Accuracy Estimation of Microwave Holography from Planar Near-Field Measurements

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Abstract

Microwave holography is a popular method for diagnosis and alignment of phased array antennas. Holography, commonly known in the near-field measurement community as "back-transformation", is a method that allows computation of the primary (aperture) fields from the secondary (far-zone) fields. This technique requires the far-zone fields to be known over a complete hemisphere and adequately sampled on a regular spaced grid in K-space.

The holography technique, while known to be mathematically valid, is subject to errors just as all measurements are. Surprisingly, very little work has been done to quantify the accuracy of the procedure in the presence of known measurement errors. It is unreasonable to think that the amplitude and phase of the array elements can be trimmed to better than the uncertainty of the back-transformed amplitude and phase. This makes it difficult for an antenna engineer to determine the achievable resolution in the measurement and calibration of a phased array antenna.

This study reports the results of an empirical characterization of known errors in the holography process. A numerical model of the near-field measurement and holography process has been developed and many test cases examined in an effort to isolate and characterize individual errors commonly found in planar microwave holography. From this work, an error budget can be developed for the measurement of a specific antenna.

Keywords: Back-transformation, error budget, Microwave holography, planar near-field.

1.0 Introduction

With the advances of high-performance active phase arrays, it is necessary to align the array aperture to increasing levels of accuracy. Alignment (or tuning) of an array requires adjustment of the feed network so that the phase (or time-delay) of each array element causes the power to add coherently in a desired direction. While it is possible to align the feed network using bench-top measurements (S_{N1} measurements) this becomes extremely difficult as the array size grows. Most importantly, bench-top techniques cannot account for the insertion characteristics of the antenna element itself. Therefore, a technique that measures the radiation properties of the antenna must be used. Microwave holography is one such technique and has proven very popular for phased array alignment.

This paper considers a specific antenna and examines the expected accuracy of the aperture hologram as computed by microwave holography. The aperture hologram is compared element by element to the known aperture fields to determine the accuracy of the technique for different sources of known error. The antenna under consideration is a planar aperture array antenna 72 inches wide by 10 inches high. The element spacing is $\lambda/2$ in both dimensions of the aperture where λ=1 inch. The amplitude distribution is –30 dB Taylor (nbar=3) in the horizontal dimension, and –50 dB Taylor (nbar=12) in the vertical dimension. <u>The goal of this paper is to establish the requirements of a planar near-field measurement system, which will allow the array to be aligned to an uncertainty of ±1 dB amplitude and ±6° phase.</u>

2.0 Estimation of Aperture Field Errors

There are several possible sources of error in the measurement and computation of the aperture hologram. Some of the dominant errors are:

- Measurement plane truncation
- Cable amplitude and phase variation
- Non-Planarity of the measurement surface (Z-position errors)
- Scan plane distance uncertainty
- Steered beams
- Antenna element and probe pattern factor
- Mutual coupling and multi-path

2.1 Measurement Plane Truncation

The Equivalence Principle requires the fields to be known on a surface completely surrounding a radiating source in order to calculate the fields on another surface which surrounds the radiating source. A plane satisfies this requirement since it theoretically extends to infinity. Of course, in practice it is not possible to extend the measurement plane to infinity so the plane must be truncated at some boundary.

Measuring the antenna fields on a finite measurement plane which is translated from the aperture (source) plane has two effects. The first effect is the truncation of the spectrum power at the edges of the measurement plane. This introduces the two-dimensional convolution of a sinc function into the far-zone spectrum of the antenna, which manifests itself as errors in the near-in sidelobes of the antenna pattern. Applying windowing (apodization) functions to the measurement plane data has been shown to minimize the errors in far-zone field[1]. Therefore, it seems reasonable that the accuracy of the aperture hologram should be improved as well. This will be the subject of future investigations.

The second effect is the failure of the measurement plane to capture energy propagating in directions approaching 90° from the aperture boresight. This is due to the translation of the measurement plane from the aperture plane. Since the energy is not captured for wide off-axis angles, the spectrum will tend toward zero. However, the effect of the sinc function may cause apparent energy at 90° from boresight.

A rule of thumb for measurement plane size is given by Equation 1[2], where **L** is the largest linear dimension of the scan plane, **D** is the largest diameter of the antenna under test, **s** is the distance from the antenna aperture to the measurement plane and q**c** is the critical measurement plane angle. The far-field spectrum can be assumed accurate for all θ<q**c**.

$$L=\mathbf{D}+2\,\mathbf{s}\,\tan(q\mathbf{c})$$

Equation 1. Required Length 'L' of Measurement Plane for Antenna Aperture of Size 'D', Measurement Plane Offset 's', and Critical Measurement Plane Angle 'θc'

For the array under consideration in this text, the amplitude and phase accuracy of the aperture hologram as a function of the critical scan angle q**c** are shown in Figure 1. From this figure it can be seen that the amplitude and phase accuracy of the hologram tends toward a limit of about 0.02 dB and 0.5 degrees respec-

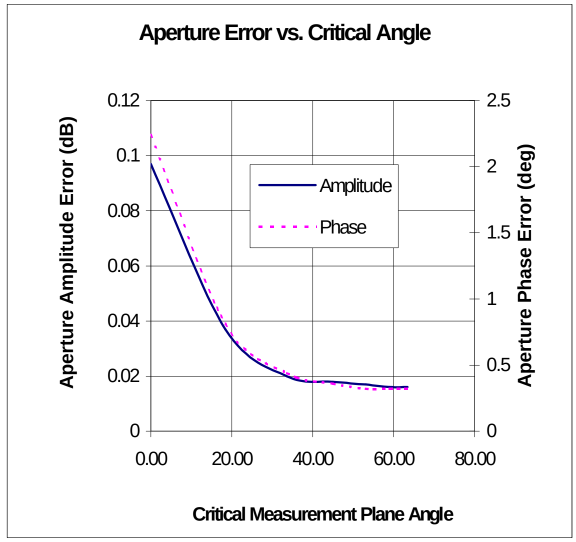

Figure 1. Accuracy of Aperture Amplitude and Phase vs. Critical Measurement Plane Angle

tively for critical angles greater than 45 degrees. *Note that if the main beam is steered off boresight to an angle q_0, then the critical angle must be »q_0+45° to maintain comparable accuracy of the aperture hologram.*

2.2 Cable Amplitude and Phase Variation

A significant source of error in holography is amplitude and phase variations of the cable. This error source is so significant because variations in the cable insertion loss and phase directly affect the fields in the measurement plane, and the measurement plane fields are tightly coupled to the aperture plane fields.

Amplitude and phase variations in the cable are caused by mechanical flexing and temperature changes along the length of the cable as the probe moves throughout the measurement plane. Changes due to temperature variation can be minimized by careful temperature control of the measurement environment during the acquisition. The Teflon used in typical coaxial cables can exhibit a change of state near standard room temperature. This critical temperature should be avoided with such cables.

The variation in cable insertion loss due to mechanical flexing for a well-maintained cable path (i.e. no pinching, binding, stretching or fraying) is typically less than 1% and is fairly constant with frequency. This type of error is typically assumed to be negligible for high quality cables; however, the change in the cable insertion phase is a linear function of frequency. Therefore, it is essential to address and correct the phase error at higher frequencies.

If the cable insertion amplitude and phase variation is repeatable, it can be characterized and removed from the measurement. One method is to make an S_{11} measurement of the cable as a function of position in the measurement plane. A correction factor of $A(x,y)\exp(jk\angle S_{11}(x,y)/2)^{-1}$ can be applied to all subsequent measurements to effectively remove the cable insertion variation from the measurement plane data. This approach can ideally reduce systematic errors down to the level of the random system errors.

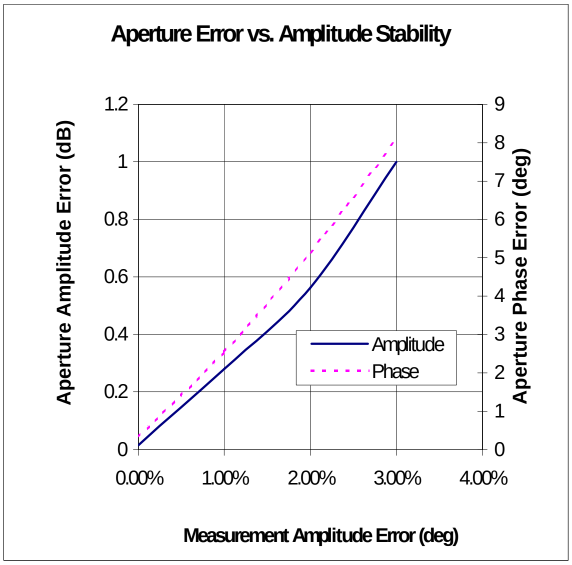

Figure 2A. Accuracy of Holography Computed Aperture Fields vs. System Amplitude Stability

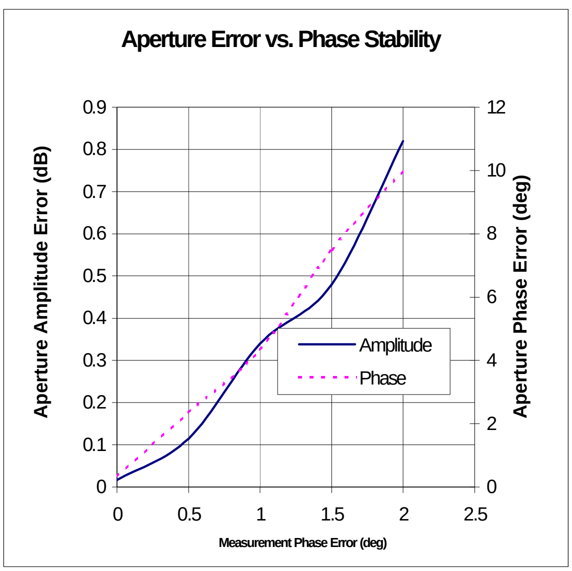

Figure 2B. Accuracy of Holography Computed Aperture Fields vs. Cable Phase Stablity.

The variation of random cable insertion loss affects the amplitude and phase accuracy of the computed aperture hologram for the simulated array, as shown in Figure 2A. In this figure only random amplitude variations are considered. Systematic variations are assumed to be reduced by the above process. It can be seen from this figure that amplitude variations of less than 2% (≈ 0.1 dB) are within the desired uncertainty budget.

The effect of random cable insertion phase variations on the amplitude and phase accuracy of the hologram is shown in Figure 2B. It can be seen from this figure that phase variations of less than 1.5° are within the desired uncertainty budget.

2.3 Non-Planarity of the Measurement Surface (Z-Position Error)

A mechanical scanning system can never be aligned so well as to move the measurement probe throughout a perfect plane in front of the antenna aperture. If the deviation of the probe from a perfect plane is taken as $\delta(x,y)$, then the induced phase shift seen by the measurement probe can be approximated to a first order by:

$$\phi(x,y) \approx k\delta(x,y)\cos(\theta_0)$$

where $k=2\pi/\lambda$ and θ_0 is the direction of the main-beam from the measurement plane normal vector. The phase error in the measurement plane due to mechanical scanner planarity errors has the same effect as variation of cable insertion phase shown above. Therefore, the plot of Figure 2B can be displayed with the x-axis expressed as the mechanical deviation from the ideal scan plane at λ=1”. This is shown in Figure 3.

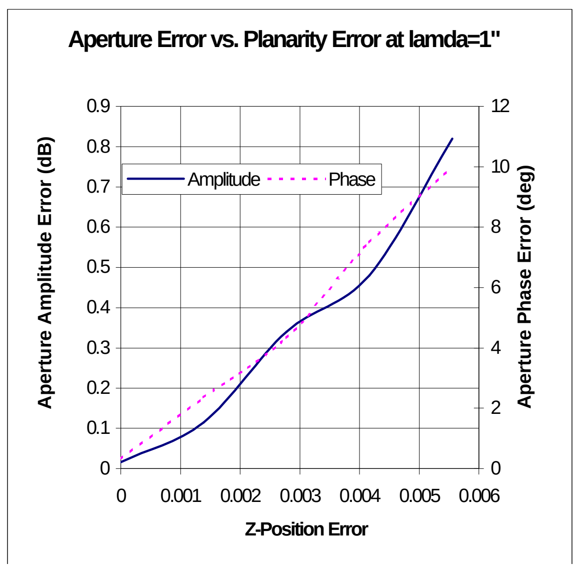

Figure 3. Accuracy of Holography Computed Aperture Fields vs. Mechanical Planarity

As with the cable insertion phase variation, the mechanical scan planarity errors can be removed if they are repeatable. A common and effective technique is "k-correction". This method simply multiplies all measurement plane data by $\exp(jk\delta(x,y)\cos(\theta_0))$ for $+\delta$ defined as mechanical motion away from the antenna aperture.

Devices such as tracking laser systems can measure the true position of the probe to an uncertainty of < 0.001 inches to allow a scan plane error map to be generated. When such an error map is generated and applied as above, the aperture amplitude and phase uncertainty can be corrected to < 0.1 dB and 2° phase respectively, which is within the desired uncertainty budget.

2.4 Scan Plane Distance Uncertainty

The translation of the measurement plane from the source plane introduces a phase shift in the far-zone spectrum of the antenna fields. The phase shift of the far-zone fields must be removed by multiplying the far-zone spectrum by $\exp(jk\mathbf{s}\sqrt{[1-\mathbf{k}_x^2-\mathbf{k}_y^2]})$, where **s** is the distance from the antenna aperture to the measurement plane and $\mathbf{k}_x$, $\mathbf{k}_y$ are direction cosines from the x and y axes, respectively. Once the phase shift has been removed, the far-zone fields can be back-transformed directly to yield the fields on a plane at a distance of **-s** from the measurement plane. If **s** has been measured properly, this will back-transform to the aperture plane.

Typically the distance to the scan plane is measured rather crudely with a tape measure. Since the location of the antenna element and measurement probe phase centers are not precisely known, this measurement approach is sufficient. Uncertainty in this measurement means that the fields calculated by the back-transform are not actually on the aperture of the antenna. This results in apparent distortion of the aperture fields and is most pronounced at the edges of the aperture plane. Using the simulation to introduce known errors in the aperture plane to measurement plane distance produced the plot in Figure 4. It can be seen from this figure that errors of < ±30% are acceptable to maintain the desired error budget.

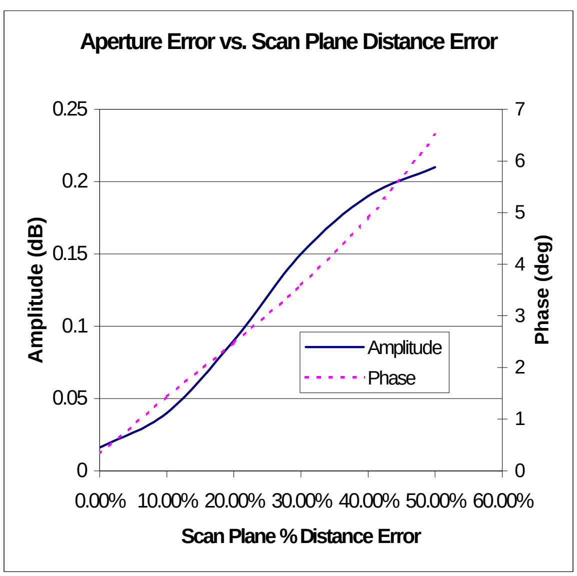

Figure 4. Accuracy of Aperture Hologram vs. Measurement Plane Distance Error.

2.5 Steered Beams

For electronically steerable antennas it is necessary to determine the far-field spectra of several steered beams. To properly tune the array, stuck bits or non-uniform phase quantization must be identified and corrected. One approach would be to directly compute the back-projection of steered beam far-field spectra. This produces increasing error in the edge elements as the steering angle increases.

The simulation of this antenna has shown that this approach provides sufficient accuracy when the beam is steered in the azimuth plane. The results are plotted in Figure 5A for azimuth steering angles up to 60°. The results in the azimuth plane are accurate over this entire range of elevation angles because the electrical size of the array is very large in the horizontal (azimuth) dimension.

Steering in the elevation plane, however, does not provide sufficient accuracy due to the relatively small electrical size in this dimension. The results of elevation plane steering are plotted in Figure 5B for angles up to 60°. It can be seen from this figure that in order to remain within the allowable measurement tolerances, the elevation steering angle must be less that 10°.

A better technique for isolating stuck bits and non-uniform phase quantization in the array would be to step all the element phase shifters in unison so that the main-beam remains broadside. The aperture hologram can be computed for each phase step sequence. Any phase shifter that is stuck or steps unevenly during the phase step sequence will appear in the corresponding aperture hologram.

2.6 Antenna Element and Probe Pattern Factors

To compute the aperture hologram, the aperture spectrum must first be known. The aperture spectrum is solely a function of the geometry and illumination of the aperture. The element pattern of the aperture does not influence the aperture spectrum. To determine the aperture spectrum, the fields on the measurement plane are first transformed to yield the coupling product.

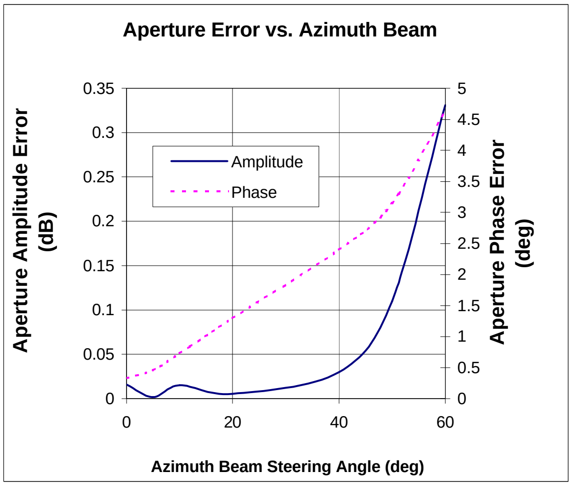

Figure 5A. Accuracy of Aperture Hologram vs. Azimuth Beam Steering Angle

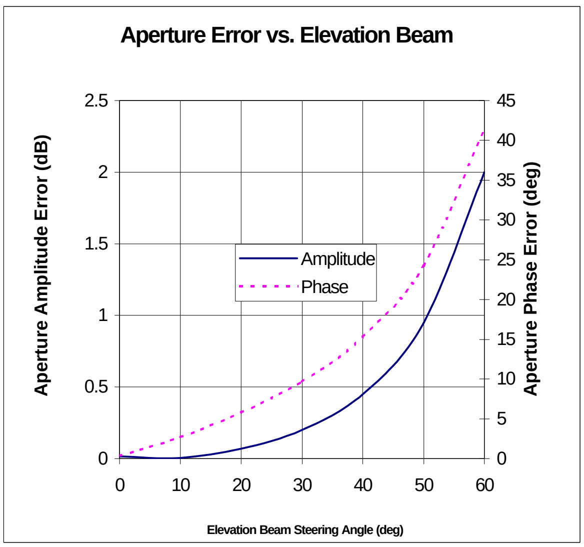

Figure 5B. Accuracy of Aperture Hologram vs. Elevation Beam Steering Angle

The coupling product is the multiplication of the aperture spectrum, the element pattern, and the probe pattern. To obtain the aperture spectrum, the spectra of the element and probe must be removed. This operation assumes that the probe pattern is constant for every probe position in the measurement plane and further assumes that every element in the array has the same pattern. This assumption allows the probe and element patterns to be moved outside of the integral and removed from the aperture spectrum by a simple division.

The accuracy of the element pattern and probe pattern around the main-beam and first few sidelobes of the antenna pattern is crucial in obtaining good accuracy in the aperture hologram. The pattern of the measurement probe can be determined with high accuracy by a standards organization such as NIST. The element pattern of the antenna under test can be determined by single element pattern measurements (which ignores mutual coupling), empirical modeling (second order effects of mutual coupling may be modeled as well), or by steering the antenna beam to several locations and recording the envelope of the main-beam peak (which assumes an average element pattern for all elements). The effect of errors in the assumed probe and/or element pattern has not been considered in this study; however, it can have a significant effect on the accuracy of the aperture hologram and should be examined carefully.

2.7 Multi-path and Multiple Reflection

Multiple reflection is defined in this document as a reflection of the incident field from the antenna under test (AUT) that is re-radiated or scattered by the AUT and impinges again on the probe. The probe reflects a portion of the energy and re-radiates energy back to the AUT. This process continues until the reflected levels are below the measurement system noise floor. The primary effect of mutual reflection is a standing wave that is setup along the aperture. The standing wave on the aperture adds to the uncertainty of the aperture fields computed by holography. The effects of multiple reflections can be reduced by making two near-field scans at z-spacing differing by $\lambda/4$ and averaging the near-field[2].

Multi-path is defined in this document as a transmission path of radiation between the AUT and measurement probe other than the direct path. Multi-path, like multiple reflections, sets up a standing wave across the aperture of the AUT. The standing wave can produce sidelobe errors in the far-field and contribute to uncertainty of the aperture hologram. Multi-path can be minimized by using anechoic absorber material on all reflecting surfaces with the exception of the probe and AUT. Multi-path can also be removed from the measurement by translating the AUT and scanner as a unit with respect to the room and making near-field measurements.

Mutual coupling and multi-path have not been specifically addressed in this analysis. However, the measurement engineer should make efforts to reduce these errors in order to improve the accuracy of the hologram.

3.0 Results

With the independent examination and simulation of the listed error sources, an error budget can be constructed to provide the expected level of accuracy in the aperture hologram. This error budget is provided in Table 1.

Table 1. Holography Uncertainty Budget

Contributing Terms	Level	Amplitude Uncertainty (dB)	Phase Uncertainty (deg)
Amplitude Stability	1.00%	0.25	2.00
Cable Phase Stability	1 deg	0.30	4.00
Z-Position Error (1)	10 mil	0.50	1.80
Scan Plane Truncation Error		0.02	0.25
Scan Plane Distance Error	10%	0.04	1.00
Mutual Coupling		0.10	1.00
Room Scattering		0.10	2.00
Resultant Aperture Uncertainty		0.65	5.41

Notes

(1) K-correction to 1-mil uncertainty

The individual contribution of error ources has been assumed independent and combined in the RSS sense. In reality, these errors are not independent and would, in the most rigorous approach, require evaluation for each possible combination of errors. Such an analysis would be very intensive; therefore the errors have been treated as independent in this study.

With the assumed error levels in Table 1, the expected level of error in the aperture hologram is within the desired uncertainty of ±1 dB amplitude and ±6° phase.

To confirm the error budget, the array was simulated with a +20° phase error introduced into one of the elements. A near-field scan with the error sources in Table 1 was simulated. The aperture hologram was computed, and a 12° phase error was measured. This is shown in Figure 6A. The element was adjusted -12° in phase (8° true error) based upon the hologram measurement. A second iteration measurement was run, and the aperture hologram computed.

The second iteration hologram produced 5° phase error on the element. However, the other elements had as much as ±6° of phase variation, making it impossible to identify the phase error of this element uniquely. This agrees with the predicted uncertainty budget of ±5.4° in Table 1, as shown in Figure 6B.

The measurement was repeated again, only this time the scan plane distance uncertainty was 0%. Reducing the scan distance uncertainty made the element clearly identifiable among the others, and a 5° phase error was measured in the hologram. This is shown in Figure 6C.

The element was adjusted -5° in phase (3° true error) based upon the hologram measurement. A third iteration measurement was run, and the resulting aperture hologram computed.

The third iteration hologram produced 1.5° phase error on the element. However, the other elements had as much as ±4° of phase variation, making it impossible to uniquely identify the phase error of this element. Therefore, the residual phase error of the aperture hologram is approximately ±4° if the scan plane distance is known accurately. This is shown in Figure 6D

4.0 Conclusions

This study has shown that it is reasonable to expect aperture phase uncertainty of <6° in the central region of the aperture hologram. Therefore, alignment of these center elements should be possible with perhaps two or three iterations. The uncertainty of the edge elements degrades very near the edge. On a highly tapered array, however, any single edge element has very little effect on the far-field pattern. Therefore, such high-degree of phase accuracy may not be necessary.

Several of the dominant sources of error have been examined and characterized for their effect on this particular antenna measurement. Many other types of errors, such as receiver dynamic range, non-linearity, and system phase drift, have not been examined. However, in a well-controlled environment with modern instrumentation these errors are typically negligible compared to the dominant ones considered herein.

Some error sources, although discussed, have not been characterized in this study. The effect of these errors, such as probe pattern, antenna pattern, multiple reflection, and multi-path, will be examined in future studies. Apodization or windowing functions on the scan plane will also be examined in future papers as a way to reduce the effects of scan plane truncation. Finally, it should be noted that extrapolation of these results to the measurement of other antennas may not be valid, since the results depend highly upon the AUT and scanner geometry and illumination.

References

[1] E.B. Joy, C.A. Rose, *Windows 96 for Planar Near-Field Measurement*, 1996 AMTA Conference Proceedings

[2] Newell, A., *Planar Near-Field Measurements,* NIST Boulder CO, 1985

Figure 6A. True Element Phase Error Compared to Hologram Element Phase

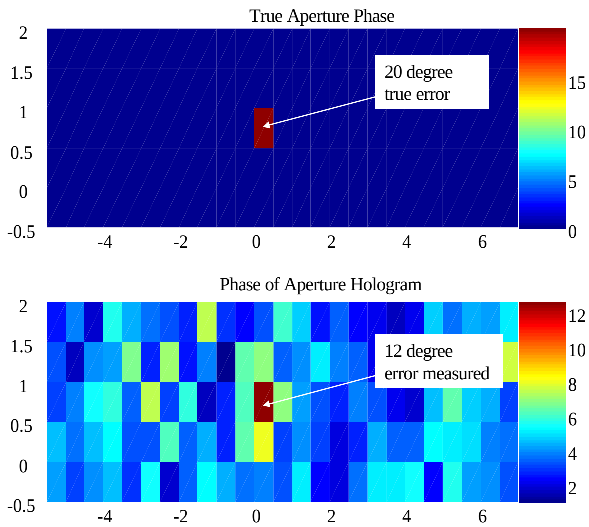

Figure 6C. True Element Phase Error Compared to Hologram Element with 0% Scan Plane Distance Uncertainty

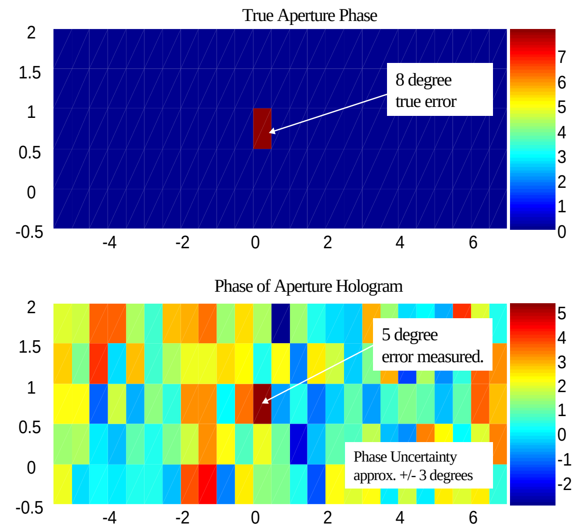

Figure 6B. True Element Phase Error Compared to Hologram Element Phase after 2nd Iteration

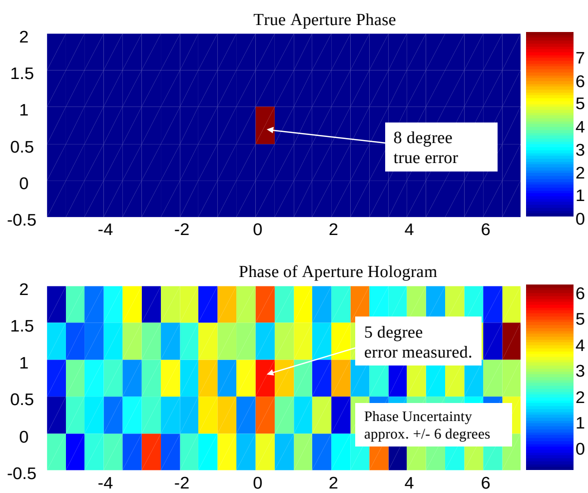

Figure 6D. True Element Phase Error Compared to Hologram Element Phase after 3rd Iteration