Development of a Hologram CATR for Submm-wavelengths

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Abstract - The hologram based compact antenna test range (CATR) is a potential method for measuring large antennas at submillimeter wave frequencies. The test results of a demonstration CATR for 310 GHz are shown. Also, further development of the hologram CATR is discussed; the hologram manufacturing and possible improvements to the hologram CATR with a dual reflector feed system is described.

INTRODUCTION

In the near future, several scientific and remote sensing satellites with submillimeter wave instruments and antennas (for example Planck and MASTER by ESA) are scheduled for launch. The testing of electrically large submillimeter wave antennas presents some technical challenges to be met, because the testing cannot be done or is problematic with existing antenna measurement facilities.

Conventional far-field measurements cannot be used for large submillimeter wave antennas. The required far-field distance may be tens or hundreds of kilometers, which makes these measurements impossible because of the high atmospheric attenuation. The radiation pattern and other properties of the antennas can also be determined by measuring the electromagnetic near-field of the antenna and performing a computational near-field-to-far-field transformation. The near-field of an antenna has to be sampled with sample spacing less than $\lambda/2$. For electrically large antennas the required number of samples is very large – several millions of measurement points are needed. The measurement is time consuming and requires great stability and positioning accuracy from the measurement equipment. Compact antenna test ranges (CATRs) are seen as the potentially most suitable measurement technique for submillimeter wave antennas [1].

The compact antenna test ranges allow the measurements to be done indoors in a controllable environment. In a CATR, a focusing element forms a planar wave into a so-called quiet-zone (QZ) from the spherical wave emitted by a feed antenna. The focusing element can be a reflector or several reflectors, a lens, or a hologram. The most commonly used CATRs are based on the use of reflectors. The highest usable frequency of a reflector CATR is limited by the surface accuracy of the reflectors. The required high surface accuracy makes manufacturing of the reflectors expensive. Lenses are not used for large CATRs, because of the lack of suitable homogenous low-permittivity lens materials.

The hologram is a transmission type focusing element with lower surface accuracy requirements than reflectors. This makes hologram manufacturing potentially much more economical than manufacturing of large reflectors. The hologram is a binarized interference pattern of the incoming spherical wave and the desired planar wave. When the hologram is illuminated with the spherical wave, the planar wave is generated into the quiet-zone. The interference pattern is realized by etching radiotransparent slots to a metallization layer on a dielectric substrate. To avoid edge diffraction the slots are tapered, i.e. narrowed, at the edges of the hologram pattern. The basic structure of the hologram CATR is presented in Figure 1.

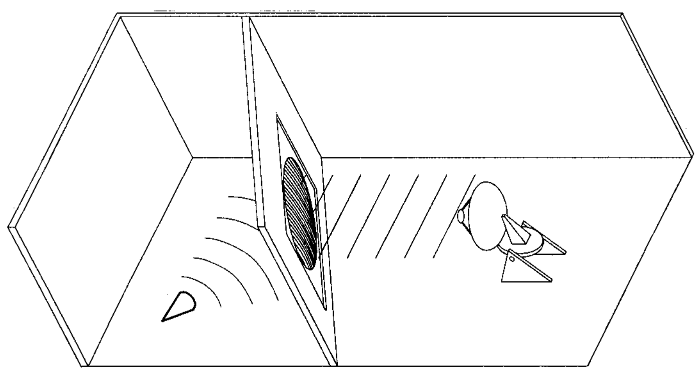

Figure 1. CATR based on a hologram.

The holograms used for CATRs are numerically generated [2]. The holograms are simulated using finite difference time domain method (FDTD) to compute the aperture field and physical optics (PO) is used for computing the quiet-zone field. The holograms are designed iteratively; a hologram is generated and after the simulation a modified hologram is generated to improve the quiet-zone. The plane wave in the quiet-zone is typically required to have an amplitude ripple less than 1 dB peak-to-peak and maximum phase ripple of 10° peak-to-peak. An example of a hologram pattern is presented in Figure 2.

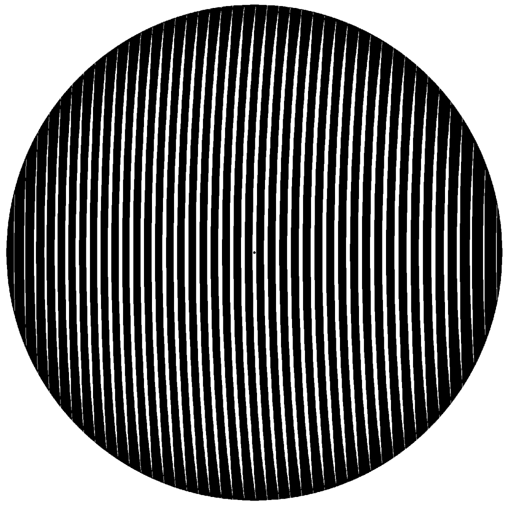

Figure 2. A binarized hologram pattern.

DEMONSTRATION COMPACT ANTENNA TEST RANGE FOR 310 GHZ

A 60 cm diameter hologram was designed for demonstration purposes. The hologram was manufactured by a commercial printed circuit board (PCB) manufacturer. The measurement instrumentation was based on a millimeter wave vector network analyzer MVNA-8-350 (by AB Millimètre). The MVNA-8-350 can be used with various source and receiver configurations. The source was a phase-locked Gunn oscillator with a frequency multiplier. The receiver was a harmonic Schottky mixer pumped with a phase-locked Gunn oscillator.

The source was mounted on a small *xyz*-scanner, which allowed precise adjustments of the source location relative to the hologram. The transmitting antenna was a 310 GHz corrugated horn antenna. The receiver was mounted on a large planar *xy*-scanner. The probe antenna was an open-ended WR-3 waveguide. The quiet-zone field of the CATR was scanned at a distance of 1.5 meters from the 60 cm hologram. The measured contour map of the quiet-zone amplitude is presented in Figure 3. The horizontal phase scan at the center of the quiet-zone is shown in Figure 4.

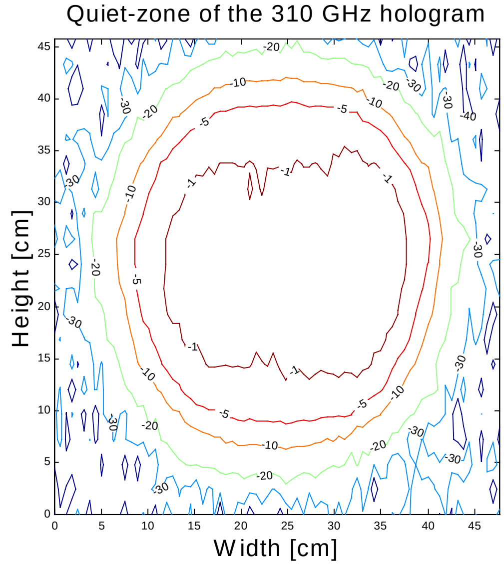

Figure 3. Measured quiet-zone amplitude of the 310 GHz demonstrator CATR.

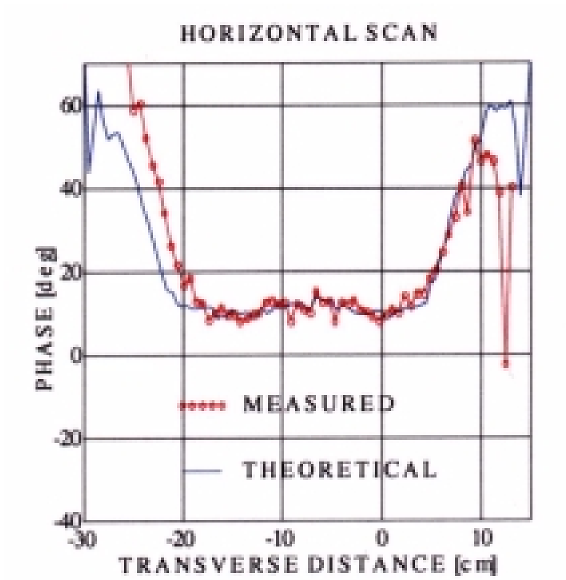

Figure 4. Measured and theoretical phases in horizontal direction.

The peak-to-peak amplitude ripple was found to be about 1 dB and the phase ripple within 10°. The quiet-zone size was found to be approximately 25 cm x 20 cm. With visual inspection of the hologram, it was found out that the narrowest slots at the edges of the hologram had not been properly etched and the hologram had actually a diameter of 52 cm instead of the designed 60 cm. The truncated slots cause the elliptic shape of the quiet-zone seen in Figure 3.

DEVELOPMENT OF HOLOGRAM MANUFACTURING

The quiet-zone of the CATR is required to be larger than the antenna-under-test. To realize a quiet-zone with a diameter of over two meters for testing of two-meter antennas, the hologram has to be 3–4 meters in diameter. The required surface flatness can be achieved by tensioning the hologram into a frame. The required hologram pattern accuracy, i.e., slot width and slot spacing accuracy in the pattern, is estimated to be about 20 and 5 µm for frequencies of 300 and 1000 GHz, respectively. Tapering of the slots, i.e., narrowing of the slots, is needed at the edges of the hologram pattern to reduce edge diffraction. The tapering causes the narrowest slots to be about 20 µm at 600 GHz. These narrow slots are difficult to manufacture. The hologram operation is, however, quite tolerable to localized manufacturing errors.

Several test holograms were manufactured by different manufacturers and these holograms were tested in the MilliLab, Radio Laboratory. The manufacturing methods tested were mainly conventional printed circuit board processes (photolithography) and modifications of these by different exposure methods. Selective metallization of mylar substrate was also tested with laser-induced chemical liquid-phase deposition (LCLD) [3]. The quiet-zone of one of these 20 cm diameter test holograms was measured in three dimensions by taking crosscuts of the quiet-zone field at several locations along the direction of the wave propagation. The resulted 3D scan of the quiet-zone is presented in Figure 5.

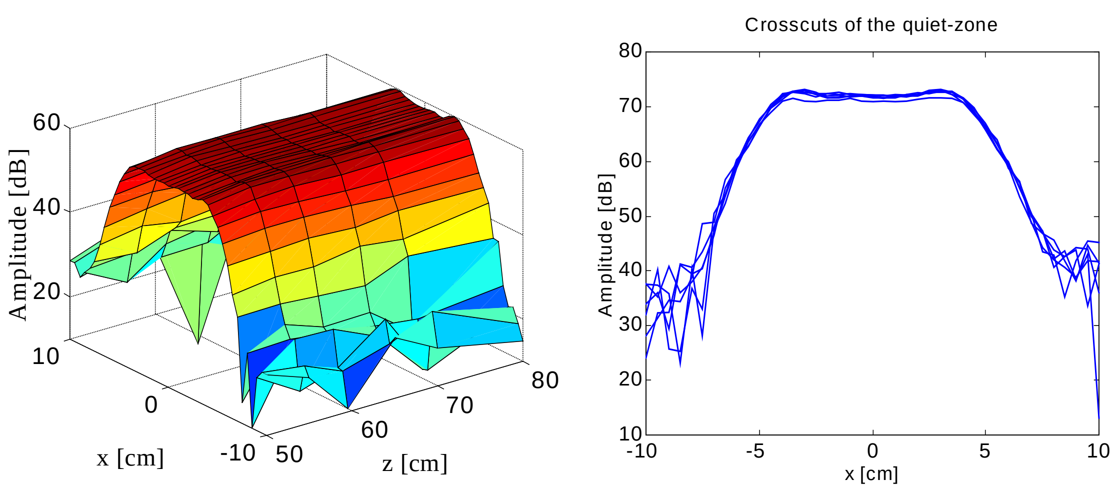

Figure 5. Quiet-zone of a small hologram along the direction of propagation.

Commonly available commercial printed circuit board (PCB) processes are usually limited to the circuit board size of 600 mm x 600 mm and etching of narrow slots at the edges of the area is problematic. In a conventional PCB process phosensitive resist is applied over the metallization on the dielectric substrate. For 310 GHz holograms, the substrate was 75 µm thick Mylar with 17 µm thick copper layer. Photomasks were used for selective exposure of the photosensitive resist. The copper was removed from the slots by chemical wet etching.

The maximum manufacturable pattern size can be increased with so-called stepwize exposure, where a rectangular area is exposed with a photomask and another photomask is then joined to the previous photomask. The pattern length can be increased by joining several masks to form several meters long pattern strips with fixed width (600–900 mm). These strips could be then joined to form a large hologram. The joining of the photomasks reduces achievable overall pattern accuracy because of the potential misaligning of the photomasks. Photomask distortions may also occur when large masks are used.

The hologram pattern can also be written directly to the photosensitive resist with a laser. The metallization is chemically etched after the laser exposure. The direct laser writing of the pattern is currently seen as the most interesting manufacturing technique for large submillimeter wave holograms. Patterns up to 1.5 m x 6 m can be manufactured in a single piece with line widths down to 40 μm.

To realize large holograms up to 3–4 meters in diameter, the holograms have to be joined from several separately manufactured pieces or custom made large-sized special equipment has to be used. Taping and glueing have been investigated as potential joining methods of hologram pieces. A seam causes a discontinuity to the hologram pattern and acts as a diffraction source. The effect of horizontal and vertical tape strips and seams were tested with 30 cm diameter test holograms. The quiet-zone was scanned in vertical direction in case of the horizontal tape, and vice versa. The tape was 23 μm thick and 5 cm wide mylar tape by Scotch. According to the tests, horizontal seams perpendicular to the hologram slots and to the used polarization affect the hologram quiet-zone the least. Therefore, the hologram should be formed by joining long horizontal strips. Measured effect of vertical and horizontal strips of tape at the center of the hologram are presented in Figure 6 (the curves have been shifted in vertical direction to avoid overlapping). The investigation on the joining techniques of hologram pieces continues and different glueing experiments will be done to find the most suitable joining method.

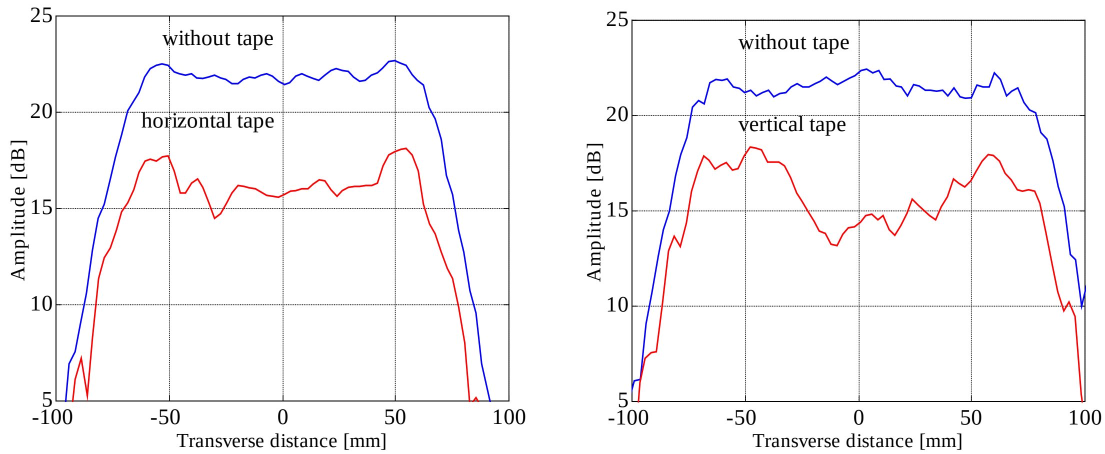

Figure 6. Effect of horizontal and vertical tape to the hologram quiet-zone.

There are some challenges to be met in the manufacturing of large submillimeter wave holograms. The required hologram size cannot be realised without joining several hologram pieces together, which reduces the achievable pattern accuracy and the operational frequency range of the hologram CATR. The tapering of slots to avoid edge diffraction leads to very narrow slots at the edges of the hologram. These narrow slots are difficult to etch.

DUAL REFLECTOR FEED SYSTEM FOR HOLOGRAM CATR

The needed tapering of the slots can be reduced by modifying the electromagnetic field that illuminates the hologram. Narrow slots are difficult to manufacture and the narrow slots increase the polarization sensitivity of the hologram. Furthermore, by modifying the hologram illumination the hologram size efficiency, i.e., the relative size of the quiet-zone compared to the hologram, can also be increased. The hologram illumination can be modified by using a dual reflector feed system (DRFS).

The DRFS modifies the radiated field of a feed horn both in amplitude and phase. The reflectors are shaped non-classical surfaces, that have to be determined numerically. The basic configuration of the DRFS is shown in Figure 7. The reflectors have elliptical rims and the surface shape is hyperbolical type with a focal point behind the reflectors. The sizes of the reflectors needed for the modified hologram illumination are approximately 20–25 % of the hologram diameter. The reflector surfaces can be determined with geometrical optics (GO) based reflector antenna synthesis from the feed horn radiation pattern and from the desired hologram illumination [4]. Ray-tracing based GO synthesis software is currently being developed.

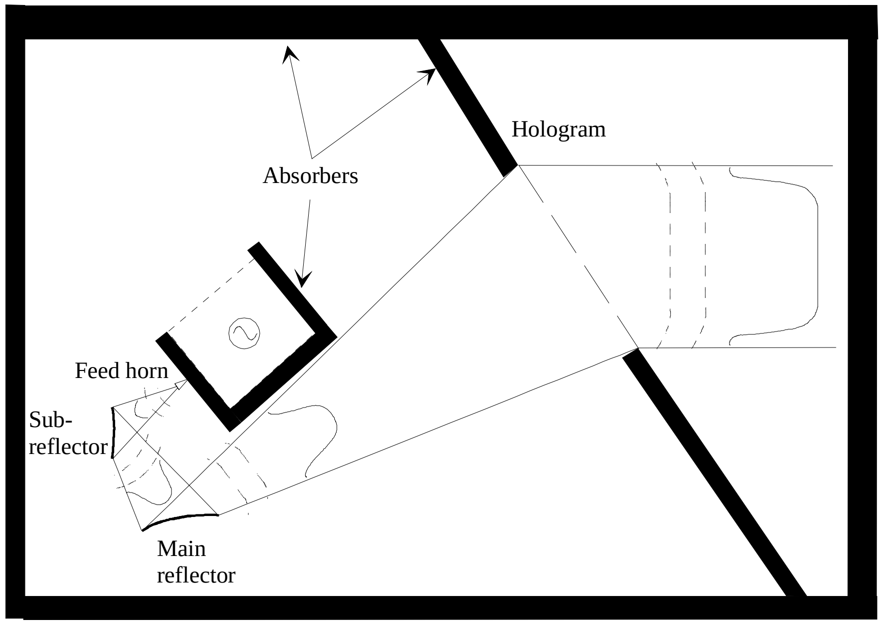

Figure 7. Hologram CATR with a dual reflector feed system.

The main advantages gained by introducing a DRFS to the hologram CATR are the increased relative quiet-zone size and the reduced need for narrow slots at the edges of the hologram pattern. The spill-over of the feed system is also slightly decreased, which increases the dynamic range of the CATR. Also, the cross-polarization level of the hologram CATR will be slightly decreased, because the hologram effective focal length can be increased. The increased focal length results to less curved slots, which reduces cross-polarization caused by the hologram. In Figure 8, the simulation results for a 60 cm hologram are presented. For example, with a third order Butterworth-type flat illumination with amplitude taper of -7 dB at the hologram edges, the quiet-zone diameter of a 60 cm hologram increases by a third compared to a hologram illuminated directly with a feed horn.

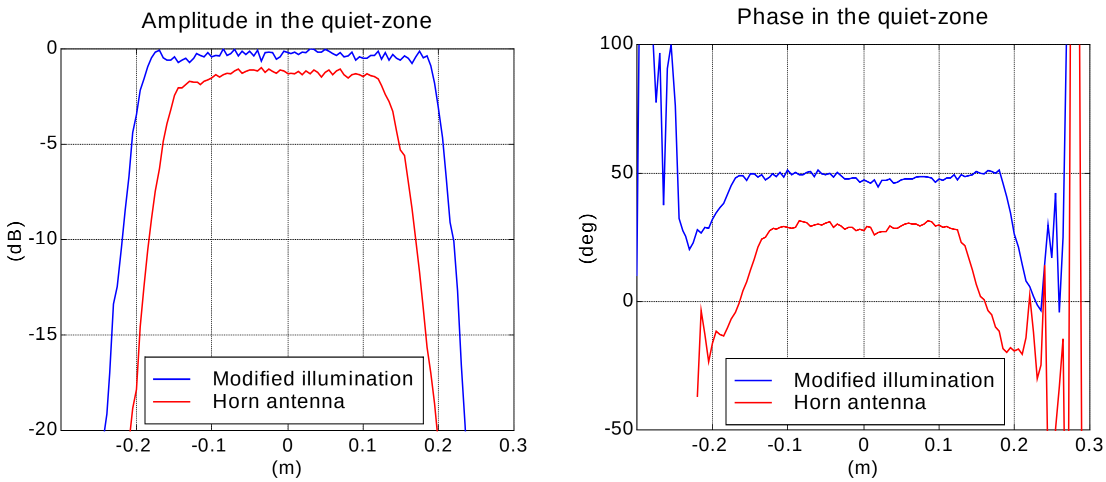

Figure 8. The increase in the quiet-zone size with modified hologram illumination.

The improved hologram illumination by the DRFS also simplifies the hologram manufacturing by widening the slots near the hologram edges. The hologram pattern slot spacings and widths with a simple Gaussian illumination, and with a more optimized illumination are presented in Figure 9. The main disadvantages of introducing a DRFS to the hologram CATR are the increased cost of the CATR and the cross-polarization caused by the reflectors itself in the DRFS.

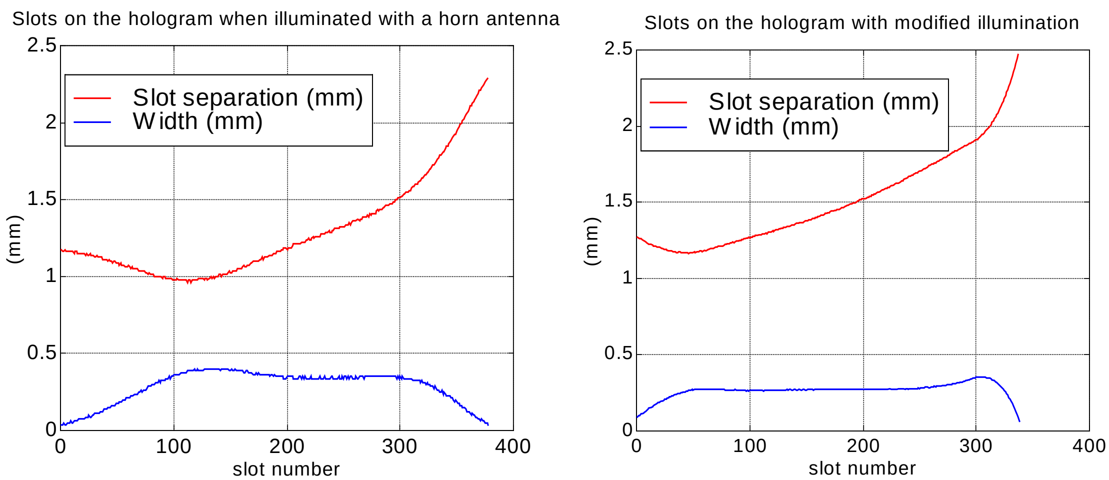

Figure 9. Hologram slot separations and widths with Gaussian and modified illumination.

CONCLUSIONS

The hologram CATR is a potential method for testing large submillimeter wave satellite antennas. The feasibility of the CATR has been demonstrated with quiet-zone testing of a 60 cm diameter hologram for 310 GHz. Progress in the hologram manufacturing is presented here, but some manufacturing challenges still have to be met before practical large-sized compact antenna ranges based on the hologram can be realized. The continuing research on the hologram manufacturing has been presented. The hologram performance and the manufacturability of the hologram can be improved with a dual reflector feed system (DRFS). The DRFS modifies the hologram illumination, which increases the achievable quiet-zone size of the hologram. The reflectors of the DRFS are shaped non-classical surfaces. The surfaces can be determined with geometrical optics based reflector synthesis.

ACKNOWLEDGEMENTS

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