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NEW PATTERN CORRECTION TECHNIQUES FOR SUBMM-WAVE CATRS

Ville Viikari, Juha Mallat, Juha Ala-Laurinaho,
Janne Häkli, Aki Karttunen, Tomi Koskinen, Anne Lönnqvist,
Eero Noponen, Matti Vaaja, Antti V. Räisänen

MilliLab, Radio Laboratory / SMARAD
Helsinki University of Technology
P.O. Box 3000, FI-02015 TKK, Finland
Email: Ville.Viikari@tkk.fi
Tel. +358-9-451 2256
Fax. +358-9-451 21

ABSTRACT

The highest operation frequency and the measurement accuracy of compact antenna test ranges (CATRs) are limited by the manufacturing technology of the range collimating element. This paper reviews antenna pattern correction techniques, which can be used to improve the measurement accuracy of a CATR. In addition three lately developed techniques, which are suitable especially at high frequencies and in hologram based CATRs are presented. The latter techniques have been demonstrated in a hologram based CATR at 310 GHz.

1. INTRODUCTION

Submm-wave antenna measurement techniques are not yet well established, but several methods are proposed [1]. Reflector and hologram based compact antenna test ranges (CATRs) are promising methods [2]-[5]. In a CATR, the plane wave field needed for antenna testing is created in a compact space with a reflector or a hologram. A hologram is a diffractive grating pattern, which transforms incident spherical wave front into a plane wave. The binary grating pattern is etched on a copper plated mylar-film by using conventional printed circuit techniques. The advantage of the hologram over the reflector is that the surface accuracy requirement of the (transmission-type) hologram is only one tenth of that of the reflector. In addition, the hologram can shape the transmitted amplitude, which potentially enables reduced edge diffraction and smoother quiet-zone field. The drawbacks with the hologram are its narrow bandwidth, generally 5-10 % and lower efficiency. A hologram based CATR is shown in Fig. 1.

The measurement accuracy of the CATR is limited by the level of the spurious signals. The spurious signal level (compared to the desired signal) should be much lower than the side lobe level of the antenna under test (AUT) that is measured. This condition is difficult to fulfill as submm-wave antennas tend to be electrically very large thus having extremely low level side lobes.

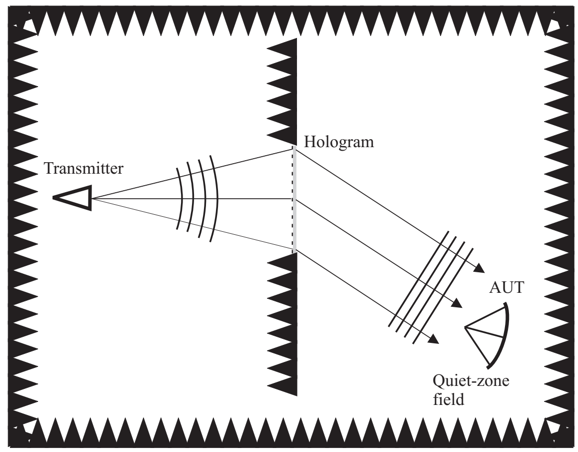

Figure 1. Geometry of a CATR based on a transmission-type hologram.

The spurious signals are caused for example by range reflections and diffraction from the edges of the collimating element. Large reflectors and holograms have to be assembled from several pieces. The misalignment between pieces may also cause spurious signals. Currently the highest frequency of the CATR is limited by the manufacturing technology of the collimating element.

The measurement accuracy of a CATR can be increased by employing antenna pattern correction techniques. This paper reviews several antenna pattern correction techniques that are originally developed for lower frequencies. In addition, three lately introduced techniques, namely feed scanning antenna pattern comparison (APC), frequency shift method, and correction technique based on an adaptive array algorithm are presented. These three latter techniques are especially suitable at submm wavelengths.

This paper is organized as follows: Section II reviews some antenna pattern correction techniques and three lately developed techniques for submm wavelengths are presented in Section III. Conclusions are presented in Section IV.

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2. CONVENTIONAL ANTENNA PATTERN CORRECTION TECHNIQUES

Antenna pattern correction techniques may be divided into three category according to what additional information the correction is based on. The techniques in the first category utilize the measured quiet-zone field for pattern correction, the techniques in the second category employ the time- or frequency response of the test range and the techniques in the third category are based on the spatial response of the test range. In the following, techniques from the each category are presented and their suitability at submm wavelengths is discussed.

2.1. Techniques Utilizing the Measured Quiet-Zone Field

The techniques in this category utilize additional information about the quiet-zone field. For example, in the deconvolution [6], a reference antenna that has at least as large aperture as the AUT is measured in the quiet-zone field. As the true pattern of the reference antenna is known, the quiet-zone field distribution can be calculated from the measured pattern. The deconvolution technique is demonstrated at 12 GHz [7]. Other techniques, which utilize information about the quiet-zone field, are presented in [8], [9]. In these techniques, the quiet-zone field is probed on a sphere enclosing the test object. The effect of the non-ideal quiet-zone field is numerically removed from the measured antenna pattern of the AUT. These techniques have been demonstrated at 9.33 GHz.

The implementation of these techniques is very challenging at submm wavelengths. There are not available large reference antennas that could be used in the deconvolution. The quiet-zone field probing is possible with a near-field scanner, but it is still as challenging as a complete near-field measurement of the AUT, and therefore it would be practical to perform the near-field measurement alone.

2.2. Time and Frequency Techniques

The correction techniques of this category utilize time- or frequency response of the antenna test range, i.e., the time- or frequency response of the AUT in the test site is measured. Time- and frequency responses contain the same information, and therefore time and frequency techniques share the same principle. These techniques separate multipath signals from each other according to time delay (time-domain) or different phase change (frequency domain) due to different signal path lengths. The frequency shift technique, time gating, matrix-pencil method, and channel equalization methods fall in this category.

In the frequency shift technique [10], the antenna pattern of the AUT is measured at several different frequencies. Due to different path lengths, the multipath components add in different phase to the direct signal at each frequency. The corrected pattern is simply obtained by averaging the measured antenna patterns.

In the time gating, the range feed transmits a short pulse. If the path lengths of the direct and spurious signals differ, the signals have different delay when arriving at the receiver. The multipath signal components are solved in time domain. The gating system may be soft or hard. In the soft gating, the measurements are performed in the frequency domain and the time domain data are obtained via inverse Fourier-transform. The hard gating is based on time domain measurements.

The methods based on matrix-pencil [11] or oversampled Gabor-transform [12] utilize the measured frequency response of the range. Instead of Fourier-transform, these techniques employ matrix-pencil or oversampled Gabor-transform to separate different multipath components from each other. The techniques have been demonstrated below 1 GHz frequency.

In the technique based on channel equalization, the response of the AUT to a special time domain sequence is measured at each angle [13]. Due to multipath propagation in the test range, the received sequence differs from the transmitted one. The received sequence is compared to the transmitted sequence, and a channel model of tapped delay lines is created. Finally the measured pattern is corrected with an adaptive equalizer, which compensates the multipath effects.

The spatial resolution and thus also the correction accuracy of these techniques are limited by the absolute bandwidth (or pulse width), over which the measurements are performed. The advantage of these techniques at high frequencies is that the required relative bandwidth is small. For example 3 GHz bandwidth enables spatial resolution of approximately 0.1 m. The required relative bandwidth at 300 GHz is only 1 %. However, depending on the instrumentation, frequency and time domain measurements may be challenging at submm wavelengths.

2.3. Spatial Techniques

The techniques in this category utilize spatial response of the antenna test range. These techniques separate the spurious signals from the direct signal according to their different spatial frequencies. These techniques include antenna pattern comparison (APC), novel antenna pattern comparison (NAPC), virtual array, and adaptive array strategy.

The APC was originally developed for range evaluation, but it can be used for pattern correction as well. In the APC the antenna pattern of the AUT is measured several times at different locations in the quiet-zone.

The reflectivity level of the range is determined from the variations between the superimposed antenna patterns [14]. The corrected antenna pattern is obtained by averaging the measured antenna patterns.

In the virtual array method, the antenna pattern of the AUT is measured twice at different positions in the quiet-zone [15]. The AUT is kept in place during the first measurement, whereas it is displaced as a function of the rotation angle during the second measurement. The displacement is adjusted such, that the measurements form an array, whose array factor has a peak to the direct signal direction and a null to the antenna pointing direction. The method has been demonstrated at 16 GHz.

The novel APC employs a circle fitting algorithm to the APC data [16]. It is assumed in the NAPC, that the received signal is a vector sum of the direct and spurious signals in each point. The received vectors are normalized so, that the direct signal components are in phase. These normalized vectors span a circle, whose center equals to the direct signal and radius equals to the amplitude of the spurious signal. The NAPC has been demonstrated with a 1.85-m diameter reflector antenna at 11.95 GHz.

The adaptive array correction strategy employs APC data. In this method, the MUSIC-algorithm is used at each antenna pointing angle to find the directions of the spurious signals. Then an array is formed, that has nulls towards spurious signals and high directivity toward the direct signal [17]. The method has been demonstrated at X-band (8 – 12 GHz).

A possibility to displace the combination of the antenna rotation stage and the AUT is needed to implement these methods. The conventional APC is not very sensitive to the displacement accuracy as the corrected pattern is obtained with a simple averaging. In the other methods, the displacement accuracy is proportional to the wavelength. At high frequencies, the displacement of potentially extremely heavy combination of the antenna rotation stage and the AUT with an accuracy of a fraction of a wavelength may be very challenging. In addition, the virtual array technique requires that the displacement is performed as a function of the rotation angle of the AUT.

The far-field conditions are assumed in these methods excluding the conventional APC. However, when measuring highly directive antennas, spurious signals usually originate from the near-field of the AUT. In such case, the spurious signal consists of several plane wave components arriving from broad angular range. The methods based on virtual arrays generate an array factor with a narrow null towards the scatterer. However, a broad null should be generated in order to completely compensate the effect of the near-field scatterer. In addition, the MUSIC algorithm used in the adaptive array strategy does not perform well in the near-field conditions. The NAPC suffers from the near-field conditions as well. As the amplitude of the spurious signal is spatially not constant, the received signals do not span a circle.

3. NOVEL ANTENNA PATTERN CORRECTION TECHNIQUES

In the following, three lately developed antenna pattern correction techniques are presented. The methods are considered to be especially suitable in a hologram based CATR at submm wavelengths.

3.1. Feed Scanning APC

The feed scanning APC is based on the conventional APC. In the feed scanning APC, the feed antenna of a compact antenna test range is moved instead of the AUT [18], as shown in Fig. 2.

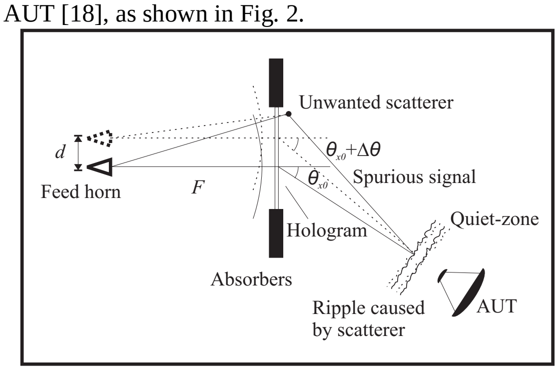

Figure 2. The phase of the direct signal and spurious signal changes differently when the range feed is displaced.

This may be more convenient, as the range feed antenna is usually a small horn whereas the combination of the antenna positioner and AUT may be extremely heavy. Moreover, range feed antenna is usually placed on a scanner in order to optimize the quiet-zone quality, and therefore no additional equipment is needed.

The angular range, which can be corrected, depends on the feed displacement interval and range. The interference period of two plane waves is

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

where θ is the angle between the plane waves. According to Nyquist sampling criterion, the displacement interval should be less than one half of the smallest interference period. On the other hand, at least one period of the largest interference period should be captured in order to compensate the spurious signal. Basically, the broader is the angular range that is corrected, the more measurements are needed, with different feed positions.

When the range feed is displaced from the focus, certain aspects have to be considered. First of all, transversal displacement of the feed steers the plane wave used for antenna testing. One should make sure, that the whole test object remains in the quiet-zone field when the feed is displaced. In addition, the quiet-zone quality is decreased when the feed is displaced. The general criteria for the quiet-zone field ($\pm 0.5\,\mathrm{dB}$ in amplitude and $\pm 5°$ in phase) should be fulfilled at every feed position.

3.2. Frequency Shift Method in a Hologram CATR

The conventional frequency shift method has a great advantage in a hologram based CATR. As the hologram is a dispersive element, the frequency shift method is able to partly correct possible non-ideal operation of the hologram in addition to range reflections [19], [20]. The frequency shift method is relatively simple to implement and it does not significantly increase the measurement time as measurements at different frequencies can be performed fast with a network analyzer.

The required bandwidth depends on the path length difference of the spurious and direct signal. The smaller is the path length difference, the larger bandwidth is required. If the path length difference between the direct and spurious signal is Δl, the frequency shift should be

$$\Delta f = \frac{c}{2\Delta l} \tag{2}$$

in order to cause a $180°$ phase difference between the signals. As the path length differences are usually not known, one need to measure the antenna pattern at several frequencies.

Electrically large submm-wave antennas have usually broad bandwidth as they are based on a reflector. Therefore the bandwidth in the frequency shift technique is usually limited by the hologram, which is a dispersive element. When the frequency is changed, the phase of the plane wave produced by the hologram becomes curved. The phase curve is similar to that in the far-field ranges, and therefore the general far-field criterion for the phase should be fulfilled at each frequency. Another minor effect of the frequency change is a slight steering of the plane wave produced by the hologram, which is taken into account in the combination of the antenna patterns.

3.3. Correction Technique Based on an Adaptive Array Algorithm

In the adaptive array correction technique, the antenna pattern of the AUT is measured several times at different accurately known locations in the quiet-zone. These measurement points form a virtual antenna array at each rotation angles of the AUT, as shown in Fig. 3.

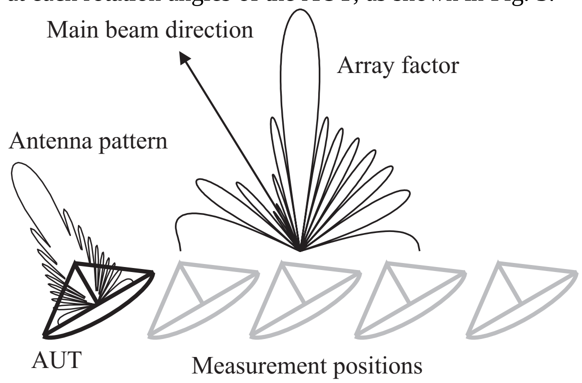

Figure 3. A virtual antenna array is formed, when the antenna pattern of the AUT is measured at different locations in the quiet-zone.

The antenna pattern of the virtual antenna (array pattern) can be calculated from

$$P_{ap}(\theta) = P_{af}(\theta) P_{AUT}(\theta - \alpha), \tag{3}$$

where P_{af} is the array factor, P_{AUT} is the antenna pattern of the AUT and α is the rotation angle of the AUT. In the adaptive array method, an array synthesis algorithm is used to synthesize such an array pattern, which effectively receives the desired signal arriving from certain direction and attenuates spurious signals arriving from other directions [21]. An array is synthesized for each rotation angle of the AUT separately. In addition, antenna pattern of the AUT (element pattern) is used in the array synthesis. An estimate for the antenna pattern of the AUT, which is used in the array synthesis, is obtained by uniformly averaging the measured patterns.

The measurement positions, i.e., the element locations define the angular range, in which the correction can be performed. If the displacement range is d_{range}, the first null in the array factor with the uniform weighting occurs at

$$\theta_{min} = \arcsin\left(\frac{\lambda}{d_{range}}\right). \tag{4}$$

This is approximately the smallest angle, in which the full correction can be performed. If the element spacing does not satisfy the fundamental sampling criterion of $\lambda/2$, the correction is not possible at all angles due to the aliasing effect.

Implementation of the adaptive array correction technique requires a possibility to move the AUT and measure its place accurately.

3.4. Measurement Results

The novel methods have been tested in a hologram based CATR at 310 GHz. The hologram operation is intentionally distorted for demonstration. Different test antennas are used with the feed scanning APC than with the frequency shift and the adaptive array correction. The antenna pattern of the test antenna used with the latter techniques is simulated with GRASP8W-S program. With the feed scanning APC, the antenna pattern of the AUT is measured 11 times with different feed positions. The feed position interval is 5 mm and range 50 mm. In the frequency shift method, the antenna pattern is measured 15 times at frequencies from 306.5 GHz to 313.5 GHz with an interval of 500 MHz. In the adaptive array correction, the antenna pattern is measured 13 times with displacement interval of 2.5 mm. In all cases, the corrected pattern is compared to that obtained with the conventional APC.

The antenna patterns with the feed scanning APC are presented in Fig. 4. The non-corrected pattern introduces a spurious side lobe caused by the distortions. The spurious side lobe ranges from $-4.5°$ to $-1.5°$ and it is 10 dB above the true about $-27\,\mathrm{dB}$ level. The agreement with the corrected patterns is good and it can be assumed that both, the APC and the feed scanning APC correct the spurious side lobe equally well.

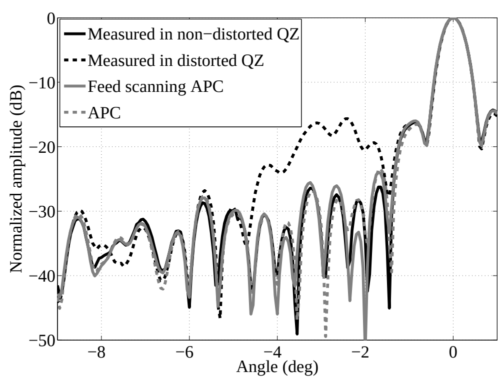

Figure 4. The antenna patterns with the feed scanning APC.

The antenna patterns with the frequency shift method are presented in Fig. 5. Also the frequency shift method corrects the spurious side lobes caused by the field distortions. The corrected pattern obtained with the frequency shift corresponds well to the simulated pattern. The correction accuracy of the frequency shift method is approximately equal to that of the APC.

The antenna patterns with the adaptive array correction are presented in Fig. 6. The corrected pattern obtained with APC deviates from the measured pattern approximately 2 dB at $-35\,\mathrm{dB}$ level. The correction accuracy of the adaptive array correction is better than that. The corrected pattern obtained with adaptive array correction deviates from the simulated pattern approximately 0.4 dB at $-35\,\mathrm{dB}$ level.

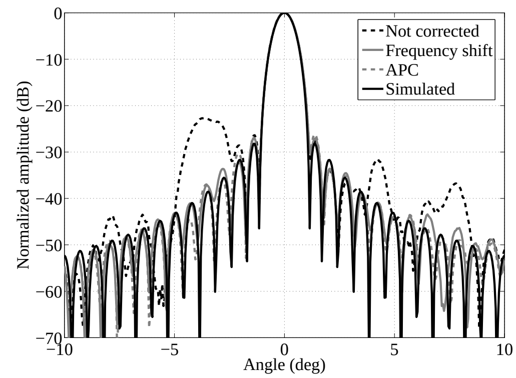

Figure 5. The antenna patterns with the frequency shift method.

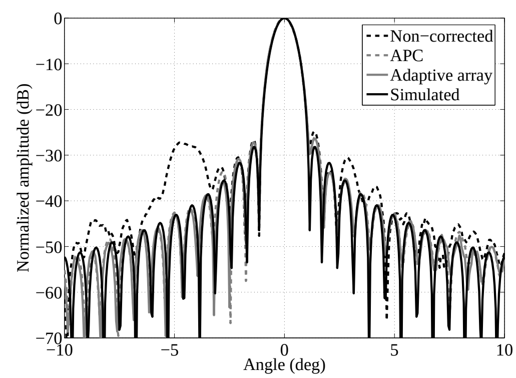

Figure 6. The antenna patterns with the adaptive array correction.

4. CONCLUSIONS

Reflector and hologram based CATRs are potential methods for characterizing large submm-wave antennas. The measurement accuracy of these ranges is still inadequate for some measurements, but it can be improved by employing antenna pattern correction techniques. In this paper, correction techniques are reviewed, and three lately developed techniques, namely the feed scanning APC, frequency shift method in a hologram CATR, and adaptive array correction technique are presented in more detail. The techniques are considered to be especially suitable for measuring large submm-wave antennas in a hologram based CATRs. The implementation of the adaptive array correction technique takes more effort than the implementation of the feed scanning APC or frequency shift. However, the correction accuracy of the adaptive array is better than those of the feed scanning APC or the frequency shift method.

REFERENCES

1. J. Tuovinen, “Methods for testing reflector antennas at THz frequencies,” *IEEE Antennas and Propagation Magazine*, vol. 35, no. 6, pp. 7 – 13, Dec. 1993.
2. J. Hartmann, J. Habersack, H.-J. Steiner, and J. Lemanczyk, “Comparative analysis and measurement of mm-wave applications,” *Proceedings of the 4th ESA Workshop on Millimetre-Wave Technology and Applications*, Espoo, Finland, Feb. 15 – 17, 2006, pp. 429 – 435.
3. T. Hirvonen, J. P. S. Ala-Laurinaho, J. Tuovinen, and A. V. Räisänen, “A compact antenna test range based on a hologram,” *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 8, pp. 1270 – 1276, Aug. 1997.
4. J. Häkli, T. Koskinen, A. Lönnqvist, J. Säily, J. Mallat, J. Ala-Laurinaho, V. Viikari, A. V. Räisänen, and J. Tuovinen, “Testing of a 1.5 m reflector antenna at 322 GHz in a CATR based on a hologram,” *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 10, pp. 3142 – 3150, Oct. 2005.
5. A. Lönnqvist, T. Koskinen, J. Häkli, J. Säily, J. Ala-Laurinaho, J. Mallat, V. Viikari, J. Tuovinen, and A. V. Räisänen, “Hologram-based compact range for submillimeter wave antenna testing,” *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 10, pp. 3151 – 3159, Oct. 2005.
6. J. C. Bennet and A. Griziotis, “Removal of environmental effects from antenna radiation patterns by deconvolution processing,” *Proceedings of the IEE Conference*, Pub. 219, Pt. 1, 1983, pp. 224 – 228.
7. P. L. Garcia Muller, J. L. Cano, and R. Torres, “A deconvolution method for correcting antenna measurement errors in compact antenna test ranges,” *Proceedings of the 17th Annual Antenna Measurement Techniques Association (AMTA) Meeting & Symposium*, USA, 1995, pp. 509 – 514.
8. D. N. Black and E. B. Joy, “Test zone field compensation,” *IEEE Transactions on Antennas and Propagation*, vol. 43, no. 4, pp. 362 – 368, Apr. 1995.
9. D. A. Leatherwood and E. B. Joy, “Plane wave, pattern subtraction, range compensation,” *IEEE Transactions on Antennas and Propagation*, vol. 49, no. 12, pp. 1843 – 1851, Dec. 2001.
10. R. E. Hiatt, E. F. Knott, and T. B. A. Senior, “A study of VHF absorbers and anechoic rooms,” Radiation Laboratory, University of Michigan, Technical Report 5391-1-F, 1963.
11. B. Fourestie, Z. Altman, J. Wiart, and A. Azoulay, “On the use of the matrix-pencil method to correlate measurements at different test sites,” *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 10, pp. 1569 – 1573, Oct. 1999.
12. B. Fourestie and Z. Altman, “Gabor schemes for analyzing antenna measurements,” *IEEE Transactions on Antennas and Propagation*, vol. 49, no. 9, pp. 1245 – 1253, Sept. 2001.
13. P. S. H. Leather and D. Parsons, “Equalization for antenna-pattern measurements: established technique – new application,” *IEEE Antennas and Propagation Magazine*, vol. 45, no. 2, pp. 154 – 161, Apr. 2003.
14. J. Appel-Hansen, “Reflectivity level of radio anechoic chambers,” *IEEE Trans. Antennas Propag.*, vol. AP-21, no. 4, pp. 490 – 498, Jul. 1973.
15. W. D Burnside and I. J. Gupta, “A method to reduce signal errors in antenna pattern measurements,” *IEEE Transactions on Antennas and Propagation*, vol. 42, no. 3, pp. 399 – 405, Mar. 1994.
16. J. van Norel and V. J. Vokurka, “Novel APC-methods for accurate pattern determination,” *Proceedings of the 15th Annual Antenna Measurement Techniques Association (AMTA) Meeting & Symposium*, USA, 1993, pp. 385 – 389.
17. M. D. Migliore, “Filtering environmental reflections in far-field antenna measurement in semi-anechoic chambers by an adaptive pattern strategy,” *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 4, pp. 1112 – 1115, Apr. 2004.
18. V. Viikari, J. Häkli, J. Ala-Laurinaho, J. Mallat, and A. V. Räisänen, “A feed scanning based APC technique for compact antenna test ranges,” *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 10, pp. 3160 – 3165, Oct. 2005.
19. V. Viikari, J. Mallat, J. Ala-Laurinaho, J. Häkli, and A.V. Räisänen, “Antenna pattern correction in a hologram CATR based on averaging in frequency domain,” *Proceedings of the 27th Annual Antenna Measurement Techniques Association (AMTA) Meeting & Symposium*, Newport, RI, USA, Oct. 30 – Nov. 4, 2005, pp. 341 – 345.
20. V. Viikari, J. Mallat, J. Ala-Laurinaho, J. Häkli, and A. Räisänen, “A frequency shift technique for pattern correction in hologram-based CATRs,” accepted for publication in *IEEE Trans. Antennas Propag.*, 2006.
21. V. Viikari, V.-M. Kolmonen, J. Salo, and A. V. Räisänen, “Antenna pattern correction technique based on an adaptive array algorithm,” submitted to *IEEE Trans. Antennas Propag.*, 2006.