Phase-Hologram-Based Compact RCS Test Range at 310 GHz for Scale Models

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***Abstract*—A compact radar cross section (RCS) test range based on a phase hologram has been developed for scale-model measurements. The phase hologram converts the feed-horn radiation to a plane wave needed for RCS determination. The measurements are performed at 310 GHz using continuous-wave operation. A monostatic configuration is realized using a dielectric slab as a directional coupler. The main advantage of a scale-model RCS range is that the dimensions of radar targets are scaled down in proportion to the wavelength. Therefore, RCS data of originally large objects can be measured indoors in a controlled environment. Test objects such as metal cylinders and simplified targets have been measured. The feasibility of the phase-hologram RCS range has been verified. The operation and measurement results of the monostatic measurement range are reported here. A comparison with simulated results is also included.**

***Index Terms*—Compact range, hologram, quiet zone, radar cross section (RCS), scale-model measurements.**

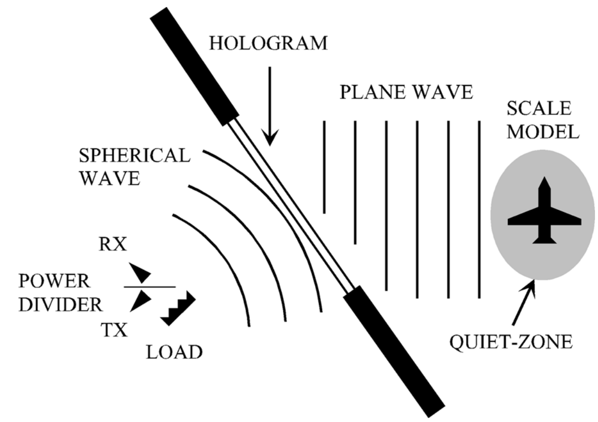

Fig. 1. Hologram-based test range for scale-model RCS measurements. (RX: receiver. TX: transmitter.)

I. Introduction

TARGET RADAR cross section (RCS) data is needed for both radar system development and target RCS reduction. Computer simulations are used for predicting the RCS, but modeling of complicated structures is difficult and simulations are time consuming. The results should at least be verified with measurements. When measuring RCS, the object has to be illuminated with a plane wave. This is possible either by measuring the object in the far-field region of the antenna or measuring it in a compact range. Traditionally, measurements have been done in the far-field ranges, which are usually placed outdoors and are, therefore, subject to changing weather conditions and unwanted observation [1].

When using a compact test range, targets can be measured indoors due to the decreased measurement distance. Compact ranges can also be used for scale-model measurements. The main advantage of a scale-model RCS range is that the dimensions of radar targets are scaled down in proportion to the wavelength. Therefore, RCS data of originally large objects can be measured in a small chamber, which is a controlled environment. After model measurements, the obtained RCS data is scaled back in order to get the real-sized target parameters. Ranges for scale-model measurements have been reported for submillimeter-wave frequencies at 524 and 585 GHz [2], [3]. These ranges are based on reflectors. The difficulty with reflectors at submillimeter-wave lengths is the high surface-accuracy requirement. The hologram is introduced as an alternative focusing element. The holograms used are transmission-type elements and, thus, the accuracy requirement for the holograms is less stringent (by the order of 10) than for the reflectors.

Amplitude holograms have been used for antenna measurements [4]–[6], but phase holograms are better suited for RCS range applications due to their higher conversion efficiency. The conversion efficiency can be defined as the ratio between the field intensities in the quiet zone and before the hologram. The conversion efficiency of the hologram has been evaluated by measuring the power level first at the plane of the hologram surface and then at the quiet zone. The measured conversion efficiency of the phase hologram used here is -4 dB [7]. It is assumed that the conversion efficiency also be will nearly the same for larger holograms, but this remains to be verified.

In a phase-hologram RCS range, the plane wave needed for the RCS determination is generated using a phase hologram. The phase hologram is a computer-generated planar diffractive element, which consists of grooves on one surface of a dielectric plate. Due to the simple lightweight structure of the hologram, it is inexpensive to manufacture. Fig. 1 shows a schematic layout of the compact range used for scale-model measurements. The scale model is placed into the quiet zone.

The hologram transforms the incident Gaussian beam (with a spherical phase front) to a plane wave. The target-under-test is illuminated with the plane wave. The wave reflected back from the target is focused by the hologram to a receiver horn, which, in a monostatic configuration, is placed behind a dielectric slab

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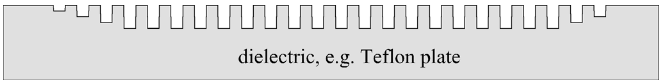

Fig. 2. Simplified cross cut of a phase hologram.

used as a 3-dB power divider. This is an improved version of the previously used quasi-monostatic system where the receiving and transmitting corrugated horn antennas were placed side by side with a small bistatic angle of 1.7° [8].

II. Phase Hologram

In a phase-type hologram, the hologram structure features a locally changing effective thickness. The phase hologram is realized by milling grooves on a dielectric plate (see Fig. 2). The field passing through the grooves acquires a phase difference with respect to that between the grooves, leading to a phase modulation of the transmitted field. A locally binary groove structure is optimized for the desired operation. Groove width and depth of the hologram profile is designed by rigorous electromagnetic theory to locally produce the required amplitude and phase modulation. [9]

The hologram also diffracts other beams than the desired plane wave, i.e., part reflects back, part propagates straight through the hologram. This causes the best possible efficiency of the phase hologram to be less than 100%. The optimized plane-wave beam propagates to an angle of 33° from the hologram and it is optimized to a distance of 1 m. This angle and also the distance from the hologram have been chosen to avoid disturbances caused by the diffraction modes traveling straight through the hologram. In the measurement system, other modes are terminated in absorbers.

The hologram structure can be manufactured by a computer-controlled milling machine. Teflon has been found to be a suitable material for holograms due to its machinability, its well-known characteristics, and low losses at submillimeter-wave lengths. The surfaces of the test holograms are good and their quality has been found adequate for operation at 310 GHz. Other materials have also been considered. First tests were made with a hologram manufactured from Obomodulan, OBO-Werke GmbH & Company KG, Stadthagen, Germany, but it was found to have relatively high loss, 0.8–1.0 dB/mm at 310 GHz [7], which decreases the dynamic range available for RCS measurements.

The hologram structure used in these measurements was fabricated on a 5-mm-thick Teflon plate. The size of the hologram is 28 cm × 24 cm. The aperture is slightly elliptical in shape in order to produce a quiet zone field with a circular cross section (see Fig 1). The relatively small test hologram was primarily intended for evaluation of design and manufacturing methods of phase holograms.

III. RCS Measurement Range

A large dynamic range is required for RCS measurements. In our case, the instrumentation is based on a millimeter-wave vector network analyzer (MVNA-8-350, AB Millimètre, Paris, France) with submillimeter-wave extensions. The test measurement facility is shown in Fig. 3. In this test setup, the distance from the receiver/transmitter to the hologram and also from the hologram to the target is 1 m.

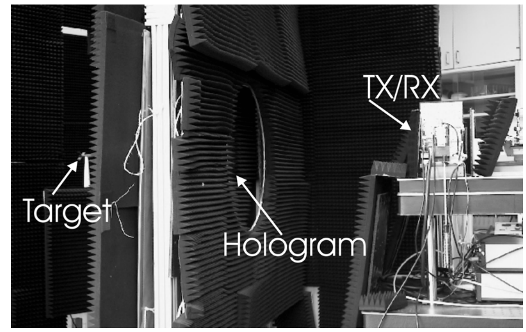

Fig. 3. Test RCS measurement facility.

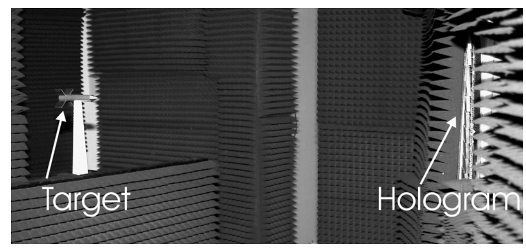

Fig. 4. Target and its support in the quiet-zone area.

A phase-locked Gunn oscillator followed by a frequency multiplier has been used as the submillimeter-wave source (ESA-1 extension). The receiver used consists of a Schottky harmonic mixer pumped with a phase-locked Gunn oscillator (ESA-2 extension). The Gunn oscillator is identical to the one used in the source. The vector measurement capability is essential for typical sensitivity enhancing methods used in scale-model RCS ranges. Corrugated horn antennas are used as the transmitting and receiving antennas. Waveguide twists are used for chancing the polarization. A planar scanner is employed to obtain the two-dimensional field profile of the quiet zone to verify the field quality. RCS measurements are done using the same system; the receiving antenna is brought from behind to the front of the hologram so that the configuration is monostatic. The target is placed behind the hologram in the quiet zone (see Fig. 4).

Absorbers (space-qualified tessalating terahertz RAM and Eccosorb VFX-NRL2) are used around the hologram and around the whole setup to block the wave propagating straight from the transmitter to the quiet zone and to minimize reflections. The desired beam propagates into an angle of 33° to avoid interference with the wave propagating straight through the hologram.

The measurements have been carried out at 310 GHz. Continuous-wave (CW) operation instead of, for example, pulsed operation, has been considered most feasible since fast enough switching is problematic at frequencies used here. The detection sensitivity is enhanced by separating the target echo signal from background reflections. This is based on moving the target along the z-axis (direction of the plane-wave propagation) (see Section V for further details). Simple and well-known radar test and calibration targets, for example, a gold-plated metal spheres, have been previously used for the phase-hologram RCS range

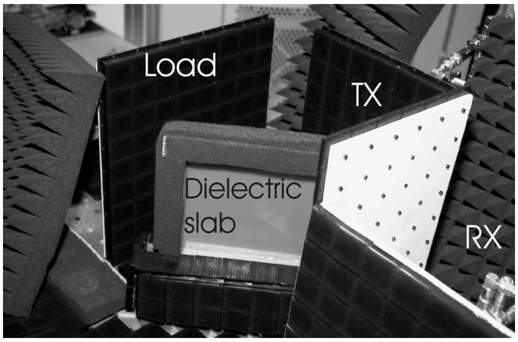

Fig. 5. Monostatic radar setup. Transmitter and receiver horns are in openings of the absorber walls.

development [10]. In this paper, we have measured a target using a cylinder as a calibration target.

The measurement system is made monostatic using a dielectric slab as a directional coupler. The dielectric slab is made out of 125-μm Mylar film. It is placed in an angle of 45° compared to the axes of the receiving and transmitting corrugated horn antennas. The frame of the slab is also covered with absorbing material. The setup can be seen in Fig. 5. The place of the load absorber is optimized to minimize the power reflected from the load and surroundings. The places of the antennas, slab, and the load are fixed to assure repeatability.

According to the measurements, the dielectric slab works with a -3-dB power-division ratio, as designed. It has also been tested that the quiet-zone field does not chance due to the coupler. The quiet-zone field was measured with the transmitter at the TX port of Fig. 5 and again with the transmitter at the RX port. The field stayed the same regardless of the port chance so it does not affect the measurement and the system works as designed.

The target and its support are placed on a computer-controlled micro translation and rotation stage. The support is a column (truncated cone) made of closed-cell rigid foam plastic based on polymethacrylimide (Rohacell 71HF). The dielectric constant of Rohacell 71HF was measured and found to be 1.10 at 310 GHz. The reflections from the support column were measured to be so low that, with current measurement setup, it is not possible to separate them from background reflections.

IV. Quiet-Zone Testing

The quiet-zone field is adjusted by tuning the feed-horn position. Changing the feed position in the transversal plane chances the direction of the plane wave and it is optimized for the planar scanner used for the quiet-zone verification. The optimization is done in vertical and horizontal directions. The adjustment of the distance between the feed and hologram is used for setting the feed to the focus of the hologram. The hologram was originally designed for vertical polarization, but horizontal polarization performance was also tested. The quiet-zone field quality was verified with the directional coupler in the setup.

Measurement results for vertical polarization are shown in Fig. 6. Amplitude is denoted via a solid line and phase is denoted via a dashed line. Both are normalized to ease the comparison.

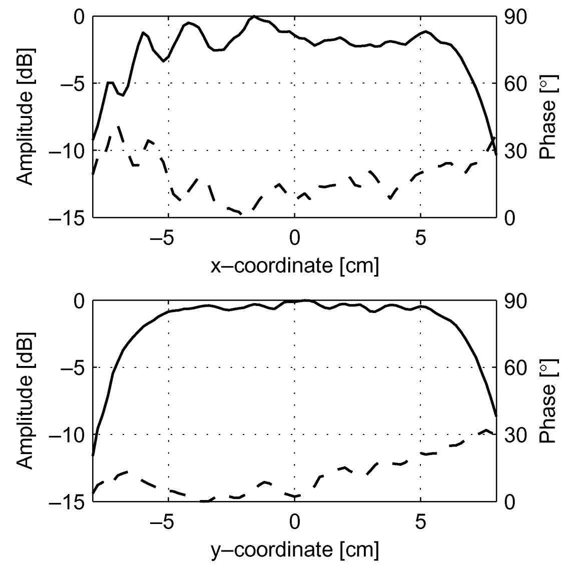

Fig. 6. Quiet-zone field cuts in horizontal and vertical directions for vertical polarization. Amplitude is denoted via a solid line and phase is denoted via a dashed line.

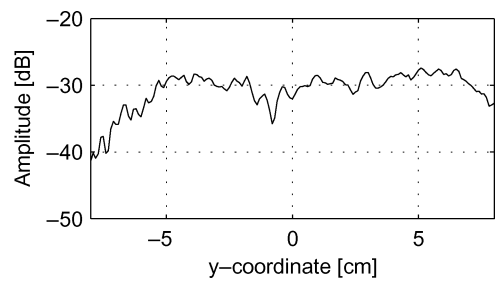

Fig. 7. Cross-polarization level; transmitting antenna horizontal and receiving antenna vertical polarization.

In the horizontal and vertical directions, the quiet-zone field amplitude and phase ripples are 3.3 dB and 23° peak-to-peak, and 0.9 dB and 23° peak-to-peak, respectively. The quiet-zone diameter is 12 cm. The ripple around -5 cm in the x-axis is likely due to slight mechanical vibration of the planar scanner. Excluding this area, the ripple is below 2 dB, as in [9]. The planar scanner is not used during the RCS measurements so the mechanical vibration does not affect the RCS measurement results.

Maximum cross-polarization level of the quiet zone field is -28 dB (Fig. 7). Since no cross-polarization calibration is used, this dominates the cross-polarization performance of the measurement range. The cross-polarization rejection ratio of a compact RCS range based on a 1.5-m reflector before cross-polarization calibration has been reported to be below -30 dB and with calibration -60 dB at 524 GHz [2], [3] in the reported experiments. In these experiments, wire grids have been used to clear the polarization.

Measurement results for the horizontal polarization are shown in Fig. 8. The amplitude and phase ripples for horizontal direction are 1.9 dB and 24°, and for vertical direction are 1.2 dB and 20.5° peak-to-peak, respectively. The quiet zone diameter is 12 cm. The maximum cross-polarization level is -28 dB (Fig. 9). The received co-polar power level is the same

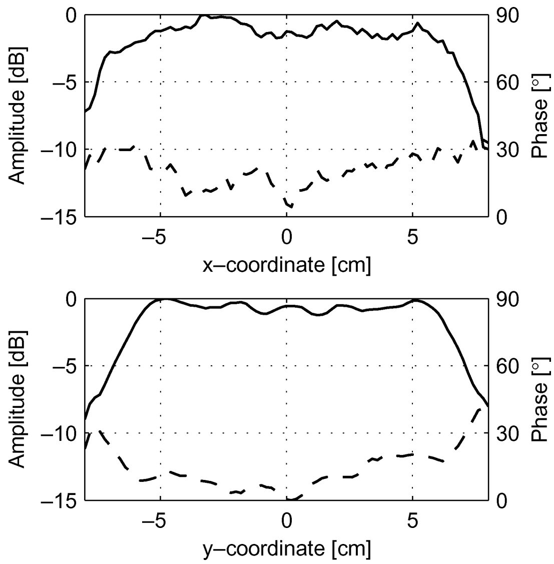

Fig. 8. Quiet-zone field cuts in horizontal and vertical directions for horizontal polarization. Amplitude is denoted via a solid line and phase is denoted with a dashed line.

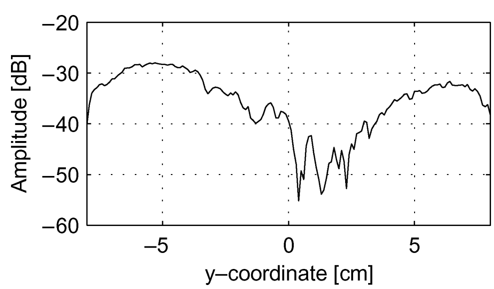

Fig. 9. Cross-polarization level; transmitting antenna vertical and receiving antenna horizontal polarization.

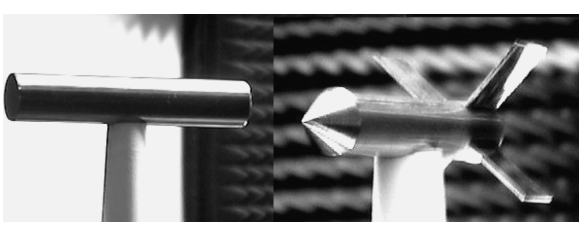

Fig. 10. (*left*) Reference target and (*right*) measured target.

for both polarizations. The quiet-zone field quality is slightly better for horizontal polarization than for vertical polarization.

V. Experimental and Simulation Results

A target "missile imitation model" was measured using a cylinder as a reference target. The target is a modified cylinder with wings and a nose (see Fig. 10). The nose is a circular cone of height 15 mm and the wings are flat plates of size 19 mm $\times$ 20 mm. Both the target and reference target are 100-mm long and just fit into the quiet-zone field. The diameter of the reference cylinder is 2 cm and the diameter of the cylinder part of the target is 1.5 cm. The RCS level of the target and the reference target can be expected to be close to each other. The sharp edges of the reference cylinder were rounded by the manufacturer (< 1 mm). This was not taken into account in the simulations.

The RCS patterns were also simulated using FEKO.[1] A combination of the method of moments and physical optics was used. The relatively simple structure of the target was selected to ease the manufacturing and simulations of the target. The reference target is made of steel and the target of brass. Both can be assumed perfectly conducting in the simulations.

The reflection from the target was separated from the background reflection by moving the target in the z-direction. For each angular measurement position, the target was moved in 50-μm steps a total of 2.5 mm (chosen to be approximately equivalent to $5\times\ \lambda/2$) and the received complex field data were recorded at each step. As a result, a periodic response was obtained. From the variation of the amplitude and phase, the field component caused by the moving target can be evaluated. Power reflected from the target can be calculated from the measured power. The measured power is proportional to the squared resultant of the coherent field vectors reflected from the background and the target

$$P_{\text{measured}} \sim |\boldsymbol{E}_{\text{background}} + \boldsymbol{E}_{\text{target}}|^2. \tag{1}$$

$\boldsymbol{E}_{\text{background}}$ consists of the reflections from the absorbers and the surroundings. The collected data is Fourier transformed and the peak coming from the target is selected. Using the basic radar equation, a relation can be found between the RCSs and the measured power levels

$$\sigma_{\text{target}} = \frac{P_{\text{target}}}{P_{\text{reference}}} * \sigma_{\text{reference}}. \tag{2}$$

The number of measurement points in each angular position affects the residual background level. To optimize the level, the length of the movement has to be close to $n \times \lambda/2$. This is due to target/target support interaction, which, with the Fourier transform, causes the fluctuation of the residual background level. This can be seen in Fig. 11, where the residual background level of the measurement of the cylinder at vertical polarization has been presented as a function of the number of measurement points.

The measurements were done both at vertical and horizontal polarizations. The reflection from the side of the cylinder was used as a reference, as its RCS can be calculated from known analytical formulas [1]. The measurement and simulation results for the cylinder can be seen in Figs. 12–15. The simulation result is the gray curve and the measured result is black.

The residual background level was -42 dBm for the vertical polarization and -36 dBm for the horizontal polarization. Since the power levels at quiet-zone field testing are the same at both polarizations, the waveguide twists do not cause the difference in the background levels. The measurement range itself can behave differently at different polarizations due to the fixed structures surrounding the quiet-zone area. At the vertical polarization, the simulated and measured results are very close to each other. The main difference is in the fluctuation of the RCS

[1] [Online]. Available: http://www.feko.info

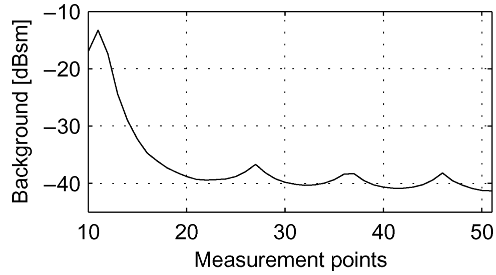

Fig. 11. Effect of the number of measurement points to residual background level of the target. The step of movement between measurement points is 50 μm.

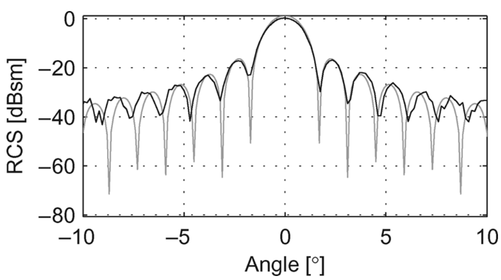

Fig. 12. RCS of the flat end of a cylinder at vertical polarization. The simulation result is the gray curve and the measured result is black.

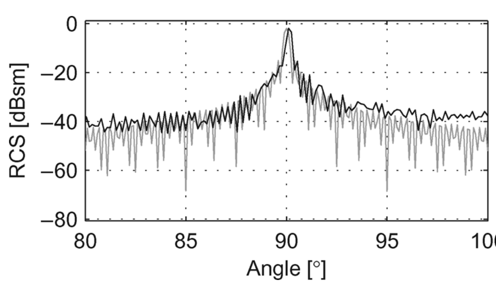

Fig. 13. RCS of the side of a cylinder at vertical polarization.

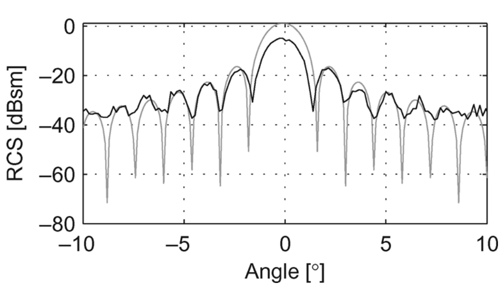

Fig. 14. RCS of the flat end of a cylinder at horizontal polarization.

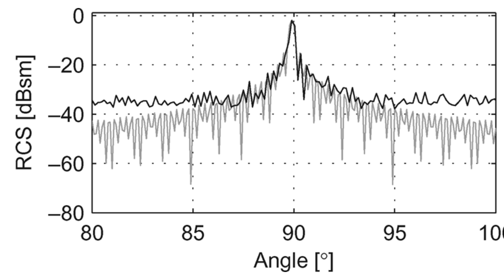

Fig. 15. RCS of the side of a cylinder at horizontal polarization.

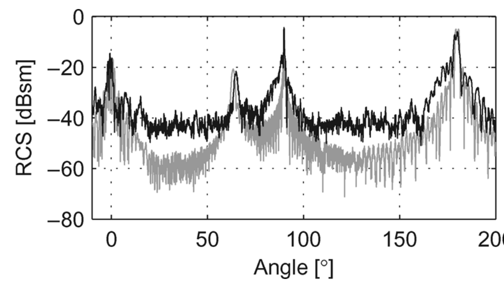

Fig. 16. RCS data of the target at vertical polarization. The target is inclined 0.8° from the horizontal direction.

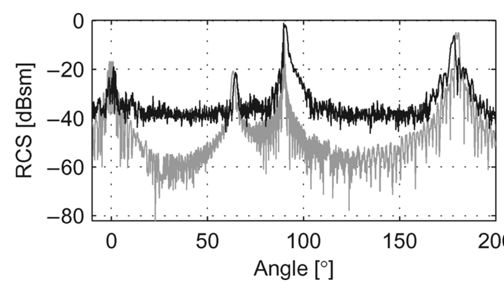

Fig. 17. RCS data of the target at horizontal polarization. The target is inclined 0.8° from the horizontal direction.

pattern near the edge of the circle. This is mainly due to the rounding of the edges of the cylinder, which was not taken into account in the simulations. At the horizontal polarization, there is a 6-dB difference in the maximum level of the RCS at the flat end of the cylinder. This can be due to the target being inclined 1.1° from the horizontal direction.

The measurement results of the target using the reflection from the side of the cylinder as the reference are shown in Figs. 16 and 17. No scaling was done for the RCS results for this demonstration target. First, the RCS peak comes from the nose of the target; second, from the wings; third, from the side; and the fourth from the flat back of the target. The target is inclined 0.8° from the horizontal direction. The reflection peak from the wings is 3° shifted from the simulated result. This can be due to manufacturing inaccuracy of the wings. According to the simulations, 1-mm difference in the length of the wing can cause a 1.5° shift in the angular position of the maximum. The target and its support column were manufactured in a student workshop. The wings are not exactly as long as planned and the angle between them varies from 87° to 93°, while the simulated angle is 90°.

VI. Discussion

The quiet-zone field quality has an effect on the measurement results. The effect of the quiet-zone field quality on the measurement results of metallic balls has been studied in [10].

The broadening of the RCS peaks can be due to the nonideal quality of the quiet zone field. The side of the cylinder was used as the reference. When the side of the cylinder is illuminated, all the parts of the cylinder side have an influence on the measured RCS value and, to a large extent, the ripple in the quiet-zone field does not affect the result. When the cylinder turns, the ripple starts to weight different parts of the cylinder differently. For the cylinder, the effect is not as large as for the target since it is a simple structure with many symmetry planes. The target has a more complex structure and the weighting has a more significant effect. What remains to be verified is how much of the broadening is caused by manufacturing inaccuracy of the target and which part can be explained with the quiet-zone field quality.

An inaccuracy of the target dimensions can have a significant effect on the results. For the next stage of development, the target and also its support column should be precision manufactured to tighter tolerances. The repeatability of target placement can also be improved. The inclination angle of the target was checked with water poise. According to the results, this still leaves approximately 1° uncertainty to the inclination angle. This can be improved by using a laser-based system for the angle verification.

The surroundings of the measurement range affect the background level. They were mostly covered with absorbers, but as can be seen in Fig. 4, there are fixed structures close to the measurement area. The reflectivity of the background limits the minimum measurable RCS level, i.e., the residual background level. The MVNA is very linear over a large range of power and its noise floor is below the level that was measurable here, thus, it has no significant effect on the residual background level. The air flow from the air conditioning also affects the background level. The background level decreased 5 dB when the air conditioning was turned off. Without air conditioning, the measurement equipment drifts with the changing temperature and this causes uncertainty to the measured result. As a compromise, the air flow was redirected away from the equipment and the measurement range was surrounded with absorber walls.

The sensitivity can be improved (i.e., residual background level decreased) by increasing the length of target movement in each angular position. This also increases the measurement time. In these measurements, the length of movement was selected as a compromise between the residual background level and measurement time. As can be seen in Fig. 11, the increase in sensitivity is slow as a function of the number of measurement points.

Thus far, no cross-polarization data have been measured. According to the simulations, the cross-polarization level of targets used here is below -48 dBm so the cross-polarization cannot be measured with the current setup. In the future, this could be achieved by using wire grids to clear up the polarization and using a proper cross-polarization calibration with a disk and dihedral.

VII. Conclusion

A novel compact range based on a phase hologram has been developed for scale-model RCS measurements and its feasibility has been verified. The phase hologram converts the feedhorn radiation to a plane wave needed for RCS determination. The measurements were performed at 310 GHz using a monostatic configuration where the identical receiving and transmitting corrugated horn antennas were placed on opposite sides of a dielectric slab working as a directional coupler. Power division of 3 dB was used in the design of the coupler. CW operation was used.

A cylinder and a "missile-like" target were both simulated and measured. All the main features of the RCS could be seen from the results. The results are very promising. In the future, wire grids will be used to clear the polarization. The development of the phase holograms is going on so better field quality can be expected from the next generation of phase holograms. Manufacturing accuracy of the target can also be improved.

Acknowledgment

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