Pilot Signal-Based Real-Time Measurement and Correction of Phase Errors Caused by Microwave Cable Flexing in Planar Near-Field Tests

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***Abstract*—Millimeter and submillimeter wave receivers in scanning planar near-field test systems are commonly based on harmonic mixing and thus require at least one flexible microwave cable to be connected to them. The phase errors originated in these cables get multiplied and added to the phase of the final detected signal. A complete submillimeter setup with on-the-fly measurement of phase errors is presented. The novel phase error correction system is based on the use of a pilot signal to measure the phase errors caused by cable flexing. The measured phase error surface in the quiet-zone region of a 310 GHz compact antenna test range (CATR) based on a hologram is shown as an application example. The maximum measured phase error due to the cable within a 80×90 cm^2 scan area was 38°.**

***Index Terms*—Antenna measurements, cable flexing, millimeter wave measurements, near field, phase detection, submillimeter wave measurements.**

I. Introduction

Many near-future scientific satellite missions including the European Space Agency's (ESA) Planck and Herschel Space Observatory have onboard submillimeter wave instruments and high gain antennas, the accurate characterization of which is vital for the success of these missions. However, conventional antenna measurement techniques are not feasible. Outdoor tests are not possible due to atmospheric distortion and attenuation. Indoor far-field measurements are neither practical due to the required distance of several kilometers or more. According to [1], the compact antenna test range and the near-field scanning method are the most potential candidates for testing large high gain antennas at submillimeter wavelengths. They can be applied indoors in reasonably sized chambers having a controlled atmosphere, less water vapor and a stable temperature.

Problems with electrical and mechanical instrumentation uncertainties in a modern antenna measurement system increase with frequency. Very high angular positioning accuracy, typically better than 0.001 degrees [1], is required for the antenna turntables used in compact antenna test ranges (CATRs) at submm wavelengths. Alternatively, steering of the plane wave direction by feed scanning can be used to measure the main lobe of the antenna. An accurate planar near-field scanning requires planarity and probe positioning uncertainties below $\lambda/100$, e.g., 6 μm at 500 GHz. The planar scanning method has been used for antenna measurements at frequencies up to 650 GHz [2], [3]. Phaseless near-field measurements based on phase retrieval have also been proposed, e.g., in [4]. Phase retrieval algorithms typically require measurements of the squared amplitude distributions over one or two surfaces. Planar surfaces are commonly used [4], but different geometries are also possible. Phaseless techniques are interesting especially for very high frequencies, but practical systems suitable for testing of high-gain submm-wave antennas have not yet been published.

Near-field measurements and testing of the CATR quiet-zone quality need highly accurate vector measurements with moving receivers. Especially at high millimeter and submillimeter frequencies, the associated cables introduce amplitude and phase errors to the measured vector values of the field [5]–[7] mainly due to twisting and bending but also because of changes in ambient temperature during scanning. According to [5], the amplitude measurement errors due to flexing of cables are negligible when the downconversion is done close to the near-field probe antenna (remote mixing), but when local mixing at the vector network analyzer is used the amplitude errors due to cable bending can be significant. The phase errors in both cases may be considerable. This paper describes our suggestion for a submillimeter wave antenna measurement system with on-the-fly measurement of phase errors introduced by flexing of the microwave cables.

II. Basic Instrumentation

The electrical test instrumentation is based on a commercial millimeter wave vector network analyzer AB Millimètre MVNA-8–350 equipped with submillimeter wave extensions ESA-1 and ESA-2. The external transmitter and receiver modules are phase-locked to the analyzer core. The back-to-back dynamic range of the analyzer system decreases from 125 dB to 50 dB across the frequency band of 300–800 GHz.

The 1.5×1.5 m^2 planar scanner AL-4951 used in our measurement system is manufactured by Orbit/FR (formerly Orbit Advanced Technologies). Its measured root-mean-square (rms) planarity is 19 μm, and it is usable for near-field scanning up to about 160 GHz. Actually, a scanner with higher accuracy should be used for submillimeter wave antenna measurements.

Manuscript received September 14, 2001; revised December 5, 2001. The hologram CATR project was funded in part by ESA/ESTEC (Contract 13096/NL/SB), Tekes (Finland), and the Academy of Finland. The work of J. Säily was supported by grants from the Nokia Foundation, TES (Finland), and EIS (Finland).

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Digital Object Identifier 10.1109/TAP.2003.809047

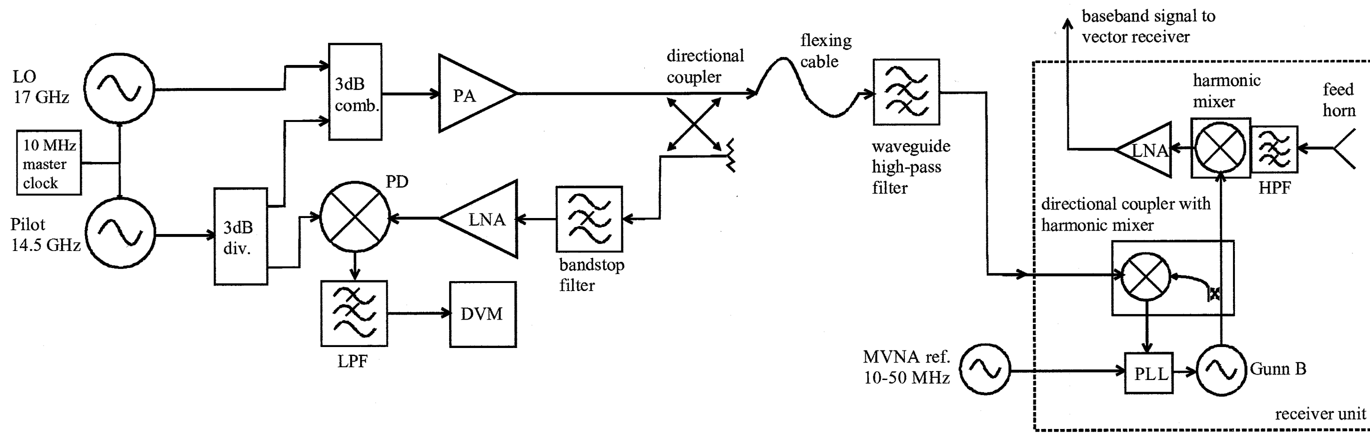

Fig. 1. Constructed real-time phase error measurement subsystem is shown with the submillimeter wave receiver. A lower frequency pilot signal is combined with the local oscillator signal, reflected back to the cable from the receiver, and coupled to the phase detector.

The present scanner is mainly used for sampling the quiet-zone field of a CATR, where planarity and positioning uncertainties are not critical. The control software is AL-2000 from Orbit/FR, and a custom receiver driver has been written to communicate with the MVNA and the constructed phase error measurement subsystem through GPIB-bus.

III. Phase Error Measurement System

The measurement and correction of phase errors introduced by flexing cables have already been found useful earlier [5], [6], particularly regarding the microwave cable carrying the local oscillator frequency to the receiver. The effect of the IF cables is much less significant. In [5], the phase error plane is measured once prior to the actual antenna tests whereby a constant bending behavior and temperature must have been assumed. This may not be valid for a measurement lasting several hours or even days.

The system in [6] is based on the use of directional couplers at both ends of the cable. The transmitting antenna is connected to the forward coupled port of the coupler after the cable, and a short-circuit in the output port reflects the signal back to the cable. The directional coupler at the other end of the cable takes a sample of the reflected signal to a vector network analyzer. This kind of system is usable at microwave and low millimeter wave frequencies where the inherent forward coupling loss of 10–20 dB in the directional coupler can be tolerated. A major drawback of the principle is that it can not be applied to vector network analyzers, which use remote harmonic frequency generators and mixers.

We have developed a real-time phase error measurement system suitable of continuous operation with the planar scanner and the MVNA vector network analyzer also at the higher submillimeter frequencies. The error correction scheme is based on the use of a separate pilot frequency injected into the microwave cable. A schematic of the constructed system is shown in Fig. 1.

A. Description of Operation

A pilot signal at 14.5 GHz is multiplexed with the 17.2-GHz local oscillator signal going to the receiver. The pilot signal gets reflected back into the cable from the waveguide high-pass filter (with cutoff of 15.1 GHz) at the receiver and is coupled to a phase detector. A digital voltmeter (DVM) under control of the scanner software is used to record the phase detector dc output at each sampling grid point. After calibrating the relationship between voltage and phase or obtaining the phase detector coefficient, the measured vector values of the field can be corrected as a post processing task.

A directivity higher than 30 dB in the directional coupler and a rejection better than 40 dB in the bandstop filter at the LO frequency are necessary in the detection chain in order to measure accurately the pilot signal phase variations. Nonidealities of the directional coupler and their effect on the measured phase accuracy are analyzed further in Section III-C. The directional coupler in the prototype setup was manufactured by Ylinen Electronics, and it had a directivity better than 40 dB at 14.5 GHz. The bandstop filter was constructed from a waveguide with a tuning stub, and was optimized to attenuate the LO frequency of 17.2 GHz.

B. Calibration Issues

The phase detector coefficient K_d must be calibrated for frequency and power. If the phase difference between the detector inputs is $\Delta\theta = \theta_i - \theta_o$, then its dc output can be calculated as

$$v_d = K_d \sin(\theta_i - \theta_o) = k_d \sin \Delta\theta. \quad (1)$$

The phase changes to be measured are very small. Therefore, a linear operation of the phase detector can be assumed which yields to

$$v_d = K_d \Delta\theta. \quad (2)$$

It is obvious from (2) that K_d can be determined by inserting a known phase shifter between the two input ports and by measuring the resulting dc voltage difference. An accurate coaxial phase shifter for these frequencies was not available, so an indirect calibration method had to be used.

It was found out in network analyzer measurements that changes in the power amplifier (PA) supply voltage resulted in small phase changes in the amplified signal. The phase changes with supply voltages between 13–14 V were measured, and the

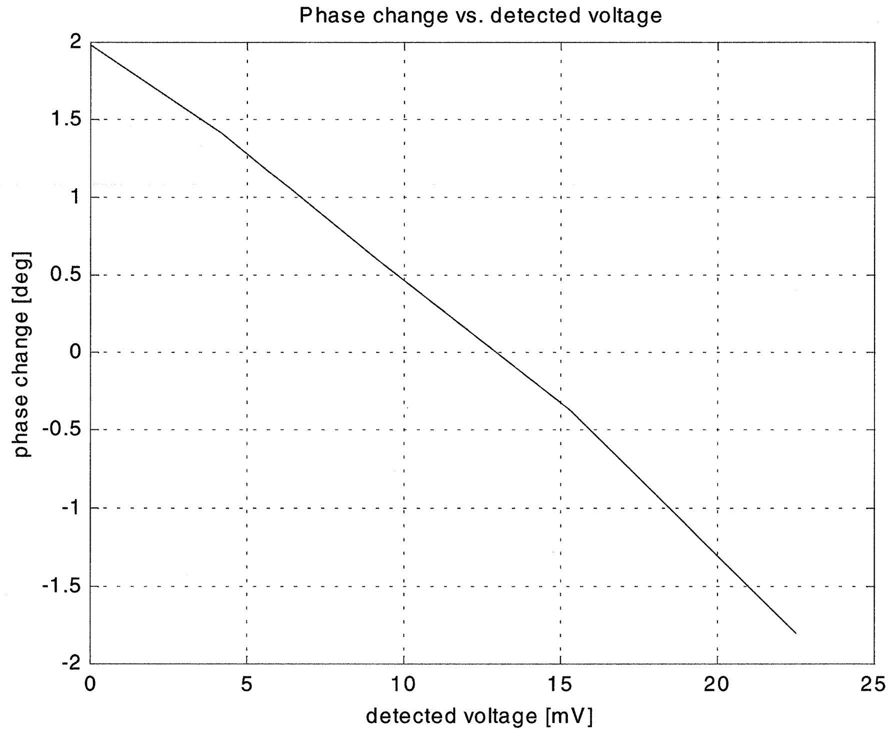

Fig. 2. Recorded phase detector output voltage versus phase change curve used for calibration. The phase detector coefficient is $K_d = 6.4683\text{mV}/^\circ$.

PA was inserted back to the signal chain and used as an electronically controlled phase shifter. The measured phase detector output voltages shown in Fig. 2 are close to linear in the 0...15 mV range with a detection coefficient of $K_d = 6.4683\text{mV}/^\circ$ when the pilot frequency is 14.5 GHz and its power level is +5 dBm.

C. Effects Associated to the Directional Coupler

As aforementioned, a directional coupler with a high directivity at the pilot frequency is vital for the success of the described method. For purposes of error analysis such a coupler can be treated as a three-port device as shown in Fig. 3, assuming the second coupled port perfectly terminated. Port three provides a raw sample of the reflected signal U_r but at the same time has unavoidably a connection to the incident wave U_i due to nonideal directivity. The insertion loss between ports one and two is negligible in terms of the phase measurement and is thus ignored in the analysis. The effects of the coupler regarding the observed phase of port three are twofold. First, there will be a phase bias caused by a constant signal feedthrough. Second, the measured differential phase changes initiated in the flexing coaxial cable can get disturbed.

If multiple reflections and frequency dispersion in the cable are excluded and operation at a single frequency is assumed, the phase difference $\Delta\varphi$ compared to the ideal case of perfect directivity can be derived to be

$$\Delta\varphi = \varphi_{32} + \varphi_c - \arctan\left[\frac{\sin(\varphi_{32}+\varphi_c) + \frac{|s_{31}|}{|s_{32}|\cdot c}\sin(\varphi_{31})}{\cos(\varphi_{32}+\varphi_c) + \frac{|s_{31}|}{|s_{32}|\cdot c}\cos(\varphi_{31})}\right]. \quad (3)$$

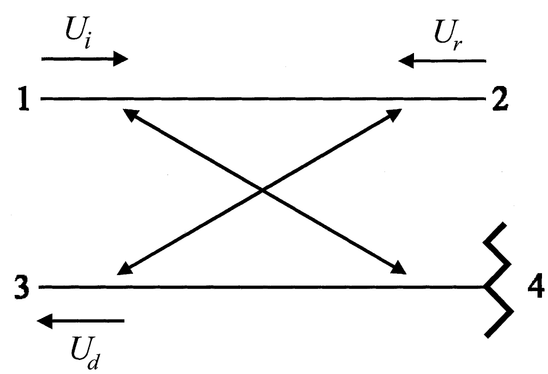

Fig. 3. The directional coupler can be thought as a three-port in which the unwanted coupling or leakage from port 1 to port 3 will cause phase performance degradation. The fourth port is assumed to be perfectly terminated. Here U_i is the incident signal, U_r the reflected signal, and U_d the raw sample to be fed to the phase detector.

In (3), c denotes the scalar effects of the two-way gain (attenuation) due to the cable plus the return loss at the receiver high-pass filter and φ_c the associated two-way phase angle. $|S_{31}|$ is the inverse of the directivity, $|S_{32}|$ is the coupling factor, φ_{31} and φ_{32} are the respective phase responses of the coupler. Further, $\varphi_{32} + \varphi_c$ is the phase of the wanted signal, and the last term is the phase of the resultant vector from summing the wanted and and unwanted signals. The vector definitions are illustrated in Fig. 4(a) and the resultant vector in Fig. 4(b). The value obtained from (3) actually tells the phase bias caused by the leaking signal. Knowledge of the phase bias is important because of the used detection principle with a balanced RF mixer. The sensitivity of the mixer can easily get degraded by any phase offsets.

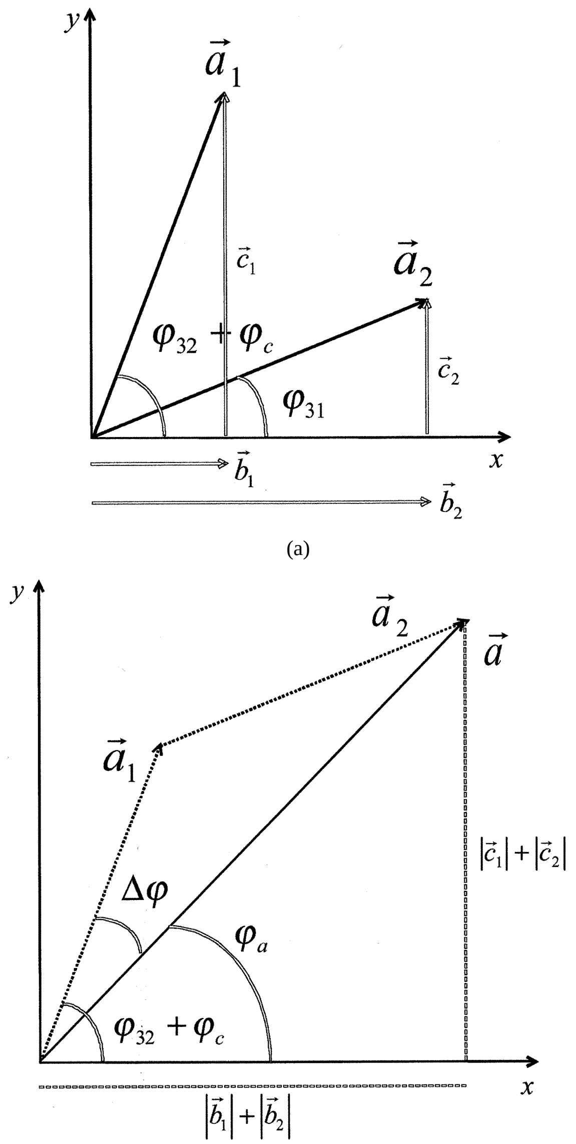

Fig. 4. (a) Definition of the used vectors for phase error calculation. $\vec{a}_1$ is the wanted signal and $\vec{a}_2$ the unwanted signal caused by the nonidealities in the directional coupler. (b) Definition of the sum vector with a phase angle of $\varphi_a \cdot \varphi_{32} + \varphi_c$ is the phase angle of the wanted signal, and $\Delta\varphi$ the phase bias caused by the unwanted signal.

The resulting maximum phase bias calculated for a typical case assuming directivity of 30 dB and two-way attenuation of 10 dB is close to 6°. The maximum phase bias occurs when the leaking signal S_{31} is in quadrature (90° phase shift) with the wanted signal S_{32}.

It is interesting to study a special case where the wanted signal's phase has been adjusted to meet that of the incident wave, e.g., through fine tuning of the power amplifier supply voltage, and thus, show the effect of the coupler's nonidealities on the measured phase changes initiated by the flexing cable. The apparent phase errors calculated from (3) as a function of coupler directivity are shown in Fig. 5 for leaking signal phase offsets of 0° (in-phase), 20° and 90°. When working with typical test-range pattern corrections below 10° it seems reasonable to require a directivity of 40 dB or more and at the same time prevent a phase difference near 90° between the wanted and leaking signals. Normally, phase differences up to 15–20° can be tolerated when the coupler-related phase errors are below 1°.

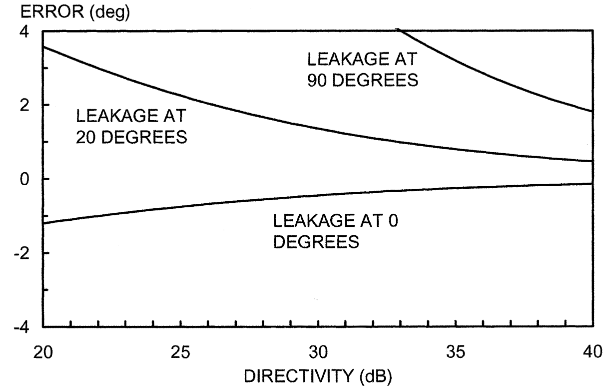

Fig. 5. Apparent phase error shown as a function of directivity with leakage phase offsets of 0°, 20°, and 90°. Phase offsets between 10–20° can normally be tolerated with coupler-related phase errors below 1°.

Finally, there are also secondary effects disturbing the accuracy of the proposed measurement system. Particularly annoying is the PM to AM conversion, which is also due to the nonideal directivity of the coupler. This will initially cause slight changes in the amplitude of the combined signal going from the coupler to the phase detector but will then, due to the operating principle of the detector, be converted into apparent phase changes. However, the effect of AM to PM conversion is thought to be small compared to the primary error sources described above.

IV. Test Results

The constructed phase error measurement system was tested with a submillimeter wave CATR based on a hologram at 310 GHz. In our CATR, a binary amplitude hologram is used to transform a spherical wave into a plane wave instead of using a reflector or a set of reflectors for this purpose [8]. The volume where the plane wave is optimized is called the quiet-zone of the CATR. The quiet-zone tests with a planar scanner are similar to low resolution planar near-field measurements. The size of the tested hologram is 60×60 cm^2, and the resulting quiet-zone area is about 20×20 cm^2. Uncorrected test results for this hologram have been presented earlier in [9]. Feasibility studies and plans for a complete hologram CATR facility can be found in [10].

A. Measured Phase Error Surfaces

The phase errors introduced by the flexing cable were recorded for the maximum scanning area of the scanner, which was 80×90 cm^2 for the used configuration. The obtained phase error surface map frequency-scaled to 310 GHz is shown in Fig. 6. The maximum phase error in the scanned area is 38°. The scanning direction was vertical, starting from grid coordinate $(-40, -50)$. The 3-m-long RF cable in all the tests was Sucoflex™ 104. Fig. 6 indicates that the phase error along a single scan line is nonlinear, and a simple curve fitting is not possible.

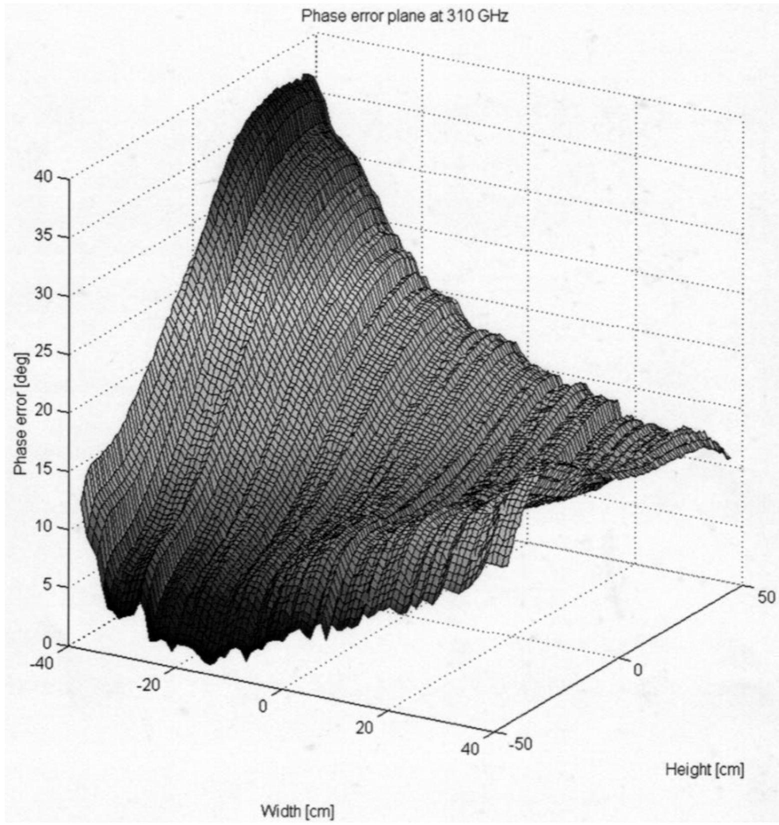

Fig. 6. Measured phase error plane across the largest scanning area of 80×90 cm^2. The results are frequency-scaled to 310 GHz, and the maximum phase error is 38°.

V. Discussion

The constructed system works very well and does not disturb the operation of the submm-wave vector network analyzer used for collecting the raw vector data. However, the operating bandwidth and phase correction accuracy are limited by the performance of individual components. The directional coupler and the bandstop filter are the most critical items. Wideband measurements are not yet possible. Fortunately, submm-wave antennas usually need testing only at some discrete frequencies at separate bands and using different setups.

For electrically large scan areas where the measurement can take tens of hours, all the measurement instrumentation must be housed in a temperature-stabilized cabinet. The results presented in this paper were obtained without temperature stabilization. Temperature variation of the amplifiers during scanning was measured to be within 1 °C after several hours of warm-up time.

VI. Conclusion

Phase measurement uncertainties caused by flexing cables can exceed several tens of degrees in submillimeter wave planar near-field measurements and CATR quiet-zone testing. The proposed phase error measurement system based on the use of a pilot signal makes it possible to measure and correct these errors down to a level of 1–2°. The constructed system works as an add-on extension to a present near-field measurement facility using the MVNA vector network analyzer.

The measured phase error plane for a 80×90 cm^2 scan area is presented. The maximum phase error at 310 GHz is 38°. The phase error plane measurements show that without correction the indicated plane wave may be tilted by several degrees in both vertical and horizontal directions from the true direction.

Acknowledgment

The authors would like to thank E. Kahra and L. Laakso from the Radio Laboratory workshop for manufacturing the high-quality waveguide components and various mechanical constructions. The help of V. Viikari with some of the hologram measurements is appreciated.

References

[1] J. Ala-Laurinaho, P. R. Foster, G. J. Junkin, T. Hirvonen, A. Lehto, D. H. Martin, A. D. Olver, R. Padman, C. Parini, A. V. Räisänen, T. Sehm, J. Tuovinen, and R. J. Wylde, "Comparison of antenna measurement techniques for 200 to 1500 GHz," in *Proc. 20th ESTEC Antenna Workshop on Millimeter Wave Antenna Technology and Antenna Measurements*, vol. WPP-128, Noordwijk, The Netherlands, June 18–20, 1997, pp. 345–351.

[2] N. Erickson and V. Tolls, "Near-field measurements of the submillimeter wave astronomy satellite antenna," in *Proc. 20th ESTEC Antenna Workshop on Millimeter Wave Antenna Technology and Antenna Measurements*, vol. WPP-128, Noordwijk, The Netherlands, June 18–20, 1997, pp. 313–319.

[3] D. Slater, P. Stek, R. Cofield, R. Dengler, J. Hardy, R. Jarnot, and R. Swindlehurst, "A large aperture 650 GHz near-field measurement system for the Earth Observing System microwave limb sounder," in *Proc. 23rd Annual Meeting and Symp. AMTA*, USA, Oct. 21–26, 2001, pp. 468–473.

[4] T. Isernia, G. Leone, and R. Pierri, "Radiation pattern evaluation from near-field intensities on planes," *IEEE Trans. Antennas Propagat.*, vol. 44, pp. 701–710, May 1996.

[5] D. J. van Rensburg, "A technique to evaluate the impact of flex cable phase instability on mm-wave planar near-field measurement accuracies," in *Proc. 22nd ESTEC Antenna Workshop on Antenna Measurements*, vol. WPP-164, Noordwijk, The Netherlands, May 11–12, 1999, pp. 163–166.

[6] J. Tuovinen, A. Lehto, and A. V. Räisänen, "A new method for correcting phase errors caused by flexing of cables in antenna measurements," *IEEE Trans. Antennas Propagat.*, vol. 39, pp. 859–86, June 1991.

[7] A. C. Newell, "Error analysis techniques for planar near-field measurements," *IEEE Trans. Antennas Propagat.*, vol. 36, pp. 754–768, June 1988.

[8] T. Hirvonen, J. Ala-Laurinaho, J. Tuovinen, and A. V. Räisänen, "A compact antenna test range based on a hologram," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 1270–1276, Aug. 1997.

[9] J. Säily, J. Ala-Laurinaho, J. Häkli, J. Tuovinen, A. Lehto, and A. V. Räisänen, "Test results of 310 GHz hologram compact antenna test range," *Electron. Lett.*, vol. 36, no. 2, pp. 111–112, Jan. 2000.

[10] ——, "Instrumentation and testing of submillimeter wave compact antenna test ranges," in *Proc. 11th Int. Symp. Space THz Technology*, Ann Arbor, MI, May 1–3, 2000, pp. 590–597.

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