HoloSim: A Methodology for Near-Field Holographic System Design

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***Abstract*—The development of most radio holography systems are experimental, often without a complete theoretical understanding of how measurements will perform beforehand. To address this, we introduce `HoloSim`, an open-source tool that streamlines the design process for holographic measurements. We present a standardized approach for designing submillimeter-wave holography systems, providing a mathematical framework for calculating key design parameters. Additionally, we detail the process of setting up and conducting holography measurements using an on-the-fly raster scan, with the transmitter positioned in the near-field of the dish aperture.**

I. Introduction

Radio holography is a technique that captures and reconstructs the electromagnetic wavefronts of radio frequency signals, preserving both amplitude and phase information. Most commonly, it is used to measure the surface deformation and performance of large-scale radio reflectors, such as antennas and satellite dishes. Traditionally, this is achieved in the far-field of the antenna ($R_F = 2D^2/\lambda$) using astronomical sources like distant quasars or radio stars. However, it has also become common to perform holography with an earth-bound transmitter, whose placement likely puts it in the near-field of the antenna under test. This complicates the analysis of electric-field measurements due to the non-plane wave nature of the wavefronts, but the error corrections to account for this are known ([1], [2]).

Despite this, the design of holography systems has often been approached experimentally with minimal theoretical groundwork. This has led to holography systems being developed independently, lacking standardized guidelines or best practices that could streamline and improve the design process for new "holographers".

To address this, we introduce `HoloSim`, a simple open-source tool that allows one to approach the design of their holography system from a theoretical perspective, and give some recommended parameters in which to design their hardware to reach a desired measured surface deformation. With this tool, we aim to bring a more systematic approach to the design of holography systems, and provide greater consistency in results across different applications.

II. Design Methodology

In the following section, we present a six-step design process for calculating the necessary parameters for a holography measurement. The equations are all expressed in terms of real design variables to improve its practicality. This approach ensures that this method is both intuitive and directly applicable in real-world scenarios.

A. Transmitter Placement

Random errors on the surface or alignment of a reflector cause scattering and reduce its efficiency. This loss in efficiency can be quantified by the Ruze equation [3]:

$$\frac{\eta_A}{\eta_{A0}} = \exp\left\{-\left(\frac{4\pi\epsilon}{\lambda}\right)^2\right\} \tag{1}$$

where η_A/η_{A0} is the fractional aperture efficiency, ϵ is the root-mean-square (RMS) error of the reflector surface, and λ is the wavelength of the incident wave. We can see the exponential decrease in efficiency as the magnitude of random errors increases relative to the wavelength. Because of this, very small amounts of rms error can cause significant reductions in efficiency, especially when the errors are comparable to the wavelength being measured.

With an understanding of what rms error is desired on a reflector, our attention moves to the set up of our holography measurement and an understanding of the design parameters needed to meet this design goal. When using an earth-bound transmitter, radio holography is most likely measured in the near-field. The far-field boundary is given by:

$$R_{\mathrm{F}} = \frac{2D^2}{\lambda} \tag{2}$$

where R_{F} is the far-field distance, D is the aperture diameter, and λ is the wavelength used in our holography measurement. It is important to note that the aperture diameter is used because, to be in the far-field, this distance must exceed the far-field boundary for both the transmitting *and* receiving antennas. In other words, both antennas need to be within each other's far-field zones.

What is the minimum distance between the holography transmitter and the test antenna? A good rule-of-thumb is for the minimum distance to be greater than approximately five aperture diameters away such that [1]:

$$R_{\min} \approx 5D \tag{3}$$

We consider this to be the minimum distance to get usable measurements and avoid significant effects due to the reactive near-field. If significant systematic errors are still measured at this distance, we recommend increasing the distance to be closer to the boundary of the reactive near-field (R_{react}) [3]:

$$R_{\text{react}} < 0.62\sqrt{\frac{D^3}{\lambda}} \tag{4}$$

B. Spatial Resolution

To optimize antenna surface settings using holography measurements, we need to measure deformations over individual panels with sufficient resolution in the aperture to detect the impact of each panel adjuster. The spatial resolution (δ_d) in the aperture plane needs to be chosen based on the positions of panel adjusters. Most commonly we can make an approximation that each panel is square, with an adjuster in each corner and one in the center of the panel. If the corner adjusters are a distance a from each from each other, then the minimum distance between any adjuster on a panel is $a\sqrt{2}$. We need at least two measurements between adjusters to detect the deformations so the spatial resolution should be set at:

$$\delta_d < \frac{a\sqrt{2}}{2} \tag{5}$$

C. Grid Point Integration Time and Total Map Time

Performing a holography measurement is not an instantaneous process, meaning there may be a need to measure the impact of environmental changes (wind, temperature, solar loading, etc.) on an antenna surface. Because of this, it is important to understand how one can minimize the total time required for a holography measurement (Δt_{map}).

The most common method used to make these measurements is on-the-fly raster scanning [4]. This technique involves continuously translating the transmitter (or rotating the aperture) in a predefined pattern, without stopping at each grid point. Unlike traditional raster scanning, where the antenna pauses at each point to collect data, on-the-fly raster scanning allows for data collection as the antenna moves. The simplest pattern to use is a boustrophedonic (or raster) pattern, where the aperture rotates in azimuth and elevation through the scan. This discussion will focus on this measurement approach.

The total map time for this scan is shown in detail in [5] and yields:

$$\Delta t_{map} = \frac{171768 f_{osr} f_1 f_{apo}^2 D(m)}{\dot{\theta}(\text{arcsec/sec})\nu(\text{GHz})(\delta d(\text{cm}))^2}\text{hours} \tag{6}$$

where ν is the chosen holography measurement frequency, f_1 is the primary beam taper factor ($f_1 \simeq 1$), f_{apo} is an apodization smoothing factor that dampens ringing at the aperture's edge ($f_{apo} = 1.3$ from [1]), f_{osr} is the oversampling factor between rows (typically 2.2 to assure Nyquist sampling), and $\dot{\theta}$ is the chosen rotation rate of the dish antenna, which is chosen to be significantly below the maximum tracking rate of the aperture.

It is also important to understand the required integration time (t_{int}) at each grid point. The integration time is the amount of time the antenna effectively "exposes" each point on the aperture to capture sufficient data as it moves. This is analogous to the exposure time a camera needs for each image it captures. The integration time, again derived in [5], can be found using:

$$t_{int} = \frac{6.2 \cdot 10^4 f_{osr} f_1 f_{apo}^2}{\dot{\theta}(\text{arcsec/sec})\nu(\text{GHz})D(\text{m})}\text{seconds} \tag{7}$$

D. Angular Extent of Map and Sampling Intervals

Assuming a boustrophedonic scanning pattern, the spatial resolution is given as:

$$\delta_d = \frac{D}{N_{row}} = \frac{f_1 f_{apo} c}{\nu \theta_{ext}} \tag{8}$$

where c is the speed-of-light and every variable is constant except for ν and the angular extent of the holography map (θ_{ext}). Having chosen our measurement frequency, we can find θ_{ext}:

$$\theta_{ext} = \frac{f_1 f_{apo} c}{\nu \delta_d}\text{deg} \tag{9}$$

By also finding the primary angular beam size (θ_b) of a single grid point on the aperture then we can calculate the angular sampling intervals along the rows and columns of the scan (θ_{sr} and θ_{ss} respectively):

$$\theta_b = \frac{61836.6 f_1}{\nu(\text{GHz})D(\text{m})}\text{arcsec} \tag{10}$$

$$\theta_{sr} = \frac{\theta_b}{f_{osr}}\text{arcsec} \tag{11}$$

$$\theta_{ss} = \frac{\theta_b}{f_{oss}}\text{arcsec} \tag{12}$$

where f_{oss} is the oversampling interval between rows.

E. Pointing Accuracy and SNR Requirement

The main design goal for our holography system is to choose a measurement frequency whereby our hardware setup can measure a desired surface deformation (δ_z). It should be noted this is equivalent to the rms error (ϵ) mentioned in Sec. II-A. The addition of pointing errors can add uncertainty to our holography measurement. Thus, there is a pointing accuracy requirement (θ_{point}) which must be met:

$$\frac{c}{\nu}\frac{1}{360} = \frac{1}{\theta_{\text{point}}}\frac{\delta_z}{2}$$

$$\theta_{\text{point}} < \frac{180\delta_z \nu}{c} = (6 \cdot 10^{-4})\delta_z(\mu m)\nu(GHz)\,\text{deg} \tag{13}$$

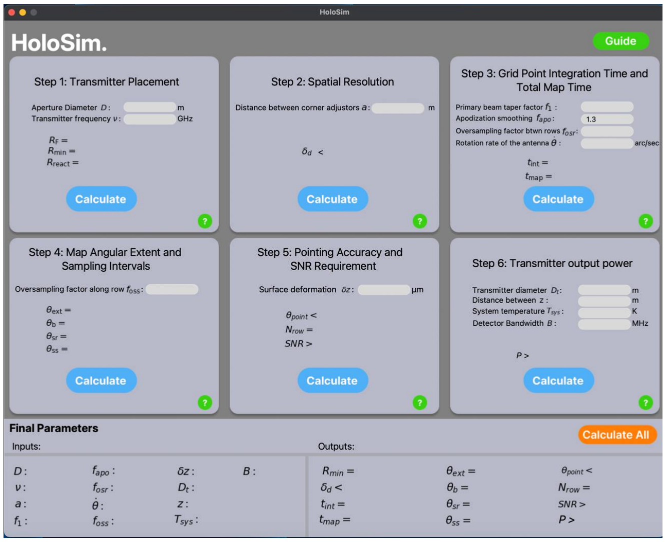

Fig. 1. The `HoloSim` user-interface

This states that our pointing accuracy should be better than half the surface deformation we want to measure. The system should be able to meet this requirement, but it is acceptable if there are small drifts in phase during a holography measurement. A typical holography measurement will include phase calibration measurements that are usually done after every few scans.

The number of grid points in a final holography map row (N_{row}), assuming a square grid is given by:

$$N_{row} = \frac{D f_{apo} f_{osr}}{\delta_d} \tag{14}$$

With this, we can use the following equation to calculate the signal-to-noise ratio (SNR) we need to measure on the edge of the aperture to be able to measure a given surface deformation:

$$\delta_z = \frac{\lambda}{16\sqrt{2}} \sqrt{\frac{N_{row}^2}{f_{osr} f_{oss}}} \frac{1}{\mathrm{SNR}} \frac{1}{\sqrt{f_{apo}}} \tag{15}$$

Eqn. 15 is modified from that found in [1] to be in terms of SNR and adds an additional factor of $1/\sqrt{f_{apo}}$.

F. Transmitter Output Power

The final step in designing a holographic measurement system is to translate this SNR requirement to a hardware design requirement: the required transmitter output power (P). We can do this by approximating our transmitter beam to a Gaussian beam and predicting how much it will diverge. This method is adopted from [6].

We start with calculating the noise floor:

$$\text{Noise Floor} = 10 \log \left(\frac{k B T_{sys}}{1 \mathrm{mW}} \right) \tag{16}$$

where B (in Hz) is the detector bandwidth, T_{sys} is the system temperature, and k is Boltzmann's constant. With a known transmitter diameter of D_t the beam radius at a distance z from the transmitter, the beam radius at any distance ($w(z)$) can be found to be:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R} \right)^2} \tag{17}$$

where w_0 is beam waist at the transmitter ($w_0 = D_t/2$) and z_R is the Rayleigh range, which is the distance over which the beam radius approximately doubles:

$$z_R = \frac{\pi w_0^2 c}{\nu} \tag{18}$$

The distance z is chosen based on the requirements described in Sec. II-A, while ν is once again the measurement frequency.

Next, we need to calculate the beam-coupling efficiency (η) which quantifies how effectively the transmitted beam's energy is captured by the receiving aperture, based on the overlap between the transmitted beam's Gaussian profile and the receiver's aperture. It is found using the overlap integral:

$$\eta = \frac{\left| \int_{\text{aperture}} E_{TX}(\mathbf{r}) E_{RX}^*(\mathbf{r}) \, d\mathbf{r} \right|^2}{\int_{\text{aperture}} |E_{TX}(\mathbf{r})|^2 \, d\mathbf{r} \int_{\text{aperture}} |E_{RX}(\mathbf{r})|^2 \, d\mathbf{r}} \tag{19}$$

where $E(r)$ is the electric field strength as a function of radial distance r from the beam's center. Since we are assuming perfect alignment between the transmitter and receiver, this simplifies to integrating the square of the beam's amplitude over the receiver's circular aperture with a radius of $D/2$:

$$\text{Overlap} = \int_0^{D/2} r \exp \left(-\frac{2r^2}{w(z)^2} \right) dr \tag{20}$$

This results in a calculation of how much of the Gaussian beam's power is captured by the receiver. The total power in a Gaussian beam (P_{total}) can be given as:

$$P_{\text{total}} = \frac{\pi w(z)^2}{2} \tag{21}$$

This serves as a normalization factor in calculating the beam-coupling efficiency:

$$\eta = 10 \log \left(\frac{\text{Overlap}}{P_{\text{total}}} \right)^2 \tag{22}$$

The transmitter output power P_{dB} is then calculated by summing the noise floor, SNR, beam-coupling efficiency, and the system gain (G):

$$P_{\text{dB}} = \text{Noise Floor} + \text{SNR} + \eta + G \tag{23}$$

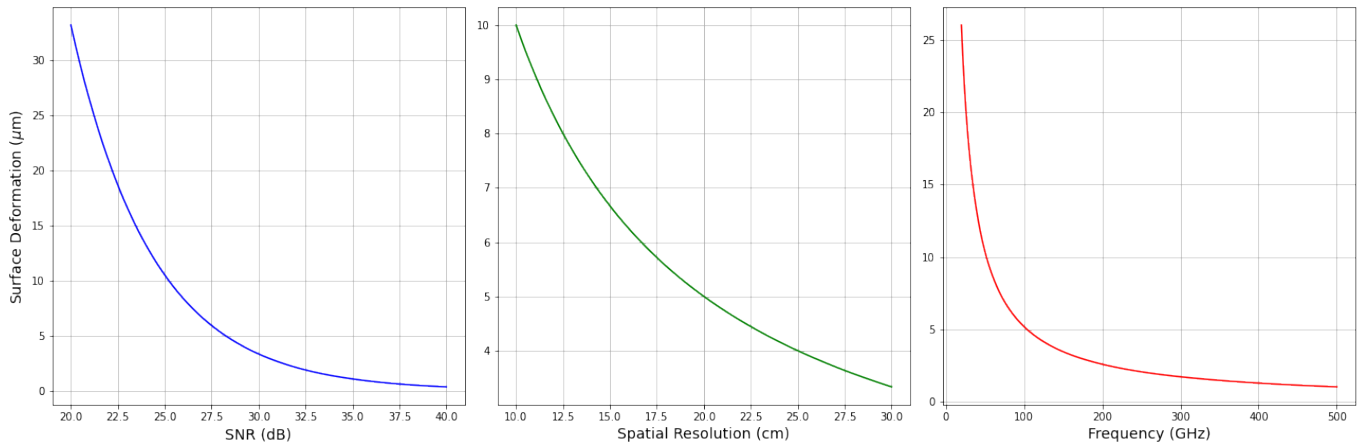

Fig. 2. Surface deformation (δ_z) as a function of (a) signal-to-noise ratio (SNR), (b) spatial resolution (δ_d), and (c) frequency (ν), all with an aperture of D = 12m.

III. Implementation

To be able to implement these methods, a simple python script with a user-interface (UI) has been developed. This tool, which we call `HoloSim`, allows users to easily visualize and select design parameters for their holography system (Fig. 1). To use `HoloSim` and access the code, visit the GitHub repository at https://github.com/djtring/HoloSim.

The UI is divided into six steps, corresponding to the sections described in Sec. II-A through Sec. II-F. It provides a clear view of the parameters that need to be selected for the holography system at each step, and the design parameters that can be derived from these choices. We also include a graphing feature which makes it easy to compare different design parameters against each other, and see their effects on a measurement.

For example, select the following design parameters: D = 12m, ν = 100GHz, f_{osr} = 2.2, f_{oss} = 15, and compute δ_d = 20cm. With a design goal of $\delta_z = 5\mu$m, we can calculate that an SNR of approximately 28dB is required to successfully perform the measurement. We recommend adding a small quality factor onto this.

`HoloSim` offers the capability to analyze how changes in various design parameters influence different design requirements. It can also show how altering one input parameter impacts the requirements of another to achieve the same design goal. Figure 2 illustrates the range of δ_z that can be measured across a range of different design parameters, for a particular case. Once each design parameter is selected, the results are summarized in a table. This summary provides a clear and compact overview of the requirements needed for the measurement set-up and the hardware design.

IV. Conclusions and Future Work

We have presented a method for determining the requirements for the holographic measurement of microwave-to-terahertz dish antennas. Our approach offers a more systematic way to develop holography systems and provides a tool for implementing these methods. By simulating different configurations and parameters, we aim to help users better understand the impact of various factors on surface deformation measurements, and improve the efficiency in the design of holography systems.

In the future we plan to expand this tool to not just provide design requirements, but also have the capability to collect and process near-field holography measurements. This includes the post-processing of measurement data to take into account additional errors associated with taking a measurement in the near-field. While such systems currently exist, they are often independently developed and lack adaptability across different applications. Our goal is to create a standardized system that can be employed in a broader range of holography systems, making the holographic antenna measurement technique more widely applicable.

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