Design Study on Near-Field Radio Holography of the 5-Meter Dome A Terahertz Explorer

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***Abstract*- The 5m Dome A Terahertz Explorer (DATE5) is a proposed terahertz telescope to be deployed in Dome A, Antarctica, to exploit one of the best observing conditions at terahertz wavelengths on earth. In this paper, a design configuration for the near-field holography of the DATE5 surface measurement is presented. Important factors, such as measurement distance, operating frequency, and signal source location, are discussed. Special efforts have been given to the reduction of truncation errors. Simulation results under typical signal-to-noise ratios and design parameters are also provided.**

I. INTRODUCTION

Dome A, Antarctica is one of the best sites on earth for terahertz astronomical observations due to its extremely low water vapor contents in the atmosphere [1]. To exploit this unique site condition, a 5-m Dome A Terahertz Explorer (DATE5) telescope, which is a fully steerable 5-m Cassegrain telescope operating at dual bands of 350μm (Band1) and 200μm (Band2) under remote control [2][3], is proposed for this site. The antenna has to have an overall equivalent surface accuracy of 10 μm rms [3]. The error budget for surface measurement of the main reflector is only ~3 μm rms, which is a challenging target for on-site measurement. Moreover, the extreme site environment and limited assembly and testing time produce further difficulties in achieving such accuracy.

In the past, a number of techniques have been used in the field of antenna reflector surface measurement, including the laser tracker method, digital photogrammetry, and radio holography, etc. Typical accuracy of a laser tracker is 10μm + 5μm/m, and that for the photogrammetric measurement is 5μm + 5μm/m, depending on the measurement distance and the scale of the measured object. These methods will not meet the accuracy requirement of the DATE5 antenna. Radio holography is considered to be more accurate for the antenna reflector measurement and it has been applied to a number of millimeter and submillimeter wavelength telescopes. The ACA (Atacama Compact Array) 12-m antennas have achieved a best surface accuracy of approximately 8 μm, while the ACA 7-m antennas achieved an accuracy of approximately 5.7μm, both using near-field holography [4][5].

Theoretically, radio holography is based on the integral transform relationship between the radiation pattern and the aperture field distribution of a reflector antenna [6]. To carry out holography measurement, it is desired to have a strong source in the farfield region, e.g., a beacon emitter from a satellite on orbit, since in this case the radiation pattern is simply the Fourier transform of the aperture field. If there is no far-field beacon emitter, as in the case of the DATE5 antenna at the Dome A site, a ground transmitter in the vicinity of the telescope has to be used.

In this paper, the system configuration for a near-field holography of the DATE5 is presented. Several important factors such as the measurement distance, the operating frequency, and the signal feed horn location, are discussed. Methods for reducing the truncating error are proposed. Simulation results under a typical signal-to-noise ratio and design parameters are also provided.

II. SYSTEM CONFIGURATION FUNDAMENTALS

A. *Hardware Configuration*

At Dome A, Antarctic, there exist no practicable far-field sources, so that a local transmitter mounted on a tower, as shown in Fig. 1, will be used. Fig. 2 shows the block diagram of a dual-channel holography receiver. In this figure, a signal feed horn illuminates the antenna reflector, while a reference feed horn looks directly to the transmitter. At the backend, the dual-channel output signals are digitized and correlated, obtaining a complex correlation function.

An antenna is normally designed for observing far-field sources. When the signal comes from a transmitter in the near-field, there will be a rapid phase variation over the antenna aperture. The phase variation can be compensated, to a large degree, by an axial displacement of the feed in the direction away from the main dish [6]. By using this method, the antenna is refocused to the transmitter and has a relatively narrow beam. Thus, a small region of the beam pattern can be scanned without much truncation errors.

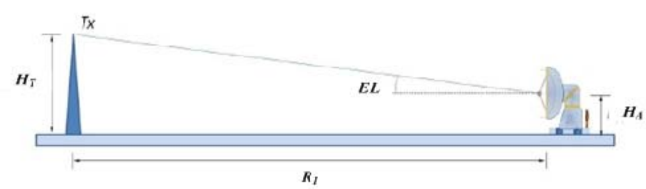

Figure 1. Configuration for near-field holography of DATE5.

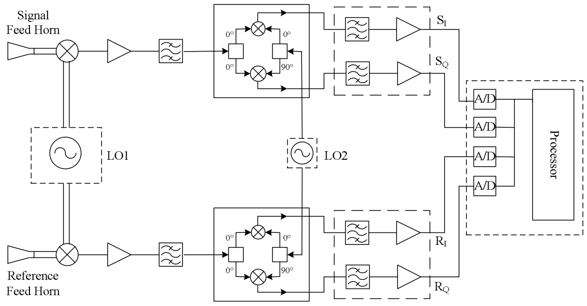

Figure 2. Holography receiver block diagram.

B. Measurement Procedures

The first step in holography measurement is to sample the beam pattern. This can be done by raster scanning the antenna beam around the transmitter. The sampling interval should be no larger than the Nyquist interval of λ/D, where D is the aperture diameter and λ the wavelength. With an oversampling factor k_s ($0.5 < k_s < 1$), the sampling interval Δu and Δv in the beam coordinates can be written as:

$$\Delta u = \Delta v = k_s \lambda / D. \quad (1)$$

The minimum scanning angle of the beam is determined by the required spatial resolution over the aperture. If the measured beam angle is $N \cdot \Delta u$, then the aperture field resolution obtained is:

$$\delta = D/(N \cdot k_s). \quad (2)$$

When the beam sampling is done, the measurement data are calibrated to remove the drifts in amplitude and phase, based on the boresight measurements at the beginning and the end of each row. The data are then fitted into a square grid.

The next step is to obtain the aperture field distribution through integral transform, resulting in the phase distribution over the aperture plane as in formulas of [6]. Phase corrections have to be made for the geometrical phase deviation and for the measured feed phase pattern. Furthermore, several phase terms accounting for phase offset, constant antenna pointing error, and small vector displacement of the signal feed relative to its nominal position have to be fitted and to be removed. Finally, the half pathlength deviation over the aperture plane, Δz, is derived as:

$$\Delta z(x, y) = \frac{\lambda}{4\pi} \cdot \varphi(x, y), \quad (3)$$

where $\varphi(x,y)$ is the phase deviation over the aperture plane of (x,y). The rms error of Δz, in the presence of white noise, can be written as [8]:

$$\sigma_z = \frac{D \cdot \lambda}{16\sqrt{2} \cdot \delta \cdot SNR}, \quad (4)$$

where SNR is the ratio of on-axis signal to rms average noise over all measurements, at the correlation receiver output.

For a paraboloidal reflector, the surface normal deviation ε_s is directly related to Δz by:

$$\varepsilon_s(x, y) = \sqrt{1 + \frac{x^2 + y^2}{4 f^2}} \cdot \Delta z(x, y), \quad (5)$$

where f is the focal length of the primary reflector. The normal deviations are then used for adjusting the reflector panels.

III. Design Considerations

A. Measurement Distance

In order to suppress the ground reflection, doing the holography measurement at a higher elevation is favorable. This is realized by constructing a higher beacon tower, or by reducing the measurement distance (the distance between the transmitter and the antenna under test). Under the extreme conditions of Dome A, it will be very difficult to build a very high tower. Therefore, a short measuring distance is desired. However, when the transmitter is closer to the antenna, the higher order phase terms (refer to [6], these are terms with their orders higher than the Fresnel term) will become significant and, therefore, more measurement error is produced [6][7]. Fig. 3 depicts a simulation result for the DATE5 antenna with N=64 (64×64 map), showing the relationship between the surface rms error increase and the measurement distance (R) decrease. In the simulation, the reduction of the truncation error is not considered. Later, one will find that the truncation error is also one of the major terms for the surface error in the near-field holography measurement. The truncation error can also be reduced significantly. In this paper, a measurement distance of 100m and a tower of 20 meters high are selected, which are thought to be practical numbers at Dome A site. If the antenna elevation axis height is 5m, the measurement elevation angle is about 8.5 degrees.

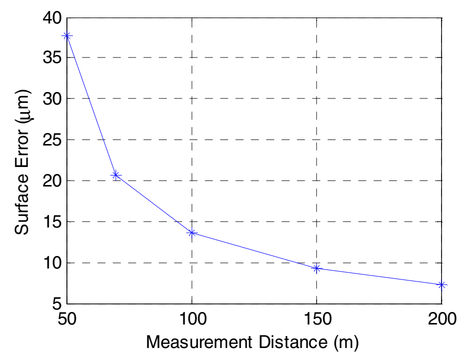

Figure 3. Surface RMS error vs measurement distance R.

B. Operating Frequency

According to Equation (4), for a given accuracy, the required SNR and dynamic range increase inversely with the frequency. Therefore, a higher frequency is preferred, since large dynamic range will increase the difficulty in the receiver development. On the other hand, as the frequency increases, the power of the transmitter will decrease and the receiver noise will increase, making the measurement SNR decrease. At the same time, the cost will increase as frequency increases. For these reasons, the preferred holography system will operate in the W-band.

Another issue in the measurement is to suppress the frequency-dependent effects, such as multipath reflection from the ground and antenna structures, and diffraction from the subreflector support structures. By assuming a path difference between the reflected and the direct signal being dx, the phase difference will change by one cycle for a frequency change of $dF = c/dx$, where c is the velocity of light. Thus, if the holography measurements were taken at several frequencies and averaged for the resulting aperture distributions, the multipath effect would be largely suppressed. For ground reflection, the path difference is usually within several meters, a frequency variation of several hundred MHz is quite enough. For suppressing the diffraction and multipath reflection with short path difference, measurements at more than one frequency with large frequency separations is required. Two nominal operating frequencies of 79GHz and 106GHz with a variation range of several hundred MHz at each frequency will be used for the future DATE5 holography measurement.

C. Signal Feed Horn Location

For holographic measurement, there are two options for the location of the signal feed, one is at the primary focus and the other is at secondary focus of the antenna. Both options have pros and cons.

Major advantage for the primary-focus configuration is that the reference and signal feed horns can be arranged back-to-back with the reference horn looking directly to the transmitter, so that a dual-channel receiver frontends can be used with the local oscillator (LO) signal being equal in length. The phase stability of the system is therefore improved. Another advantage for this configuration is that the reflector surface deviations can be obtained directly since the displacement of the signal horn could be easily separated from the measured aperture distribution during data post-processing. A major disadvantage for this configuration is that the subreflector assembly has to be removed from the antenna so that the holography receiver frontend can be mounted.

For the Cassegrain focus configuration, one advantage is that an overall surface deviation is obtained through the measurement, including subreflector surface error and errors from the reflector misalignment. In this configuration, there is no receiver installation problem. However, several disadvantages exist. Firstly, a separate reference frontend has to be installed away from the signal horn, resulting in phase instability of the system. Secondly, it is difficult to isolate the exact contributions from individual reflector and feed misalignment, which include the effects of displacements and tilts as cross correlations may exist between them. Based on such a measurement, the main reflector may be adjusted away from a true paraboloid. In addition, as the DATE5 antenna has a small half extending angle of subreflector from the Cassegrain focus (< 2 deg, refer to [2]), there may be a risk that the signal feed sees the transmitter directly during the beam scanning.

In summary, the primary-focus configuration has less error in measurement. It will be our first choice, especially for the first-time antenna installation on site. Even so, the second option still provides an alternative way, as long as the error contributions are at an acceptable level.

IV. Truncation Error Reduction

Although the radiation field of an antenna extends over the whole 4π space, only a small beam region around the boresight is sampled in holography measurement with a sampling interval stated in (1). This results in a systematic truncation error. Simulations for the DATE5 antenna have been carried out under different beam map size in the absence of noise, and the corresponding residual errors are shown in Table I. The simulation parameters used are: D=5m, f=2m, k_s=0.75, F=100GHz, R=100m, axial refocusing displacement δf=53mm (at which the antenna is refocused on the transmitter), and edge taper ET=6dB. The error reduces as the sampling map becomes larger, showing that truncation effect being one of the major contributions to the systematic error.

TABLE I
Residual Error for Different Size of Beam Map

Map size N×N	64×64	128×128	256×256	512×512
Surface Error (µm rms)	12.9	4.78	2.36	1.13
Aperture spatial resolution (mm)	104	52	26	13

To minimize the truncation error, a larger beam map should be used. However, a larger beam map means longer sampling time for the measurement, resulting in an instability risk. For the DATE5 antenna, a fast holography measurement is of special importance because the limited assembly and testing time is set by the site condition. In fact, an aperture spatial resolution of ~100mm is sufficient for the reflector adjustment. Such a resolution corresponds to N=64. However, from Table I, the truncation error is not acceptable. Therefore, two methods are proposed for further reduction of the truncation error. These two methods are discussed in following paragraphs.

A. Refocus Displacement Optimization

Simulations have been performed for different refocus displacement δf, and an optimum value has been found where the residual error reaches its minimum, as shown in Fig. 4. The optimum focus displacement is slightly larger than the value for the antenna being refocused on the transmitter. Simulation parameters are the same as for Table I except N=64. At the optimum refocus displacement, the residual surface rms error is only 1.4µm when δf=76mm instead of 12.9µm when δf=53mm. A simulation for a 128×128 map size is also performed. The error can be further reduced from 4.8µm when δf=53mm to 0.70µm when δf=76mm.

B. Map Size Extension and Iteration

The iteration procedure is as follows:

(a) The measured N×N beam map size is extended to 2N×2N by using zero-padding technique.

(b) A 2N×2N aperture field distribution is computed using the extended beam map.

(c) A new 2N×2N beam map is calculated based on the aperture distribution obtained in the previous step.

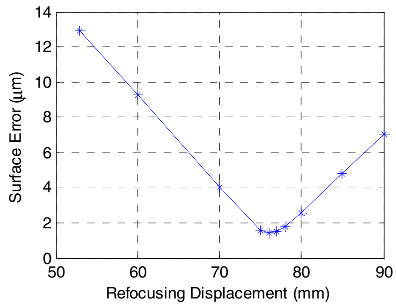

Figure 4. Residual surface error vs refocusing displacement δf.

(d) The central N×N part of the beam map obtained in step (c) is replaced with the original measured beam map.

(e) A new aperture field distribution is computed.

(f) Repeat steps (c) through (e).

Finally, the interpolations are made to obtain an N×N aperture distribution from the derived 2N×2N aperture map.

Fig. 5 shows the iteration procedure for a 64×64 measured beam map (other parameters are the same as for Table I). The map is extended to a 128×128 beam map first. After 9 iterations, the surface rms error is reduced from 12.2μm to 5.85μm. Finally the aperture field distribution is interpolated back to a new 64×64 map, and the error is further reduced to 2.84μm rms. This method reduces the truncation error significantly with the aperture spatial resolution unchanged for the measured beam map size.

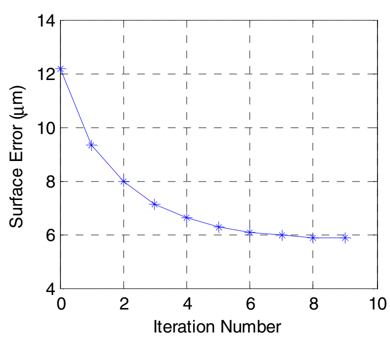

Figure 5. Error reduction iteration procedure.

V. Simulation Results

Simulation is carried out under the following design parameters: $R = 100$m, $F = 106$GHz, $k_s = 0.75$, N=64, $\delta f =$ 76mm (at which the truncation error is a minimum), $ET = 6$dB, P_t = 1μW (transmitter power), $G_t = G_r = 29$dB (gain of transmitter and reference feed respectively), $T_{sys} = 3000$K (SSB), and B=10kHz, and $\tau = 0.04$s. The system noise temperature T_{sys}, bandwidth B and integration time τ are assumed to be identical for both receiver channels. The resulted SNR for signal channel is SNR_s=84.5dB, and for reference channel SNR_r=46.6dB. The truncation error reduction methods mentioned above have been used in the simulation. The surface deviation distribution is shown in Fig. 6, and a surface rms error of 1.1μm is achieved.

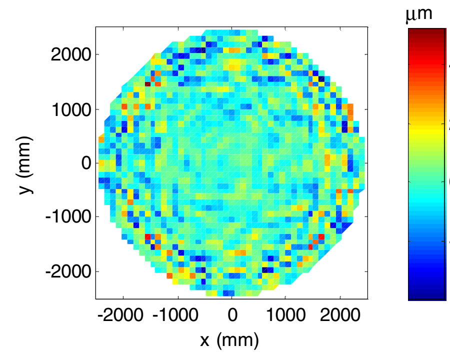

Figure 6. Simulated surface deviation distribution.

VI. Conclusion

Near-field holography is the most practical method for the proposed DATE5 antenna which requires a 10μm rms surface accuracy. The proposed measurement system includes a transmitter on top of a 20m high tower 100m away from the antenna. The transmitter will operate at two frequencies, 79 GHz and 106 GHz, each with a variation of several hundred MHz, to suppress those frequency-dependent errors. The signal feed can be located either at the primary focus or at the secondary focus. The truncation error, which is significant for near-field holography, can be greatly reduced by the proposed methods. Simulation shows that surface rms error of 1.1μm can be achieved when a 64×64 beam map size is used under typical SNR and design parameters.

Acknowledgment

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