 mm. The hologram is fed with a corrugated horn. A similar horn is used to probe the quiet-zone field. The hologram is of transmission type, and it produces a plane wave propagating to an angle of 33° from the normal of the hologram surface. A planar near-field scanner is employed to measure the quiet-zone field. Quiet-zone diameter is 350 mm. A linear scanner is used to move the transmitter. The test antenna is a dielectric-loaded flat reflector antenna [10]. The antenna aperture is approximately 120 mm. The virtual antenna aperture is circular with a diameter of 150 mm, and it has a Gaussian amplitude distribution with -12 dB edge illumination and flat phase. Both the virtual and the test antenna fit well inside the quiet-zone. When simulating the measurements of the virtual antenna the quiet-zone field is distorted by adding a vertical metal rod behind the hologram. The rod distorts the radiation pattern at the angle of -5° in the horizontal plane. In the case of the test antenna the field distortions are caused by attaching a dielectric plastic strip on the hologram surface. The strip distorts the radiation pattern at the angle of -3° in the horizontal plane.

V. RESULTS

A. Quiet-Zone Fields

The deterioration of the quiet-zone field caused by the feed displacement is studied. Fig. 3 represents two horizontal cuts of the quiet-zone field. The solid line is the quiet-zone field when the feed antenna is in the center position. The gray line is the measured field when the transmitter is in one of the extreme positions, i.e., it is moved 25 mm transversally. The lines are shifted for clarity and the linear phase slope is extracted to illustrate the amount of quiet-zone field degradation due to moving the transmitter. As can be seen, the quiet-zone field quality remains very good. The general criteria for the quiet-zone field quality (± 0.5 dB and $\pm 5^\circ$) are fulfilled in the aperture of the test antennas (-75 mm \dots 75 mm). The dashed line represents the quiet-zone phase calculated with (10). The measured phase coincides well with the calculated. After adding a metal

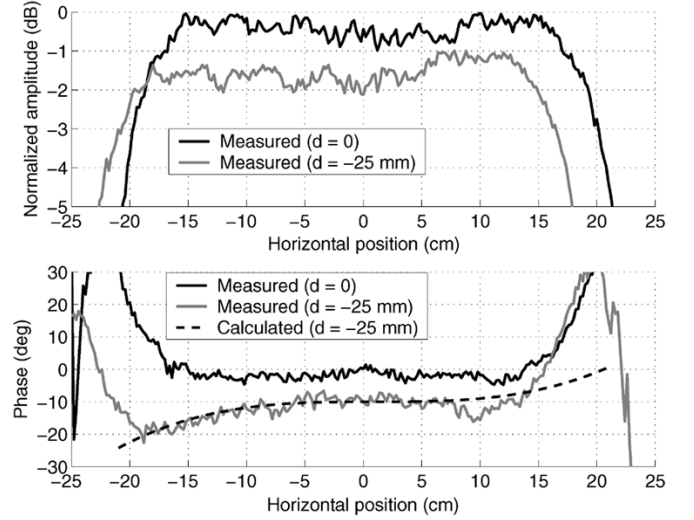


Fig. 3. Measured and calculated quiet-zone fields with different feed antenna offsets.

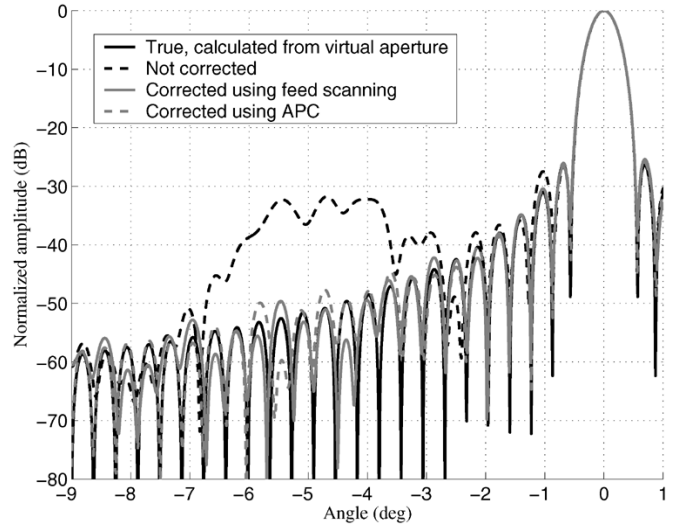


Fig. 4. Antenna patterns of the virtual antenna.

rod, the peak-to-peak amplitude ripple increases to 2 dB and the phase ripple to 20° . The metal rod is used with the virtual antenna. The vertical plastic strip, which is used with the real test antenna, causes approximately 5 dB amplitude ripple and 40° phase ripple to the quiet-zone field.

B. Antenna Patterns of the Virtual Antenna

Fig. 4 depicts the antenna patterns of the virtual antenna in the angular range of $-9^\circ \dots 1^\circ$. The solid black line is the calculated (true) antenna pattern. The dashed black line is the antenna pattern, which would be obtained by measuring the antenna pattern in a distorted quiet-zone field without using correction techniques. The measured antenna pattern has a 20 dB difference to the true antenna pattern approximately in the region of $-6^\circ \dots -4^\circ$. This is caused by the metal rod, which is in the horizontal direction of approximately 5° from the AUT. The gray line is the antenna pattern obtained using the proposed feed scanning based APC technique and the dashed gray line is the antenna pattern corrected with the conventional APC. Both

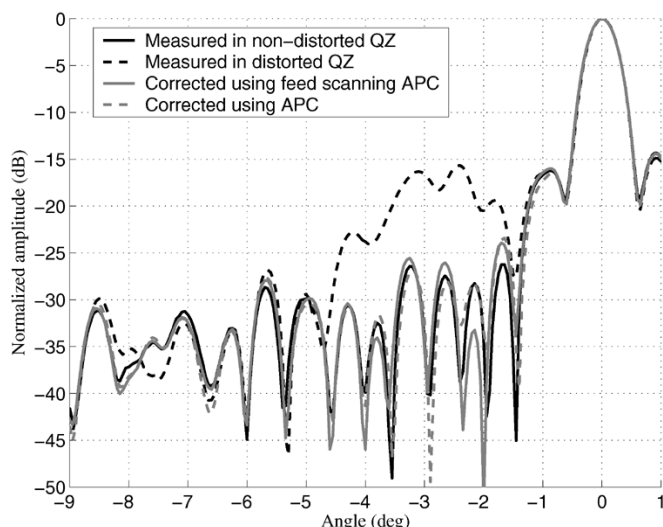


Fig. 5. Antenna patterns of the test antenna.

methods correct the errors very efficiently. The largest errors occurring in the corrected patterns are approximately 5 dB at the level of -50 dB. The accuracies provided by both methods are practically equal.

C. Antenna Patterns of the Test Antenna

Fig. 5 shows the antenna patterns of the test antenna in the angular range of $-9^\circ \dots 1^\circ$. The solid black line is the antenna pattern measured in a nondistorted quiet-zone field and represents the true pattern. The dashed black line is the antenna pattern measured in the distorted quiet-zone field. The latter measured pattern shows a 10 dB difference in comparison to the nondistorted pattern in the angular range of $-4.5^\circ \dots -1.5^\circ$. The gray and the dashed gray lines are the patterns obtained using feed scanning APC and conventional APC, respectively. Both methods correct the error equally well, with about 1 dB average variation in side lobe level in this case.

VI. CONCLUSION

We have proposed a new feed scanning based antenna pattern comparison method for compensating the field distortions in high-accuracy antenna pattern measurements at compact ranges. The suitability of the method is studied, and a procedure to implement the method is introduced. The method compensates the errors as effectively as the conventional APC, but in certain cases it is much easier to implement. The method is applicable for all types of compact antenna test ranges. The proposed method is especially applicable at submillimeter wavelengths, where many other error compensation methods are difficult to apply.

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