TESTING REFLECTOR ANTENNAS IN THE THz FREQUENCY RANGE

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Abstract

Possibilities of applying far-field, near-field, and compact range techniques on reflector antennas in the THz frequency range are critically discussed. In addition, other methods such as defocusing, and combining of the mechanical reflector surface measurements and the feed horn radiation patterns are discussed. The discussion of the compact range measurement method includes a description of a recently introduced hologram type of compact range. Antenna test methods in the THz range, are needed for several future scientific satellites. None of the current methods have, so far been validated for use in the THz range. One may conclude from the analysis of the different methods in this work, that the far-field method can be discarded for certain, due to the atmospheric effects. The near-field method remains a possibility, however, an expensive, high quality moving stage is needed, and phase errors caused by flexible cables have to be dealt with. In some cases, a defocusing method to bring the far-field closer may prove to be practical. Technically, the most feasible and least expensive method appears to be the hologram type of compact range. In this method, a planar amplitude hologram is used to form the required plane wave. The hologram is inexpensive to manufacture, and it is also less sensitive to surface accuracy errors than a reflector.

1 Introduction

Several scientific satellite missions with submillimeter wave radiometers operating at THz frequencies have been planned for the future. FIRST (Far Infrared and Submillimeter Space Telescope) of ESA for 500–2000 GHz and SMIM (Submillimeter Intermediate Mission) of NASA for 400–1200 GHz are two examples of this kind of mission. In both projects, the most important active elements of a radiometer, i.e., the mixers and local oscillator sources, have been selected as areas requiring significant development. Also required for a high performance radiometer, is some kind of a reflector antenna. Manufacturing a reflector antenna for space application at 1 THz is a challenging task. An additional challenging task is accurate testing of this antenna prior to launch. Presently, a convenient method for this kind of test is not readily available. In NASA's SWAS (Submillimeter Wave Astronomy Satellite) for 490–550

GHz, the antenna with an aperture size of 0.55×0.71 m, will be tested using a conventional near-field method utilizing a granite reference plate. Extending this approach for 1–2 THz testing of large antennas is difficult and promises to be extremely expensive.

One objective of this paper is to critically discuss the possibilities of applying far-field, near-field, and compact range techniques on THz antennas. In addition, other methods such as defocusing, and combining of the mechanical reflector surface measurements and the feed horn radiation patterns are discussed. The discussion of the compact range measurement method includes a description of a recently introduced hologram type of compact range. This method is considered a strong candidate for 1 THz antenna testing.

The other objective of this paper, is to stimulate discussion and raise awareness of the importance of THz antenna testing, which has often been disregarded and its difficulty underestimated in satellite technological development programs. This may lead to the situation where the mixers and solid-state sources will be ready for the satellite, but the mission will be delayed because there is not any way of adequately testing the antenna.

2 Far-field method

A natural starting point when considering an appropriate antenna test method for a particular case, is the far-field method. This method is the most direct and also, if applicable, the simplest. In the far-field method, the probe antenna is moved a distance d away from the antenna under test (AUT) so that the spherical wave from the probe antenna is virtually a plane wave in front of the AUT. The distance is usually required to be at least $d = 2D^2/\lambda$, where D is the diameter of the AUT and λ is the wavelength. This requirement for the minimum value of d, implies that a 22.5° phase change of the virtual plane wave is accepted over the aperture of the AUT. For example, for an antenna with $D = 1$ m, distance $d = 6.7$ km at 1 THz.

At microwave and low millimeter wave frequencies the large distance d is the main complication for an electrically large antenna. At higher frequencies, even though the large value of d remains a great problem, the atmospheric effects on the transmitted signal become the most significant limitation. Firstly, around 1 THz the attenuation is many tens to hundreds of dB/km [1]. Secondly, the temperature gradients and changes, and the humidity variations cause short term fluctuations in the signal path attenuation. Due to the above reasons, far-field measurements on a 1 THz reflector antenna with D > 0.2 m (d=270 m) are practically impossible.

3 Near-field method

In the near-field method, the amplitude and phase of a field over the antenna aperture is measured. The far-field is obtained then by taking a Fourier transform of the measured field. The near-field data acquisition can be carried out over a plane, a sphere or a cylinder. For a high gain antenna, like an electrically large reflector antenna, planar or cylindrical scanning are obvious choices. In planar scanning, the AUT is kept fixed and the field probe movement is realized with two linear stages. In the cylindrical case, usually the antenna is rotated and the probe is moved on a linear stage. In satellite payload antenna testing, rotating the antenna would obviously require the rotation of the whole satellite. Therefore, specific acceptable sampling point spacing and an estimate of the error due to aliasing can be derived from a theoretical antenna pattern along with measurements of system noise and error levels [6].

As an example, Figure 2 shows the effect of aliasing with different sample spacings. The antenna that is used in the simulations is a 1 m Cassegrain antenna with a 12 dB taper in the aperture amplitude distribution. Subreflector blockage of 70 mm in diameter is included in the analysis. In this case, the main beam and first sidelobe can be determined if the spacing of the sample points is not greater than about 100 λ.

The main concern in near-field antenna measurements at 1 THz, is the phase errors caused by the flexible cables and probe positioning errors. The error analysis for planar near-field measurements in [6], reveal that a one degree RMS phase error in the near-field measurements causes less than a 0.12 and 1.2 dB inaccuracy at –10 and –30 dB far-field amplitude pattern levels, respectively. In other words, as the pattern level decreases by 20 dB, the amplitude error caused by the near-field phase error increases by a factor of 10.

The phase errors caused by flexible cables are usually minimized by carefully selecting the flexible cable and by properly designing its mechanical attachment to the moving probe. One possible way to reduce bending of the cable, would be to use a cable with the form of a helix. The disadvantage of this would be the additional length of the cable.

Since the possibilities for directly eliminating cable phase errors are limited, schemes to first measure the phase error and then to remove the errors numerically have been developed. The method described in [7] is a simple and easy method to realize. This method is based on the measurement of the phase of the signal passing twice through the flexible cable. Therefore, it works best for low loss cables. A more complicated three cable method is described in [8]. This method enables one to measure phase errors on lossy and longer cables.

There are two techniques that can be used to overcome the phase errors caused by probe positioning inaccuracies, especially those perpendicular to the measurement plane: to design and build a very high quality moving stage, or to supply a reference plane for the measurements. The latter approach has been chosen for the tests of the 600 GHz antenna of NASA's SWAS satellite. The reference plate will be a highly flat granite plate, against which the planarity of the probe scanning area will be calibrated.

A phase retrieval method may be also used to overcome the phase problems in the near-field measurements. Much work has been done lately on this area [9]–[13]. In these methods, only amplitude data in front of the antenna is measured. The phase value of the field is then recovered from the amplitude data. The development efforts are pointed towards algorithms, which can reliably recover phase information from a single amplitude scan. Presently, most of the methods require amplitude scans over two planes, or over one plane with two focal positions of the antenna feed horn.

Phase retrieval methods entirely overcome the problem of the flexible cables (assuming obviously that the effect of the cable on the amplitude of the signal is constant) and requirements for the moving stage can be assumed to be eased somewhat. However, presently there does not exist a thorough analysis of the errors caused by factors such as probe positioning inaccuracies along the direction of the propagation and perpendicular to this direction.

Phase retrieval methods have been applied in holographic surface testing for the *far-field and Fresnel zone data* of large telescopes up to about 100 GHz (see, for example, [14]). However, so far, for the *near-field data* the methods have been used only up to high

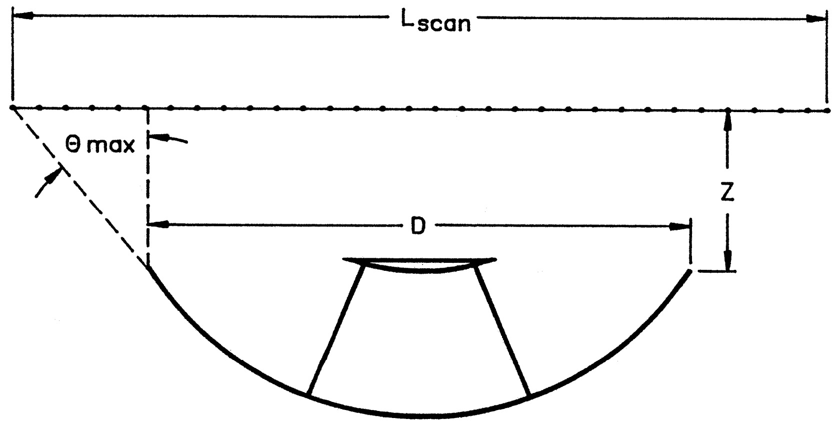


Figure 1: *Angular region of validity θ_{max} defined by the scan length.*

for satellite antenna testing, planar scanning is the most preferable method. In this method only the probe antenna in front of the test antenna is moved. Comprehensive reviews and analysis of the near-field measurements can be found, e.g., in [2,3].

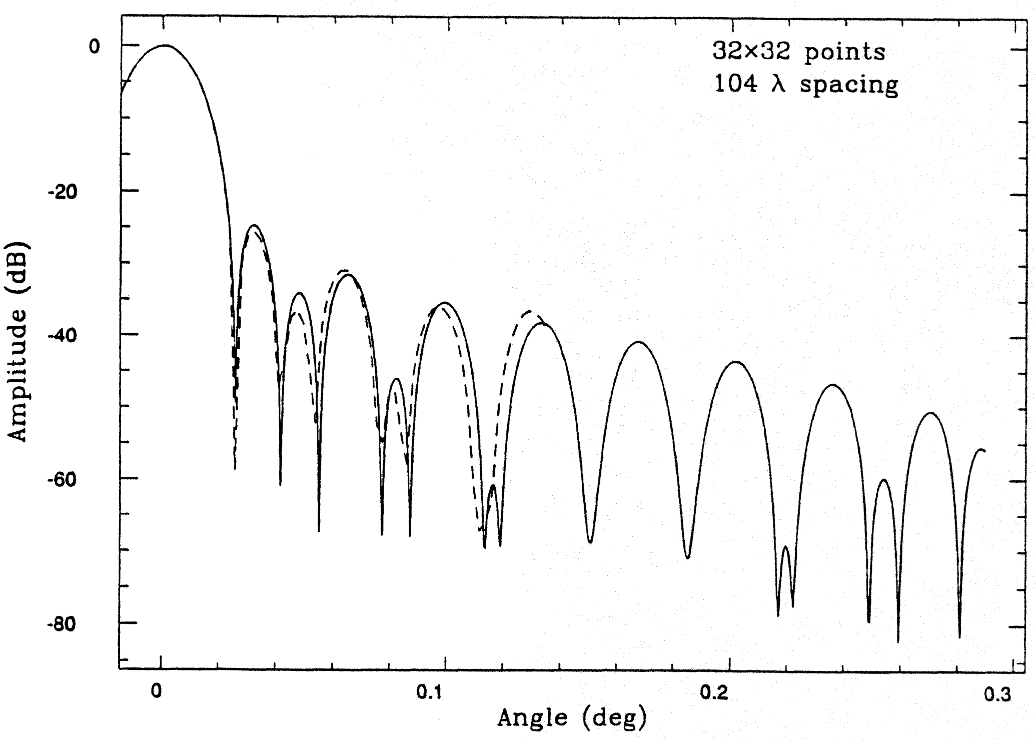
Planar near-field measurements are most frequently realized with an x-y-stage in a rectangular coordinate system. However, plane polar scanning can sometimes lead to a simpler mechanical moving stage [4,5].

Proper sampling of the near-field of an antenna requires first, to define the area required to adequately cover the aperture field and second, to choose a dense enough sampling interval. A too small sampling area and a too large sampling interval cause truncation and aliasing of the data, respectively. For a high gain reflector antenna, which even a small reflector antenna at the THz range is, truncation of the data due to a finite size scan area is not a problem. A scan area that is slightly larger than the projected area of an antenna is sufficient. The angular region for accurate far-field patterns is defined by the geometry of the antenna and the scan area, as shown in Figure 1. Angle

$$\theta_{\mathrm{max}} \approx \tan\left(\frac{L_{\mathrm{scan}} - D}{2z}\right) \tag{1}$$

is the maximum angle for accurate far-field [6]. This criterion can be used to determine the minimum size of the scan plane for a given desired angular region and separation distance z. Aliasing can be fully avoided only if the Fourier transform of the measured data is band limited, and the sampling interval is $\lambda/2$ or less [6]. For an aperture field, the band limited requirement implies that the field should change smoothly and there should be no discontinuities in the field.

If band limits do not exist or if the sampling criteria is violated by using too large a data point spacing, aliasing errors occur in the use of the FFT to calculate the Fourier transform. If an antenna with a diameter of 1 m at 1 THz is sampled with a $\lambda/2$ spacing in a rectangular grid, about 11 million points are needed. Evidently, to carry out the near-field measurements, a larger data point spacing is desired. As the spacing is increased, aliasing first starts to have an effect on the far sidelobes. If only the main beam and possibly the first sidelobes are of interest, the total number of points can be reduced significantly. The



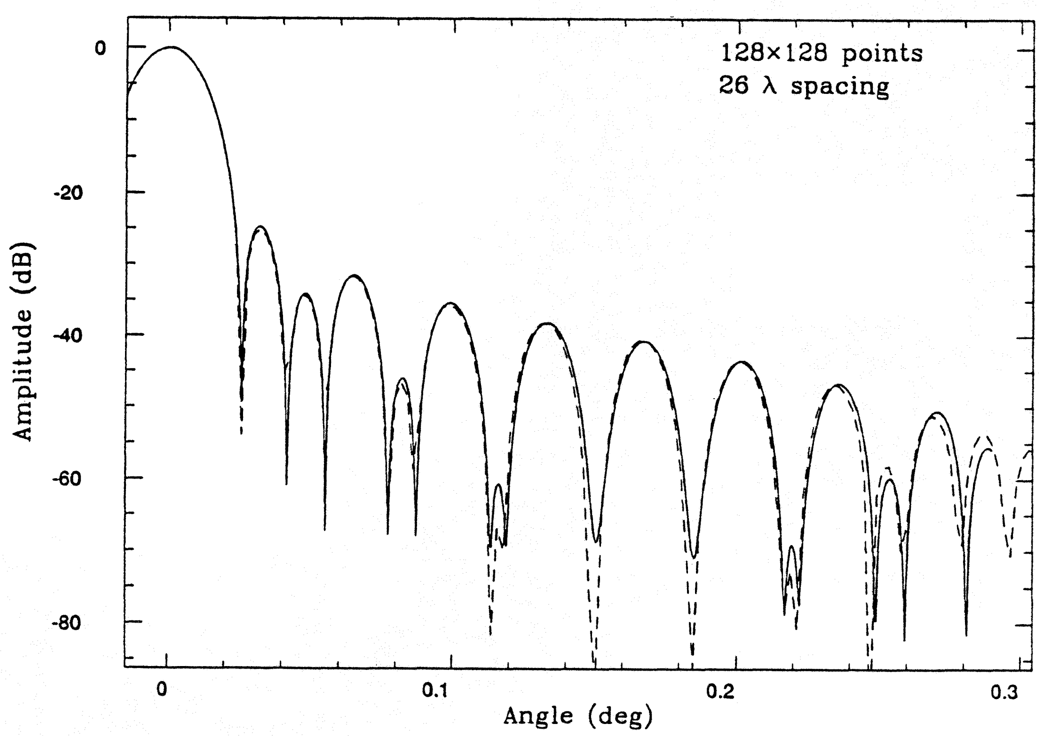


Figure 2: *Simulated effect of aliasing on a far-field pattern of a 1 m Cassegrain antenna at 1 THz. Error free far-field (—). Far-field pattern with different near-field sampling intervals (- - -).*

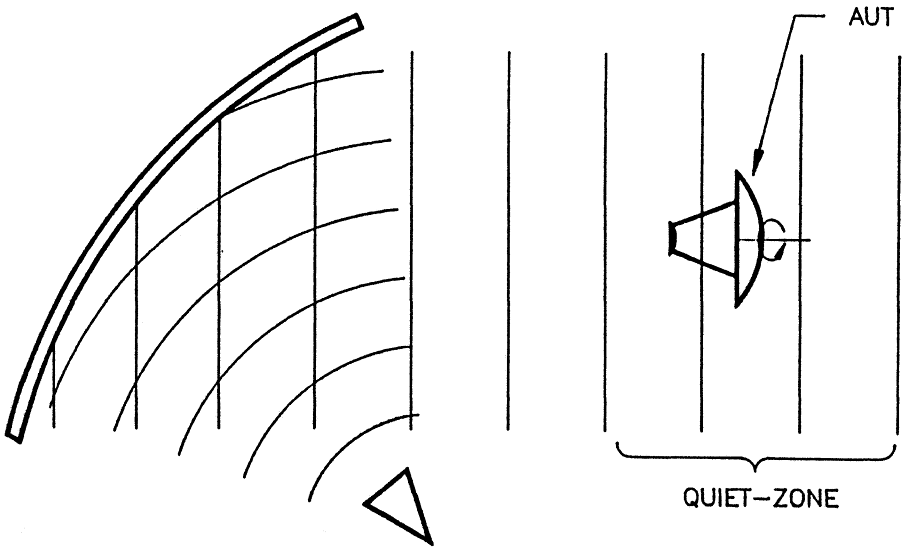


Figure 3: *A compact antenna test range (CATR) using a reflector.*

microwave frequencies (< 30 GHz) and usually for relatively small antennas. How easy it is to extend these methods to the THz frequency range is not obvious. One of the concerns is the sampling interval and whether it can be many wavelengths. A long sampling interval is essential for testing submillimeter antennas. Another concern is the required amplitude measurement accuracy. In spite of all the above unknowns, phase retrieval is an attractive alternative for testing antennas at 1 THz, especially if a near-field testing method is desired.

4 Compact antenna test range method

In a compact antenna test range (CATR) an artificial far-field plane wave is formed in front of the antenna under test (AUT). The main advantage of a CATR is that direct far-field radiation patterns can be measured the same way as in the far-field method under a controlled environment and especially in a short range.

The required plane wave is formed from a feed horn spherical wave with a focusing element, which is commonly realized with use of one or more reflectors. A typical CATR arrangement is shown in Figure 3. All of the commercial CATRs use reflectors and they are available up to about 200 GHz. The quiet-zone size, i.e., the plane wave region, defines the maximum diameter of the AUT. The diameter of the quiet-zone is usually 50–70 % of the diameter of the main reflector of the CATR. The presence of diffraction from the edges of the focusing reflector is the factor that primarily defines the useful quiet-zone area. The diffraction is reduced with a special curved or serrated edge treatment of the reflector. Edge diffraction is most pronounced at low microwave frequencies, and it gets less severe as the frequency increases. Another way of looking at this, is that the effects of diffraction are smaller, the larger the aperture (reflector) is in wavelengths.

While the diffraction effects become smaller, the high surface accuracy required for the reflectors becomes a real problem as frequency increases. Usually, a surface accuracy of $\lambda/100$ is required. Therefore, for example, the surface error should be less than 3 μm RMS

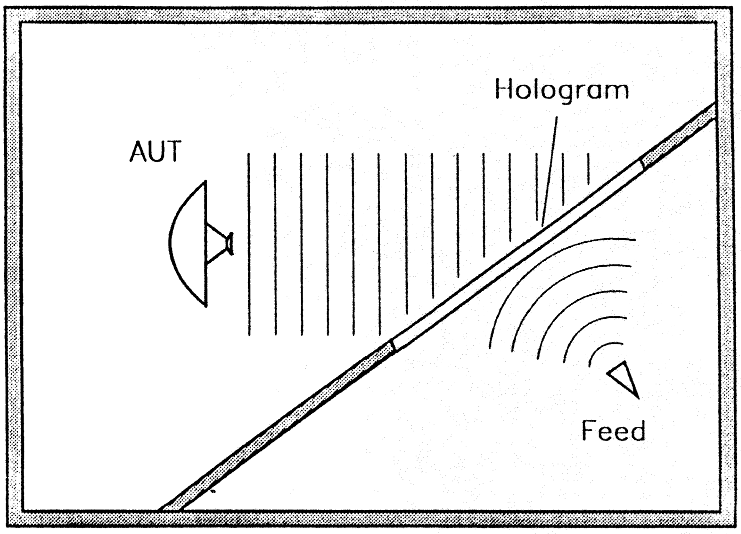


Figure 4: *A hologram type of CATR.*

at 1 THz. This implies that the cost of a reflector CATR will be very high at 1 THz.

The use of a lens instead of a reflector in a CATR has been considered as an option to overcome the high surface accuracy tolerances [15,16]. For a lens with a low dielectric constant ϵ_r, the surface accuracy requirement is much less stringent.

For a lens, the surface accuracy is weighted by the factor of $\sqrt{2}/(\sqrt{\epsilon_r}-1)$, as compared to a reflector. For example, for a foam lens with $\epsilon_r = 1.1$, the requirement for the lens surface is 90 μm RMS at 1 THz. With $\epsilon_r = 1.1$, and a focal length to lens diameter ratio $F/D = 3$, the thickness of the foam lens would be slightly less than the diameter of the lens [17]. The thickness of the lens starts to increase rapidly as ϵ_r of the lens is decreased from the value of 1.1. A lens could be a less expensive alternative than the use of a reflector. Primary concerns about the use of a foam lens at 1 THz, are the granulation of the foam and also how easily and smoothly a foam surface can be shaped.

Perhaps, the most feasible way of realizing a compact range at THz frequencies is the recently introduced hologram approach [18]. In this method, a planar, computer generated hologram structure is used as a focusing element. Figure 4 shows an arrangement for a hologram CATR. The hologram is placed at the opening in the wall, which divides the anechoic chamber into two parts.

In general, a hologram structure changes both the amplitude and phase of the field transmitted through or reflected from the structure. In practice, holograms are usually realized so that they only change the amplitude or phase of the field. In this case, the hologram is called correspondingly either an amplitude or a phase hologram. A transmitting amplitude hologram, like the one used here for the compact range, can be approximated by an appropriately shaped metallization pattern etched on a dielectric film with a thin copper layer. Figure 5 shows an example of a binary amplitude hologram pattern used at 110 GHz [18]. This pattern is generated based on a known incident field, i.e., feed horn spherical wave and the desired output plane wave. To reduce edge diffractions, the hologram is designed

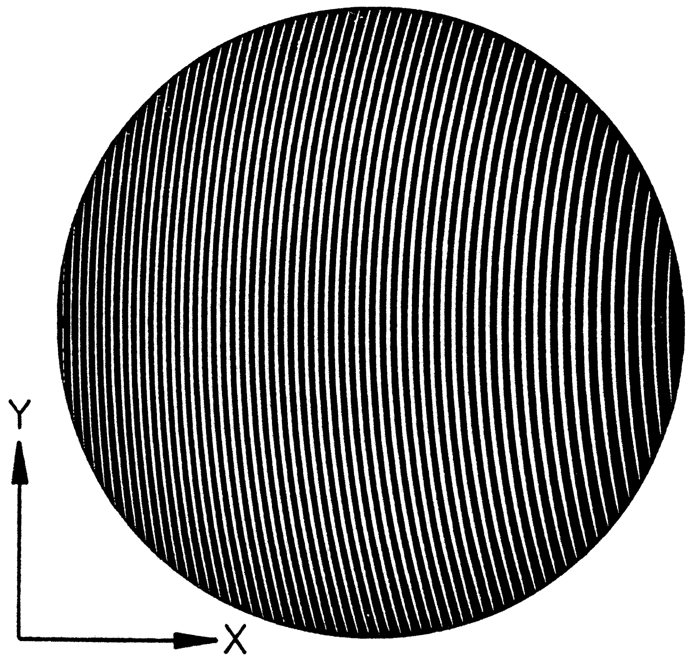


Figure 5: *An example of a binary amplitude hologram pattern. Non-transparent and transparent parts are shown with black and white, respectively.*

to give a cosine amplitude taper. Furthermore, the hologram is designed so that the plane wave leaves the hologram at an angle of about 33°. This is important to separate the desired plane wave and unwanted wavemodes, which are due to the binarization of the hologram transmittance. Using this pattern, the operation of a hologram CATR has been successfully demonstrated at 110 GHz. The diameter of the hologram was 300 mm. Figure 6 shows the measured and theoretical amplitude of the quiet-zone field. The measured ripple is about ± 1 dB and the diameter of the quiet-zone is about 2/3 of the diameter of the hologram.

Manufacturing an amplitude hologram is very inexpensive, only a few percent of the cost of a comparable curved reflector. The hologram can be manufactured with a similar etching process to the one used for making printed circuits. Since only the amplitude of the incoming spherical wave is changed, the surface accuracy requirement is much less stringent than for a reflector. Furthermore, high flatness is easy to achieve, since the hologram is simply stretched onto a frame. The only disadvantage of a hologram structure is the fairly strong frequency dependence, due to the diffractive nature of the component. This is not, however, a problem in testing antennas of scientific satellites, because they are usually designed to operate at a few specific spectral line frequencies.

As important as building the compact range well, is verifying the quality of the quiet-zone. At lower frequencies, the quiet-zone is tested by measuring amplitude and phase distribution on several cuts across the quiet-zone. Measuring amplitude cuts should not be significantly more difficult even at 1 THz. Measuring phase cuts faces basically the same problems as measuring phase in the near-field method. However, the situation in a CATR is somewhat easier, since phase is only needed on linear cuts and not on a whole plane. Making a very high quality linear moving stage is obviously much easier than to make an x-y-stage. This is

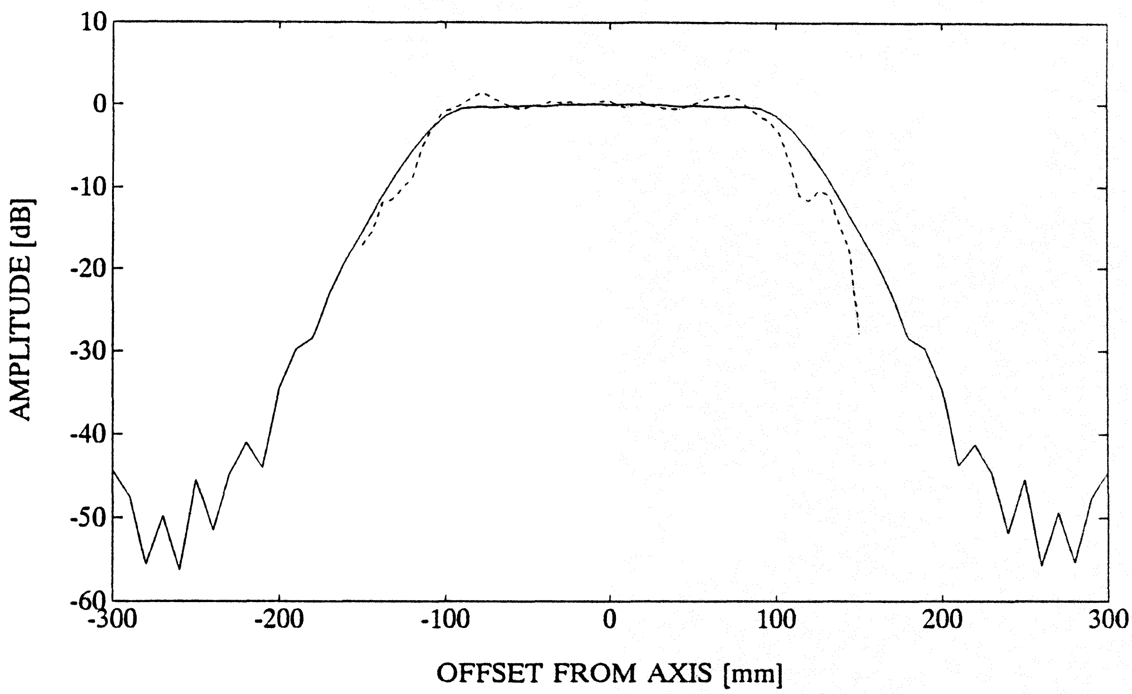


Figure 6: *Theoretical (——) and measured (- - -) amplitude of the quiet zone field at an angle of 33.06° with respect to the normal of the hologram.*

especially true, because the linear stage does not have to extend over the whole quiet-zone at one time. Therefore, phase errors due to the scanning mechanism can be neglected or at least they can be estimated quite accurately.

Phase errors caused by flexing of the cable can not be neglected. However, they are easier to handle in the case of the quiet-zone than in the near-field testing, again because of the more limited scanning requirements. Furthermore, it is possible to totally overcome the phase errors caused by the cables with the use of the differential phase method [20]. In this method, a two channel receiver is moved across the quiet-zone and the phase difference between the two channels is recorded. Then from the differential phase pattern, the normal phase information is calculated. Very short period ripple and phase front tilts are difficult to measure with this method.

Another common test is to measure the radiation pattern of a smaller reflector antenna in a CATR and then to compare it to the one measured in the far-field. This would be a valuable test to carry out in addition to the above mentioned quiet-zone tests. The size of the test reflector antenna has to be limited to about 50–100 mm in diameter. Otherwise, the far-field distance becomes too large. A comparison of the patterns of a small test antenna measured at different points of the quiet-zone indicate the uniformity of the plane wave region.

5 Other methods

In addition to the above described method, there exists some other methods, which can be considered, in general, only as marginal alternatives. However, in some specific cases, they can prove to be useful. Two such methods are described in the following section.

Defocusing

It is well known that an antenna far-field radiation pattern, which exists ideally an infinite distance away from the antenna, can be brought closer by moving the feed horn further out from the focal position [19]. This is shown in Figure 7. Interesting to note, is that for a fast optical system (F/D is small) a relatively small defocusing brings the far-field conveniently close. This can be calculated from the well known thin lens formula:

$$\frac{1}{d_2} = \frac{1}{F} - \frac{1}{d_1}. \tag{2}$$

For example, if $F = 1$ m and the defocusing distance is 20 mm ($d_1 = 1$ m + 20 mm), we find that the far-field of the antenna has been brought to $d_2 = 51$ m from the antenna. Figure 8 shows theoretical far-field patterns at $2D^2/\lambda = 6.7$ km and 51 m distances in defocused and in focused cases at 1 THz. The antenna is a 1 m diameter Cassegrain antenna with $F/D = 1$. The aperture field has a 12 dB amplitude taper and a subreflector blockage 170 mm in diameter. Aperture phase distribution was calculated by ray tracing with an axial defocusing distance of 21.5 mm. This value was chosen, because it gave the best fit to an ideal spherical phase deformation, caused by a defocusing of 20 mm. The high sidelobe level of the antenna pattern is due to the large diameter of the subreflector, which is required for a $F/D = 1$ Cassegrain system. A real antenna would be rather an off-set antenna.

A drawback of the defocusing method is the need to move the feed, or alternatively, the subreflector relative to the antenna. This can be a significant problem in satellite payload antenna testing. Another disadvantage is that the accuracy of the far-field relies on the validity of the assumption that the defocusing affects only the phase distribution of the aperture field. An obvious advantage of the defocusing technique is that one may carry out measurements with the same simplicity as in conventional far-field measurements, but use a shorter range.

Combined electrical and mechanical measurements

The far-field radiation pattern of a reflector can be calculated if both the amplitude and phase pattern of the feed horn or feed system, as well as the surface of the reflector are all accurately known. Measurement of the amplitude pattern of the feed horn is fairly straight forward and includes no major problems, since a dynamic range of 30 dB should be sufficient. Measurement of the phase pattern with conventional measurement methods is difficult at 1 THz. The main problems are the complexity of the measurement set-up, and errors caused by flexing of cables needed in the system. Using the differential phase measurement method [20,21], phase pattern measurements should not be a major problem either, even at 1 THz. Mechanical antenna surface measurements can become the real bottleneck of this approach. If the antenna surface is measured with a mechanical probe, the number of surface grid

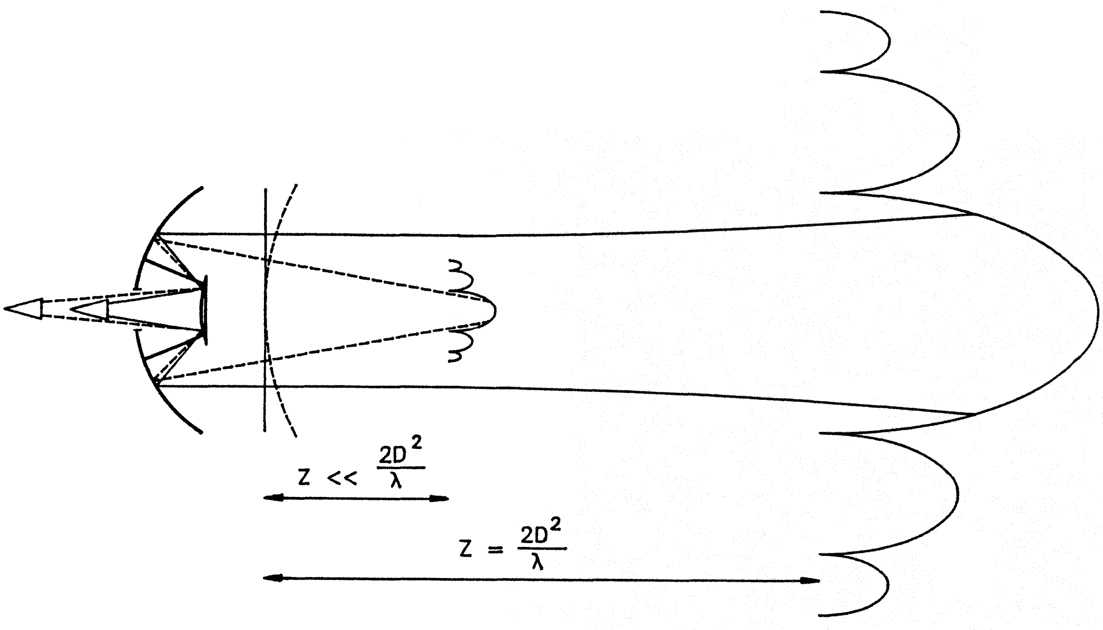


Figure 7: *Defocusing brings the far-field to a conveniently close distance.*

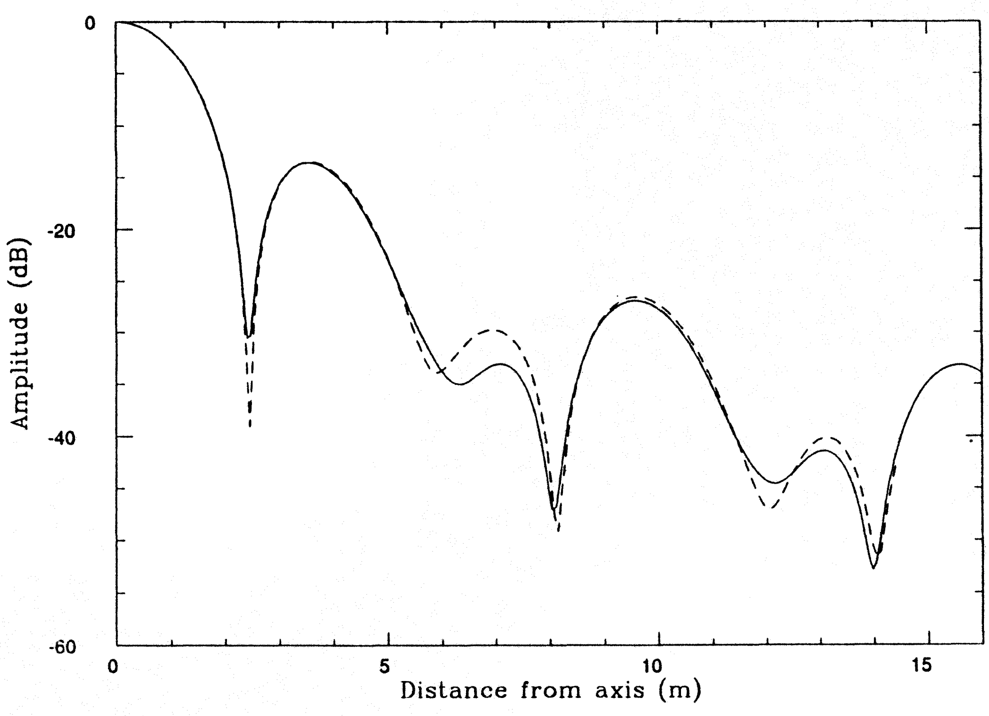


Figure 8: *Far-field pattern calculated as the antenna is in focus (—–) and defocused by 21.5 mm (- - -). Calculations are based on an exact near-field integration of the aperture field of a 1 m Cassegrain antenna at 1 THz. To enable the comparison, the distance from the axis values are multiplied by 131 in the defocused case.*

points has to be limited to a fairly small number. Optical interferometric methods can be used to obtain the mechanical surface, if the antenna surface is of optical quality on a small scale.

The far-field of an off-set antenna structure can be calculated most accurately from the feed horn radiation and mechanical surface properties. In a Cassegrain system, diffraction from the subreflector and its support beams is difficult to predict, which causes inaccuracies in the far-field pattern.

6 Conclusions

Antenna test methods for measuring the far-field pattern of a reflector antenna in the THz frequency range have been reviewed. No method has so far been validated for this kind of test.

One of the conventional lower frequency methods, namely the far-field method can be discarded for certain, due to atmospheric effects.

The near-field method remains a possibility for the tests. However, a very high quality moving stage is needed, and phase errors caused by flexible cables have to be dealt with. Phase retrieval or amplitude-only methods overcome the latter problem. However, little experience exists on the use of phase retrieval methods above microwave frequencies. Therefore, these methods need more work to be validated for use in the THz range.

Technically, the most feasible and least expensive method appears to be the hologram type of compact range. In this method, a planar amplitude hologram is used to form the required plane wave. The hologram is inexpensive to manufacture, and it is also less sensitive to surface accuracy errors than a reflector.

In some cases, a defocusing method to bring the far-field closer can prove to be practical. The use of this method requires that the defocusing option has already been taken into account in the satellite's radiometer and antenna design. An alternative possibility is mechanical reflector surface measurements and accurate measurement of the feed system phase and amplitude patterns, followed by a reflector radiation pattern computation. This can be considered only as a marginal alternative, if other methods are not available.

Acknowledgments

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