Modern Topics in Antenna Measurements, Diagnostics and Optimizations: From Fundamentals to Recent Advances

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AMTA Antenna Measurements Short Course
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http://www.antlab.ee.ucla.edu

Agenda

- **Overview of Near-Field Antenna Measurements**
- **The Plane-Polar and Bi-Polar Planar Near-Field Antenna Measurement Techniques**
  - Basic Concepts and Implementation
  - Data Processing Methods
- **Theory**
  - Probe-Corrected Planar Near-Field Antenna Measurements
  - Optimal Sampling Interpolation (OSI), Jacobi-Bessel, Fourier-Bessel
- **Microwave Antenna Imaging and Diagnostics**
  - Holographic Image Formation
  - Measurement Example
- **Phase Retrieval and Phaseless Antenna Diagnostic Imaging**
  - Algorithm for Bi-Polar Measurements
  - Measurement Examples
- **Conclusion**
Overview of Antenna Measurement Techniques

Antenna Configuration

Direct
- Far-field
- Defocusing
- Compact Range

Indirect
- Near-field Techniques
  - Planar
  - Cylindrical
  - Spherical
  - 1960's
  - 1990's
  - Planar-Rectangular
  - Plane-Polar
  - Bi-polar
  - Linear-Spiral

Computer Process

Far-field Pattern
- Beamwidth
- Pointing
- Gain
- Sidelobes
- Nulls
- Phase
- Cross-pol

Overview of the Near-Field Measurement Process

- Far-field pattern is computed from elemental measurements made in the radiating near-field of the antenna under test (AUT)
- Holographic image is computed from the far-field spectrum of the AUT
Planar Near-Field Sampling Geometries

Planar Near-Field Measurements

- Plane-rectangular
- Plane-polar
- Bi-polar
- Linear Spiral

Plane-Polar and Bi-Polar Near-Field Measurement Ranges

Plane Polar Facility at JPL

Bi-Polar Facility at UCLA
A Review paper on the fundamentals of Planar Near field measurements with emphasis on bi-polar technique

The UCLA Bi-polar Planar-Near-Field Antenna Measurement and Diagnostics Range

Yashar Restani-Dastmal, Lawrence J. Willis, and Robert G. Turner

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1. Introduction

The electrical engineering department at UCLA has enjoyed the use and development of a new review titled UCLA Review Paper on the fundamentals of Planar Near Field measurements, with emphasis on bi-polar technique. This review paper provides an overview of the fundamentals and applications of planar near field measurements, with emphasis on the bi-polar technique.

1.4.3 Biomedical near-field measurement techniques at UCLA

The UCLA Biomedical Engineering Department has recently developed an advanced biomedical near-field measurement system. This system is designed to measure near-field parameters in a minimally invasive manner, providing important information for the development of biomedical devices and applications.

1.5.3 The Biomedical Planar Near-Field range at UCLA

The Biomedical Planar Near-Field range at UCLA includes a variety of advanced near-field measurement techniques, including non-invasive and minimally invasive methods. This range is equipped with state-of-the-art equipment and is available for research and development purposes.

Plan-Polar Near Field Measurement Paper

Far-Field Patterns of Spaceborne Antennas from Plane-Polar Near-Field Measurements

Yaiya Rahmat-Samii, Helen, and Mark S. Gatti, 2003

In this paper, we present far-field patterns of spaceborne antennas obtained from plane-polar near-field measurements. The near-field measurements are used as input to the far-field pattern calculation, providing an accurate and efficient method for predicting the far-field behavior of spaceborne antennas.

II. INSTALLATION DESCRIPTION

The probe was driven in Fig. 1. A simple beam that has been designed for this purpose. The probe location has been determined using a 3D model of the antenna, and the far-field patterns are obtained using an iterative optimization technique. The far-field patterns are then compared with the measured data to validate the accuracy of the model.
The Valid Angle - A Limitation of All Planar Near-Field Techniques

- Planar Near-Field Scan Plane Must Be Theoretically Infinite
  - scan plane can not, in practice, be infinite
  - far-field pattern is effected by scan plane truncation
    » wide angle behavior of far-field pattern may be inaccurate

- Valid Angle
  - based on a high frequency model
  - derived geometrically
  - observed empirically

\[ \theta_{\text{Valid}} = \tan^{-1}\left(\frac{L - D}{2d}\right) \]

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  - Cylindrical
  - Spherical

Plane-Rectangular
- 1960's
- 1980's
- 1990's

Plane-Polar
- 1960's
- 1980's
- 1990's

Bi-polar
- 1960's
- 1980's
- 1990's

Linear-Spiral
- 1960's
- 1980's
- 1990's

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Far-field Pattern
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Plane-Polar Planar Near-Field Technique

- Large scan plane size
- Only one translational movements
- Highly accurate
- Both Antenna and Probe are gravitationally balanced

\[ \phi = 3 \Delta \phi \]
\[ \phi = 2 \Delta \phi \]
\[ \phi = \Delta \phi \]
\[ \phi = 0 \]
Plane-Polar Near-Field Measurements
Example (1.4 m Viking Spacecraft Antenna)

Viking High Gain Antenna Copol and X-pol Pattern at X-Band

Plane-Polar Facility at the Jet Propulsion Laboratory (Galileo Mission)
Bringing the Galileo High Gain Antenna to JPL Facility

Carrying the Galileo High Gain Antenna to JPL Plane-Polar Near-Field Facility
Installing the Galileo High Gain Antenna

Deployed High Gain Galileo Antenna
Probe Cage Supported on the Ceiling-Mount Bearns (JPL Plane-Polar Facility)

Measured Near-Field of Galileo High Gain Antenna

Near-field at X-Band Frequency of 8.415 GHz

Near-field at S-Band Frequency of 2.295 GHz
Extracted Galileo’s Antenna Far-Field from Plane-Polar Near-Field Measurement

Far-field at X-Band Frequency of 8.415 GHz

Far-field at S-Band Frequency of 2.295 GHz

Galileo Gain Calculation in Plane-Polar JPL Facility with Substitution Method

\[ G_f = G_R + 20 \log \left( \frac{E_{\text{max}R}}{E_{\text{max}T}} + g_{\text{attenuater}} \right) + 10 \log \left( \frac{1 - \Gamma_H^2}{1 - \Gamma_A^2} \right) \]

<table>
<thead>
<tr>
<th></th>
<th>( E_{\text{MAX}}^* )</th>
<th>( P_{\text{RX}} ) (dBm)</th>
<th>( P_{\text{OT}} ) (dBm)</th>
<th>( \Gamma )</th>
<th>Measured Gain (dBi)</th>
<th>Design Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Antenna</td>
<td>Galileo 1590897.5</td>
<td>______</td>
<td>8.11</td>
<td>0.0385</td>
<td>49.87(^*)</td>
<td>50.1</td>
</tr>
<tr>
<td>Reference Antenna</td>
<td>Viking 116224.85</td>
<td>-2.95</td>
<td>______</td>
<td>0.1304</td>
<td>38.27</td>
<td>__________</td>
</tr>
</tbody>
</table>

\* Computer Output (dimensionless)
\*\* This Gain was measured pre-environmental test

We worked so hard to get this accuracy.
What did happen after all our hard work?

Antenna did not unfurl and we had to use the low gain antenna!

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Bi-Polar Planar Near-Field Technique

- Large scan plane size
- Minimal "real-estate" requirements
- Simple mechanical implementation
- Highly accurate
- Cost-effective

\[ \alpha = 3 \Delta \alpha \]
\[ \alpha = 2 \Delta \alpha \]
\[ \alpha = \Delta \alpha \]
\[ \alpha = 0 \]
\[ \beta \]
\[ \text{Probe Arm} \]

General Features:
- 16 Foot Scan Plane Diameter
- 7 Foot Antenna Diameter
- 5 Foot Antenna Depth
- 200 Pound Antenna Weight

RF Subsystem:
- 2 - 40 GHz
- Wide Dynamic Range
- High Sensitivity and Linearity
- Balanced External Harmonic Mixing

Mechanical and Robotic Subsystem:
- Uni-structure Design (Base Frame)
- High-precision Rotary Positioners
- Micrometer-based Tilt Platform
- Probe Rotation / translation Stage

Acquisition and Control Subsystem:
- Computer Control of Robotics, RF
Bi-Polar Coordinate System
and Sampling Options

- Sampling can be performed using:
  - Radial
    - Equal Arm Angle Increments ($\Delta \beta$)
    - Equal Radial Increments ($\Delta \rho$)
  - Azimuthal
    - An Identical Azimuthal Spacing For All Rings ($\Delta \alpha$)
    - An Independent Azimuthal Spacing For Each Ring $n$ ($\Delta \alpha_n$)
Examples of Three Possible Bi-Polar Sample Arrangements

- Uniform arm increment ($\Delta \beta$)
- Common azimuth increment ($\Delta \alpha$) for all rings
- “Original” and validated bi-polar sample arrangement

- Uniform radial increment ($\Delta \rho$)
- Independent azimuth increment ($\Delta \alpha_n$) for each ring
- Fewer required samples

- Radial position linearly coupled to azimuth position
- Common azimuth increment ($\Delta \alpha$) along linear spiral
- First near-field measurement using linear spiral samples
- Most natural and rapid data acquisition mode

Bi-polar and Plane-Polar Near-Field Data Processing Method

1. Discard Phase
2. Optimal Sampling Interpolation
3. Jacobi-Bessel Transform
4. Fourier-Bessel Transform
5. FFT
6. Probe Correction
7. Phase Retrieval
8. Holographic Image
Waveguide-fed Slot Array Antenna

- X-Band (9.3 GHz)
- 196 Elements
- Elliptical Aperture
  - 14.8λ (E-Plane)
  - 8.7λ (H-Plane)
- Rectangular Lattice
  - 0.689λ (E-Plane)
  - 0.738λ (H-Plane)
- Tapered Aperture Illumination

Measured Far-Field Pattern Results:
Bi-Polar versus Plane-Rectangular Planar Near-Field

Waveguide-fed Slot Array with Elliptical Aperture
Frequency = 9.3 GHz

E-Plane

H-Plane
The Spillover Effect on the Directivity Calculation of Reflector Antennas in Planar Near-Field Measurements

S. F. Razavi, S. Xu, T. Brockett, and Y. Rahmat-Samii

In planar near-field measurements, part of the radiated power from the primary feed cannot be captured by the reflector antenna under test, resulting in spillover losses.

\[ P_{\text{rad}} = P_{\text{cap}} + P_{\text{non-cap}} \]

The measured directivity is calculated based on \( P_{\text{cap}} \) in stead of \( P_{\text{rad}} \), resulting in a higher directivity.

\[ D_{\text{meas}} = \frac{4\pi U}{P_{\text{cap}}} = \frac{4\pi |E_{\text{co}}|^2}{P_{\text{cap}}} \]

The actual directivity can be improved by taking into account the spillover losses.

\[ D = D_{\text{meas}} - L_{\text{spill}} \quad \text{(in dB)} \]

\[ L_{\text{spill}} = -10\log_{10} \frac{P_{\text{cap}}}{P_{\text{cap}} + P_{\text{non-cap}}} \]
A Quick Estimate of Spillover Loss

- Use the exact measured or simulated feed pattern, and calculate $P_{\text{rad}}$ and $P_{\text{cap}}$ by integrating the feed pattern mathematically.

- An alternative quick estimate based on the matching $\cos^q(\theta)$ pattern.

$$ L_{\text{spill}} = -10 \log_{10} \left[ 1 - \frac{(2q_1 + 1)\cos^{2q_2 + 1} \Omega}{2q_1 + 2q_2 + 1} - \frac{(2q_2 + 1)\cos^{2q_1 + 1} \Omega}{2q_1 + 2q_2 + 1} \right] $$

Two Simulation Approaches

- **PO Analysis** – Find the PO currents on the reflector surface and directly calculate the far fields.

- **Aperture Field** – Simulate the near fields in an aperture plane and calculate the far fields using Fourier transform.
Near Fields in the Aperture Plane

Simulation

Measurement

Directivities w/o and w/ Compensation

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Directivity (dB)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Compensation ($D_{\text{meas}}$)</td>
<td>After Compensation ($D$)</td>
<td></td>
</tr>
<tr>
<td>Simulation / PO</td>
<td>N/A</td>
<td>36.70</td>
<td></td>
</tr>
<tr>
<td>Simulation / NF</td>
<td>37.37</td>
<td>36.70</td>
<td></td>
</tr>
<tr>
<td>Measurement / NF</td>
<td>37.25</td>
<td>36.58</td>
<td></td>
</tr>
</tbody>
</table>

$L_{\text{null}}$ is estimated to be 0.67 dB based on the integration of the measured feed pattern.
Jacobi-Bessel and Fourier-Bessel Transform Introduction

• Near-Field Expansion
  – expand the near-field in a set of orthogonal basis functions

• Expansion Coefficients
  – found from orthogonality considerations
  – calculated numerically
  – independent of far-field observation coordinates

• Far-Field
  – found in “closed-form” as a series employing the expansion coefficients and defined functions

The Direct Expansion of the Near-Field Eliminates the Need for Interpolation of the Near-Field Samples!

Jacobi-Bessel Transform

• Near-field expansion

\[
Q(s, \varphi) = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} [C_{nm}\cos(n\varphi) + D_{nm}\sin(n\varphi)]F_{m}^{n}(s)
\]

• Coefficient Calculation*

\[
C_{nm} = \int_{0}^{2\pi} \int_{0}^{a} Q(s, \varphi)\cos(n\varphi)F_{m}^{n}(s)s \, d\varphi \, ds
\]

\[
Q(s, \varphi) = \frac{a^2}{2\pi} b(s, \varphi) e^{jka[s\cos\varphi + v_0\sin\varphi]}
\]

* \(D_{nm}\) computed similar to \(C_{nm}\) except for \(\sin(n\varphi)\)

s = normalized radial coordinate
a = scan plane radius
\(\varphi\) = azimuthal coordinate
\(b(s, \varphi)\) = measured or simulated near-field
\(C_{nm}, D_{nm}\) = expansion coefficients
k = wavenumber
\(F_{m}^{n}(s)\) = modified Jacobi polynomial
\(u_0, v_0\) = expansion center
\(\varepsilon_n\) = Neuman number
Far-Field Calculation

\[
D(u, v) = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} [C_{nm} \cos(n\varphi) + D_{nm} \sin(n\varphi)] \sqrt{2(n + 2m + 1)} \frac{J_{n+2m+1}(kB)}{kB}
\]

\[kB = ka \sqrt{(u - u_0)^2 + (v - v_0)^2}\]

\[\Phi = \tan^{-1} \left( \frac{v - v_0}{u - u_0} \right)\]

\[u, v = \text{observation coordinate}\]

\[J_n = \text{order nth Bessel function of the first kind}\]
Fourier-Bessel Transform

- Near-field expansion

\[ Q(s, \varphi) = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} G_{nm} e^{-j \left( \frac{m \pi x}{a} + \frac{n \pi y}{a} \right)} \]

- Coefficient Calculation

\[
G_{nm} = \int_{0}^{2\pi} \int_{0}^{\infty} Q(s, \varphi) e^{jmk\cos(\varphi)+n\sin(\varphi)} e^{jka} \, ds \, d\varphi
\]

\[ Q(s, \varphi) = a^2 b(s, \varphi) e^{jka[u_0 \cos \varphi + v_0 \sin \varphi]} \]

- Far-Field Calculation

\[
D(u, v) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} G_{nm} \frac{J_1(kB_{nm})}{kB_{nm}}
\]

\[
kB_{nm} = ka \sqrt{\left( \frac{u - u_0 - \frac{m \pi}{ka}}{u_0} \right)^2 + \left( \frac{v - v_0 - \frac{n \pi}{ka}}{v_0} \right)^2}
\]

- Fourier-Bessel Pattern Construction

\[ u, v = \text{observation coordinate} \]
Fourier-Bessel Transform

- Expansion Center $u_0, v_0$
- Bi-polar Near-Field $Q(s, \phi)$
- Expand
- Integration for Coefficients $G_{mn}$
- Observation Points $u, v$
- Airy Disc Function $J_1(kBmn)/kBmn$
- Near-Field Scan Plane
- $a$
- $d$
- $s$
- $\theta_0$
- $\phi$
- $u_0 = \sin\theta_0 \cos\phi_0$
- $v_0 = \sin\theta_0 \sin\phi_0$

Comparison of Jacobi- and Fourier-Bessel Transforms

### Jacobi-Bessel
- Coefficients **independent** of observation coordinates
- Coefficients calculated by numerical integration
- Bessel function of **integer orders** required
- Parameter $B$ **independent** of $m,n$ (all terms centered at expansion center)
- Most efficient for circular apertures
- Less efficient for angles away from expansion center

### Fourier-Bessel
- Coefficients **independent** of observation coordinates
- Coefficients calculated by numerical integration (bi-polar grid inhibits use of FFT)
- Bessel function of **order one** required
- Parameter $B$ **dependent** of $m,n$ (each term centered at different location)
- Most efficient for circular apertures
- Less efficient for angles away from expansion center
### Comparison of Interpolation/FFT and Expansion Methods

<table>
<thead>
<tr>
<th>Interpolation/FFT</th>
<th>Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Near-field is interpolated</td>
<td>• No interpolation necessary</td>
</tr>
<tr>
<td>• Yields <em>rigorous</em> sampling criteria</td>
<td>• No inherent sampling criteria</td>
</tr>
<tr>
<td>• Results depend on over-sampling and retained samples</td>
<td>• Results depend number of expansion coefficients</td>
</tr>
<tr>
<td>• Far-field point must, in general, also be found by interpolation</td>
<td>• Far-field point may be calculated directly</td>
</tr>
<tr>
<td>• NF-FF transformation computed <em>efficiently</em> by FFT</td>
<td>• NF-FF transformation inefficient if many far-field points are desired</td>
</tr>
<tr>
<td>• NF-FF transformation by FFT <em>independent</em> of the AUT radius, AUT shape, and scan plane radius</td>
<td></td>
</tr>
<tr>
<td>• Near-field data must be stored</td>
<td>• Only coefficients need to be stored</td>
</tr>
</tbody>
</table>

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**Elliptical Slot Array**

- **Freq** = 9.3 GHz
- **Rmax** = 14.9 wvl
- **d** = 4.5 wvl
- **p = 33, q = 99**
- **Valid Angle** = 57 degrees

**Graphs**:
- **H-plane**
- **E-plane**
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Microwave Antenna Imaging and Diagnostics

- Microwave Holographic Imaging
  - determine the magnitude and phase of the electric field in the aperture plane of the antenna under test (AUT)
  - has revolutionized modern antenna diagnostic techniques
- Applications
  - array antennas
    » location of defective radiators
    » “phase-up”
  - reflector antennas
    » surface profile and anomalies
- Mathematical Formulation
  - almost exclusively performed, for planar near-field antenna measurements, using plane wave spectrum (PWS) techniques and the fast Fourier Transform (FFT)
• Goal
  – to determine the x and y components of the electric field in the aperture plane (z=0) of the AUT

• Cartesian components of the probe compensated PWS

  \[ t_x(k) = \left[ \sin \phi \cos \phi (\cos \theta - 1) \right]_m(k) + \left[ -\cos \theta \cos^2 \phi - \sin^2 \phi \right]_c(k) \]
  \[ t_y(k) = \left[ \cos \theta \sin^2 \phi + \cos^2 \phi \right]_m(k) + \left[ \sin \phi \cos \phi (1 - \cos \theta) \right]_c(k) \]

• Probe compensated aperture fields of the AUT

  \[ E_x(x, y, 0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} t_x(k_x, k_y) e^{-j(k_x x + k_y y)} \, dk_x dk_y \]
  \[ E_y(x, y, 0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} t_y(k_x, k_y) e^{-j(k_x x + k_y y)} \, dk_x dk_y \]

Use 0-filled FFT or DFT for enhanced image production.
• Antenna Description
  - waveguide-fed slot array
  - communications application
  - square aperture, 23 in. on a side
  - 400 radiating slots
  - frequency band 7.1 - 7.7 GHz
  - designed for uniform illumination

• Results Overview

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Beam Max (degrees)</th>
<th>Beamwidth (degrees)</th>
<th>Directivity</th>
<th>Area Gain</th>
<th>Avg SLL</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 GHz</td>
<td>Theta: 0.09, Phi: 180.00</td>
<td>E-plane: 3.72, H-plane: 3.69</td>
<td>33.07</td>
<td>33.81</td>
<td>-38.56</td>
</tr>
<tr>
<td>7.4 GHz</td>
<td>Theta: 0.09, Phi: 180.00</td>
<td>E-plane: 3.58, H-plane: 3.57</td>
<td>33.86</td>
<td>34.17</td>
<td>-41.08</td>
</tr>
<tr>
<td>7.7 GHz</td>
<td>Theta: 0.09, Phi: 180.00</td>
<td>E-plane: 3.40, H-plane: 3.40</td>
<td>33.87</td>
<td>34.52</td>
<td>-41.17</td>
</tr>
</tbody>
</table>

Antenna Patterns
Frequency = 7.4 GHz

0
-10
-20
-30
-40
-50
-90 -75 -60 -45 -30 -15 0 15 30 45 60 75 90

relative power (dB)

theta (deg)

H-plane
E-plane
Holographic Images
Frequency = 7.4 GHz

Magnitude Image

Phase Image

Holographic Images
Frequency = 7.1 GHz

Magnitude Image

Phase Image
Holographic Images
Frequency = 7.7 GHz

Magnitude Image
Phase Image

Magnitude (dB)
Phase (deg)

4×16 Dual Polarized Array

Frequency = 13.4 GHz
Bi-Polar Near Field Measurement of H-Port

- Similar patterns to far-field and spherical near field measurements are observed.
- Similar holographic images to spherical near-field measurements are also achieved, including the non-radiating 1-by-4 subarray due to the small defect in the feeding line.

Defect observed Again!

H-Port, xz-plane
H-Port, yz-plane

Near Field Measurement of the Fixed Array

 vz-plane, H-Port
 yz-plane, H-Port

Defect Fixed

REMARKS

- Narrow beams are still observed in xz-plane for both ports after fixing the array.
- Directivity: 22.37dB $\rightarrow$ 23.19dB (H-port), 22.16dB $\rightarrow$ 22.71dB (V-port).
Holographic Images of the Fixed Array

The subarray is radiating!

REMARKS

• The uniform amplitude and phase distributions demonstrate that the defect in H-port feeding network has been successfully fixed.

Waveguide-Fed Slot Array Antenna with “UCLA” Blockage

Co-pol Aperture Phase

![Co-pol Aperture Phase Image]
An Interesting Application

- To Compensate Reflector Surface Distortions by a Sub-reflectarray in a Cassegrain System through Simulations, Measurements, and Microwave Holographic Diagnostics.
- For the first time demonstrate this by an actual measurements.

Nominal Design  Ring-type Distortion  Compensation

Simulation and Measurement Approach

- The feed and the subreflector are analyzed and simulated in full-wave EM software.
- The total fields from the feed-sub system is used as input for the in-house reflector code for PO/PTD diffraction synthesis (discrete data in theta-phi grids).

**Nominal Design – Cassegrain System**

Reflectarray acting as a hyperboloid

**CASSEGRAIN SYSTEM**

**Simulation:**
- Directivity\(_{\text{max}}\) = 41.57dB
- Side Lobe level\(_{\text{max}}\) = -14.24dB

**Measurement:**
- Directivity\(_{\text{max}}\) = 42.15dB
- Side Lobe level\(_{\text{max}}\) = -13.61dB
- 1dB Bandwidth = 0.8GHz (6%)

The phase at the aperture *shows an almost uniform phase* thus the sub-reflectarray acts as a hyperbola.
An annular ring was created to mimic thermal/gravitational distortions. This distortion caused phase errors at the aperture leading to performance degradation.

• The ring distortion caused an increase in the side lobe levels and an overall decrease in the total directivity (6dB).
**Distortion Compensation**

1. **Use Conjugate Field Matching (CFM) Method**
   - Excite the reflectarray elements one-at-a-time with excitation of $1 \angle 0^\circ$
   - Obtain the Far-Field Amplitude and Phase in the boresight direction
   - The excited reflectarray elements excitation for the compensation array is the complex conjugate of the obtained far field data

2. **Amplitude and phase excitations obtained**

3. **Use phase excitations and discard amplitude excitations**
   - These phases are the phase excitations of each element of the sub-reflectarray

4. **Use reflectarray design method**
   - Generate ‘S’ curves
   - Determine the required reflection phase at the element location
   - The required element sizes are looked up from the design curve

---

**Surface Distortion Compensation – Measurements**

Reflectarray compensating for ring distortion

**Simulation:**
- $\text{Directivity}_{\text{max}} = 40.93\text{dB}$
- $\text{Side Lobe level}_{\text{max}} = -10.85\text{dB}$

**Measurement:**
- $\text{Directivity}_{\text{max}} = 40.17\text{dB}$
- $\text{Side Lobe level}_{\text{max}} = -8.36\text{dB}$

- 4.67dB improvement with lower side lobes indeed validates the sub-reflectarray compensation technique.
The phase at the aperture shows almost uniform distribution thus the sub-reflectarray has compensated for the ring distortion effects.

Compensation of Reflector Surface Distortion by a Sub-reflectarray in a Cassegrain System through Simulations, Measurements, and Microwave Holographic Diagnostics.
Agenda

• Overview of Near-Field Antenna Measurements
• The Plane-Polar and Bi-Polar Planar Near-Field Antenna Measurement Technique
  – Basic Concepts and Implementation
  – Data Processing Methods
• Theory
  – Probe-Corrected Planar Near-Field Antenna Measurements
  – Optimal Sampling Interpolation (OSI), Jacobi-Bessel, Fourier-Bessel
• Microwave Antenna Imaging and Diagnostics
  – Holographic Image Formation
  – Measurement Example
  • Phase Retrieval and Phaseless Antenna Diagnostic Imaging
    – Algorithm for Bi-Polar Measurements
    – Novel Simulations
    – Measurement Examples
• Conclusion

Introduction to Phaseless Bi-Polar Near-Field Antenna Measurements

• The Phase Retrieval Problem
  – amplitude only near-field measurements
  – processing required to “retrieve” the phase
• Motivation
  – millimeter wave frequency measurements and diagnostics
  – relaxed mechanical positioning/RF instrumentation requirements
  – implementation on “conventional” and/or existing near-field systems
• Bi-Polar Near-Field Measurements and the Phase Retrieval Problem
  – iterative Fourier approach
  – squared amplitude optimal sampling interpolation (OSI) algorithm
  – measurements obtained on two near-field planes
  – practical limitations require plane separations of just a few wavelengths
  » typically adversely affects any phase retrieval algorithm
Phase Retrieval Methods Overview

### Phase Retrieval Methods

**Fourier Iterative**
- Error Reduction (Gerchberg & Saxton)
- Input-Output (Fienup)
- Misell
- Plane-to-Plane (Anderson, Sali)

**Minimization**
- Steepest-Descent
- Conjugate Gradient
- Least Squares
- Inverse Methods (Isernia, Leone, Pierri)

**Other**
- Stochastic Models
  - Autoregressive
  - Maximum Entropy

- Phase retrieval algorithms have, for the most part, originated in the optical regime
  - measurement planes typically separated by a very large electrical distance, e.g. $O(100\lambda)$ and $O(1000\lambda)$ are not uncommon

---

Pictorial Representation of Phase Retrieval Algorithm

**Phase Retrieval Algorithm - Fourier Iteration**

1. Phaseless Bi-Polar Measurements
2. Squared Amplitude OSI
3. Propagate AUT Aperture Plane Field to Measurement Plane #1 (#2)
4. Propagate Field at Measurement Plane #1 (#2) to AUT Aperture Plane
5. Replace Computed Field Amplitude with Measured Field Amplitude and Retain Phase
6. Apply AUT Aperture Constraint
7. Near-Field to Far-Field Transform

REPEAT
**Squared Amplitude Optimal Sampling Interpolation (OSI)**

- Radiated electric field is quasi-bandlimited (Bucci, Franceschetti)
  - radiating source of finite extent $a$
  - the reduced field $F(r) = E(r)e^{jkr}$ is bandlimited to a band $w \approx ka$

**Fourier Convolution Theorem**

If $f(x) \rightarrow F(k)$ then $f^*(x) \rightarrow F^*(-k)$

and $|f(x)|^2 = f(x)f^*(x) \rightarrow F(k) \otimes F^*(-k)$

- the squared amplitude $|f(x)|^2$ is bandlimited to a band twice that of $f(x)$

**Optimal Sampling Interpolation**

$$|b(s, \alpha)|^2 = \sum_{n=n_0}^{n_0+q} \sum_{m=m_0}^{m_0+p} |b(n \Delta s, m \Delta \alpha_n)|^2 \Omega(\gamma'_{mn}) D_{M_n}(\gamma'_{mn}) \psi(\gamma''_{mn}) \text{sinc} \left[ \frac{\pi}{\Delta s} \gamma''_{mn} \right]$$

where $\gamma'_{mn} = \alpha - m \Delta \alpha_n$, $\gamma''_{mn} = s - n \Delta s$

**Phase Retrieval Issues for Bi-Polar Planar Near-Field Measurements**

- Measurement
  - Sample Rate
  - Single/Multiple Planes
  - Plane Separation
  - Acquired Polarizations

- Interpolation
  - Amplitude/Squared Amplitude
  - Output Sample Rate
  - Polarization

- Processing
  - Stagnation/Trapping
  - Global "Capture" Region
  - Probe Correction
  - Aperture Masking
  - Error/Stopping Criterion
  - Polarization
  - Beam Direction
Iterative Fourier Transform (IFT) Result for a Broadside-Directed Simple Pattern: Simulations

PROBLEM DEFINITION
- Array of 21×21 infinitesimal Dipoles separated λ/2 from each other
- Uniform-amplitude y-directed elements
- Plane size of 50λ
- Measurement planes distance to the AUT plane 5λ and 7λ respectively
- Valid angle of 70.7° (sin(θ) = .94)
- Total number of iteration =100

REMARKS
- Excellent in Reconstruction of the main beam-direction, beam-width, SLL and even the position of the nulls

Iterative Fourier Transform (IFT) Result for a Broadside-Directed Complex Pattern

PROBLEM DEFINITION
- Array of 21×21 infinitesimal Dipoles separated λ/2 from each other
- Uniform-amplitude mostly y-directed elements
- Plane size of 50λ
- Measurement planes distance to the AUT plane 5λ and 7λ respectively
- Valid angle of 70.7° (sin(θ) = .94)
- Total number of iteration =100

REMARKS
- Excellent in Reconstruction of the main beam-direction, beam-width, SLL and even the position of the nulls
• Using the infinitesimal dipoles one can effectively simulate any kind of aperture by picking the right amplitude and phase for each element.

• Both exact near-field and far-field can be calculated.

We inject random probe position errors in both planes of measurements.

An array of 21×21 infinitesimal dipoles separated λ/2 from each other

Amplitude Measurements Stability vs. Phase Measurements Stability

Exact Near-field

Near-field with Error
Caused by Randomly Positioning of the Probe along z-axis (Maximum Error 1λ)
Antennas with High Side Lobe Levels

**Uniform Aperture**

- 13.3 dB SLL Chebyshev Tapering

- Amplitude & Phase with Error

Antennas with Medium Side Lobe Levels

**20 dB SLL Quadratic Tapering**

- Amplitude & Phase Exact

- Amplitude Only with Error
Antennas with Low Side Lobe Level

30 dB SLL Quadratic Tapering  30 dB SLL Chebyshev Tapering

The Effect of the Probe Positioning Error on the Amplitude and Phase

<table>
<thead>
<tr>
<th>Aperture Tapering Distribution</th>
<th>Amplitude Error Standard Deviation</th>
<th>Phase Error Standard Deviation</th>
<th>Amplitude Mean Error</th>
<th>Phase Mean Error</th>
<th>Amplitude Maximum Error</th>
<th>Phase Maximum Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform [13.3 dB SLL]</td>
<td>-39.3 dB</td>
<td>114°</td>
<td>-47.4 dB</td>
<td>-0.7°</td>
<td>-16.2 dB</td>
<td>358.6°</td>
</tr>
<tr>
<td>Chebyshev [12.3 dB SLL]</td>
<td>-29.9 dB</td>
<td>111.9°</td>
<td>-39.9 dB</td>
<td>-0.6°</td>
<td>-7.7 dB</td>
<td>358.3°</td>
</tr>
<tr>
<td>Chebyshev [20 dB SLL]</td>
<td>-36 dB</td>
<td>113°</td>
<td>-44.3 dB</td>
<td>-1.7°</td>
<td>-12.4 dB</td>
<td>358.8°</td>
</tr>
<tr>
<td>Chebyshev [30 dB SLL]</td>
<td>-47 dB</td>
<td>111°</td>
<td>-56.5 dB</td>
<td>-2.6°</td>
<td>-22.1 dB</td>
<td>358.3°</td>
</tr>
<tr>
<td>Quadratic [20 dB SLL]</td>
<td>-53.2 dB</td>
<td>113.8°</td>
<td>-62.7 dB</td>
<td>-2.9°</td>
<td>-27.9 dB</td>
<td>357.8°</td>
</tr>
<tr>
<td>Quadratic [30 dB SLL]</td>
<td>-69.9 dB</td>
<td>110.9°</td>
<td>-83.3 dB</td>
<td>1.5°</td>
<td>-46.1 dB</td>
<td>358.4°</td>
</tr>
</tbody>
</table>
Phase Retrieval Measurements Overview

• Waveguide-fed Slot Array Antenna
  – X-band, 9.375 GHz
  – $23.0 \lambda$ (H-plane) x $21.4 \lambda$ (E-plane) Aperture

• Near-Field Measurement Parameters
  – measurements obtained on two closely spaced ($2.59 \lambda$) near-field planes
  – valid angle of $\sin(\theta)=0.76$
  – 2x oversampling

<table>
<thead>
<tr>
<th>Measurement #1</th>
<th>Measurement #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>9.375 GHz</td>
</tr>
<tr>
<td>Acquired Polarizations</td>
<td>Co-pol</td>
</tr>
<tr>
<td>No. Rings</td>
<td>85</td>
</tr>
<tr>
<td>No. Points/Ring</td>
<td>9...313</td>
</tr>
<tr>
<td>Antenna to Probe Spacing (d)</td>
<td>6.25 $\lambda$</td>
</tr>
<tr>
<td>Probe Arm Length (L)</td>
<td>41.30 $\lambda$</td>
</tr>
<tr>
<td>Scan Plane Radius (a)</td>
<td>19.32 $\lambda$</td>
</tr>
</tbody>
</table>

• Squared Amplitude OSI
  – 128 x 128 samples
  – 0.485 $\lambda$ sample spacing

The Measured Near-Field Amplitude Data
Phase Retrieval Results Overview

- **Initialization**
  - pseudo-random (±3 dB amplitude, ±30 degrees phase) estimate of the field in the AUT's physical aperture

- **Error Metric**
  \[
  \mathcal{E} = \frac{\sum_{i,j} |E_{ij}\text{computed} - |E_{ij}\text{measured}|^2}{\sum_{i,j} |E_{ij}\text{measured}|^2}
  \]

- **Algorithm Termination**
  - 134 iterations
  - error metric failed to further decrease on successive iterations

Phase Retrieval Antenna Pattern Comparison

**H-plane**

**E-plane**
Phase Retrieval Antenna Pattern
Comparison

Pattern from Amplitude and
Phase Measurement

Phase Retrieval Pattern

Comparison of Far-Field Pattern
Statistics

- Far-Field Pattern Statistics

<table>
<thead>
<tr>
<th></th>
<th>Amp &amp; Phs Measurement</th>
<th>Phase Retrieval</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-plane Beamwidth</td>
<td>2.90 degrees</td>
<td>2.90 degrees</td>
</tr>
<tr>
<td>E-plane Beamwidth</td>
<td>3.43 degrees</td>
<td>3.39 degrees</td>
</tr>
<tr>
<td>Directivity</td>
<td>35.54 dB</td>
<td>35.56 dB</td>
</tr>
<tr>
<td>Average Sidelobe Level</td>
<td>-44.99 dB</td>
<td>-44.94 dB</td>
</tr>
<tr>
<td>Peak Sidelobe Level</td>
<td>-24.46 dB</td>
<td>-22.68 dB</td>
</tr>
</tbody>
</table>

Note: Average sidelobe level is defined to be a measure of the power in the pattern excluding a 10 degree one-sided cone about the main beam.

- Comments
  - far-field pattern statistics confirm accuracy of the phase retrieval
  - difference in peak sidelobe level attributed to the increased first sidelobe level (shoulder) on the phase retrieval H-plane pattern
Holographic Images of Aperture Magnitude

Image from Amplitude and Phase Measurement

Phase Retrieval Image

Holographic Images of Aperture Phase

Image from Amplitude and Phase Measurement

Phase Retrieval Image
Phase Retrieval Measurements
Overview

- Waveguide-fed Slot Array Antenna
  - X-band, 9.3 GHz
  - $14.8\lambda$ (H-plane) x $8.7\lambda$ (E-plane) aperture
  - aperture blockage is $3 \times 3$ slots

- Near-Field Measurement Parameters
  - obtained on two closely spaced ($2.56\lambda$) near-field planes
  - valid angle of $\sin(\theta)=0.91$
  - 2x oversampling

- Squared Amplitude OSI
  - 128 x 128 samples
  - $0.485\lambda$ sample spacing

<table>
<thead>
<tr>
<th>Measurement #1</th>
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</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>9.3 GHz</td>
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<tr>
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</tr>
<tr>
<td>No. Rings</td>
<td>81</td>
</tr>
<tr>
<td>No. Points/Ring</td>
<td>9...209</td>
</tr>
<tr>
<td>Antenna-Probe Spacing (d)</td>
<td>4.73 $\lambda$</td>
</tr>
<tr>
<td>Probe Arm Radius (L)</td>
<td>40.97 $\lambda$</td>
</tr>
<tr>
<td>Scan Plane Radius (a)</td>
<td>17.61 $\lambda$</td>
</tr>
</tbody>
</table>

The Measured Near-Field Amplitude Data

Amplitude at $z=4.73\lambda$

Amplitude at $z=7.29\lambda$
• Initialization
  – pseudo-random (±3 dB amplitude, ±30 degrees phase) estimate of the field in the AUT’s physical aperture
  – NO apriori knowledge of aperture blockage

• Error Metric
  \[ E = \frac{\sum_{i,j} (|E_{ij}|_{\text{computed}} - |E_{ij}|_{\text{measured}})^2}{\sum_{i,j} |E_{ij}|_{\text{measured}}^2} \]

• Algorithm Termination
  – 104 iterations
  – error metric failed to further decrease on successive iterations
Phase Retrieval Antenna Pattern Comparison

Pattern from Amplitude and Phase Measurement

Phase Retrieval Pattern

Comparison of Far-Field Pattern Statistics

<table>
<thead>
<tr>
<th>Blockage</th>
<th>No Blockage</th>
<th>Amp &amp; Phs Measurement</th>
<th>Phase Retrieval</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-plane Beamwidth</td>
<td>5.01 deg</td>
<td>5.11 deg</td>
<td>5.12 deg</td>
</tr>
<tr>
<td>E-plane Beamwidth</td>
<td>7.90 deg</td>
<td>7.73 deg</td>
<td>7.63 deg</td>
</tr>
<tr>
<td>Directivity</td>
<td>29.68 dB</td>
<td>29.34 dB</td>
<td>29.41 dB</td>
</tr>
<tr>
<td>Average Sidelobe Level</td>
<td>-41.48 dB</td>
<td>-37.14 dB</td>
<td>-37.05 dB</td>
</tr>
<tr>
<td>Peak Sidelobe Level</td>
<td>-23.05 dB</td>
<td>-18.75 dB</td>
<td>-18.41 dB</td>
</tr>
</tbody>
</table>

Note: Average sidelobe level is defined to be a measure of the power in the pattern excluding a 10 degree one-sided cone about the main beam.

- Far-field pattern statistics confirm accuracy of the phase retrieval
- 1.3% reduction in the phase retrieval E-plane beamwidth accounts for the slight increase in directivity
- Directivity and average sidelobe level within 0.1 dB of the reference calculation
Holographic Images of Aperture Magnitude

Holographic Images of Aperture Phase
UCLA Table-Top Bi-Polar mm-Wave Near Field Scanner

Millimeter-Wave Bipolar Planar Antenna Measurement System
The Bipolar Planar Scanning Technique - Post-processing

- Bi-polar Near-field Data
- Optimal Sampling Interpolation
- FFT
- Jacobi-Bessel Transform
- Fourier-Bessel Transform
- Probe Correction
- FFT^-1
- Holographic Image

30 GHz Ka-Band Standard Gain Horn Measurement

- A Ka-Band Standard Gain Horn was mounted and measured at 30GHz.
- Near-field data was processed to produce far-field patterns.

- Co-polarized Amp.
- Co-polarized Phase
- Cross-polarized Amp.
- Cross-polarized Phase
**30 GHz Ka-Band Standard Gain Horn Measurement**

Far-field Patterns

- Far-field patterns are consistent with well-known standard gain horn patterns.
- Valid Angle was 70 degrees.

- Co-pol. H-plane

- Co-pol. E-plane

Co-pol. $\varphi = 45^\circ$ Cut  
Co-pol. Phase $\varphi = 135^\circ$ Cut

**92 GHz W-band Reflector Feed Measurement**

- Honeywell, Inc. designed and built a W-band feed and measured it with the system.
- External mixing was used to extend the measurement frequency.
- Feed was measured at 92 GHz with a valid angle of 40 degrees.
92 GHz W-band Reflector Measurement

Two measurements with different sampling spacing were conducted and processed to produce far-field patterns. The results were then compared.

Advanced Topics in Phaseless Measurements

Dealing with Complex Pattern Antenna

Solving the Polarization Issue

Mitigating the Need for Probe Co-rotation

Uniqueness of Converged Solutions

Iterative Fourier Technique


Rahmat-Samii’s Journal Papers on Antenna Measurements (Cont.)


Rahmat-Samii’s Conference Papers on Antenna Measurements

Rahmat-Samii's Conference Papers on Antenna Measurements (Cont.)


