Microwave and Millimeter Wave NDT&E

Principles, Methods and Applications

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This presentation is based on the results of research and activities in the areas of microwave and millimeter wave NDT&E performed at the:

Applied Microwave Nondestructive Testing Lab. (*amntl*)

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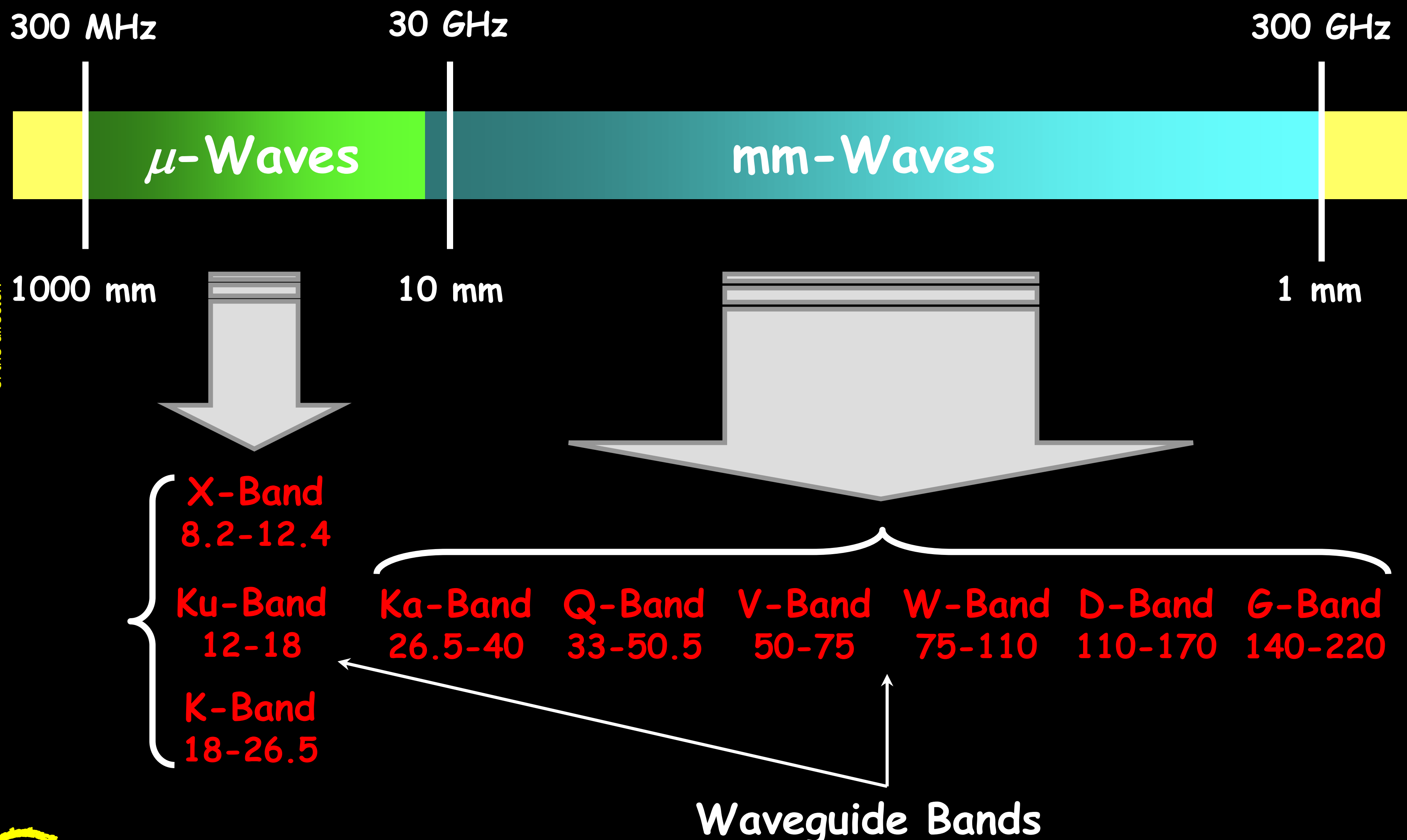
Outline

- Background.
- Material characterization.
- Multi-layer composite inspection.
- Corrosion and corrosion precursor pitting detection under paint.
- Surface crack detection and evaluation.
- Real-aperture, synthetic aperture and holographical imaging for inspection of several different types of composites.
- Future.

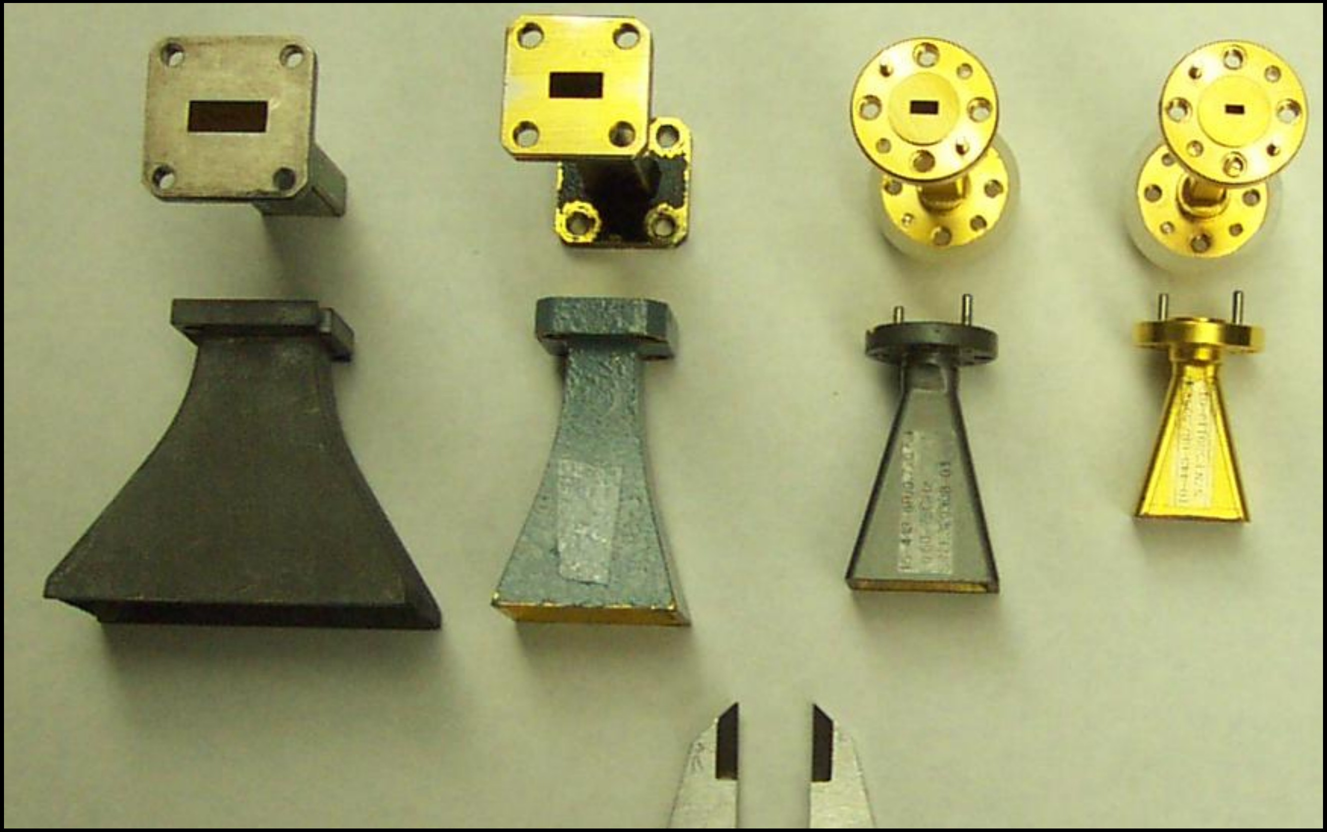
BACKGROUND

Frequency Spectra



Waveguides & Horn Antenna Examples

K-Band	Ka-Band	V-Band	W-Band	
10.7 x 4.3	7.11 x 3.56	3.8 x 1.9	2.54 x 1.27	(mm x mm)



10 mm

Background

- These signals penetrate into dielectric materials, as a function of their dielectric properties and frequency.
- Sensitive to dielectric property variation:
  - ✓ abrupt (boundaries)
  - ✓ local (inclusions)
  - ✓ gradual (gradient in material change).
- Polarization, frequency, measurement parameter (near-field vs. far-field) & probe type diversity-degrees of freedom.
- Sensitive to conductor surface properties – cracks, impact damage, etc.

Advantageous Features

- Coherence properties – magnitude & phase.
- Large available bandwidth.
- Life-cycle inspection possibilities.
- Electromagnetic modeling (analytical, numerical and empirical).
- On-line and real-time inspection.
- Operation in industrial environments.
- Little to no need for operator expertise.
- Relatively inexpensive.
- Applications to where "standard" NDT&E techniques have limited applicability.

Advantageous Features

- Measurement systems are:
  - ✓ non-contact
  - ✓ one-sided
  - ✓ mono-static
  - ✓ compact and small
  - ✓ low power
  - ✓ in-field & operator friendly
  - ✓ adaptable to existing scanning platforms
  - ✓ robust & repeatable

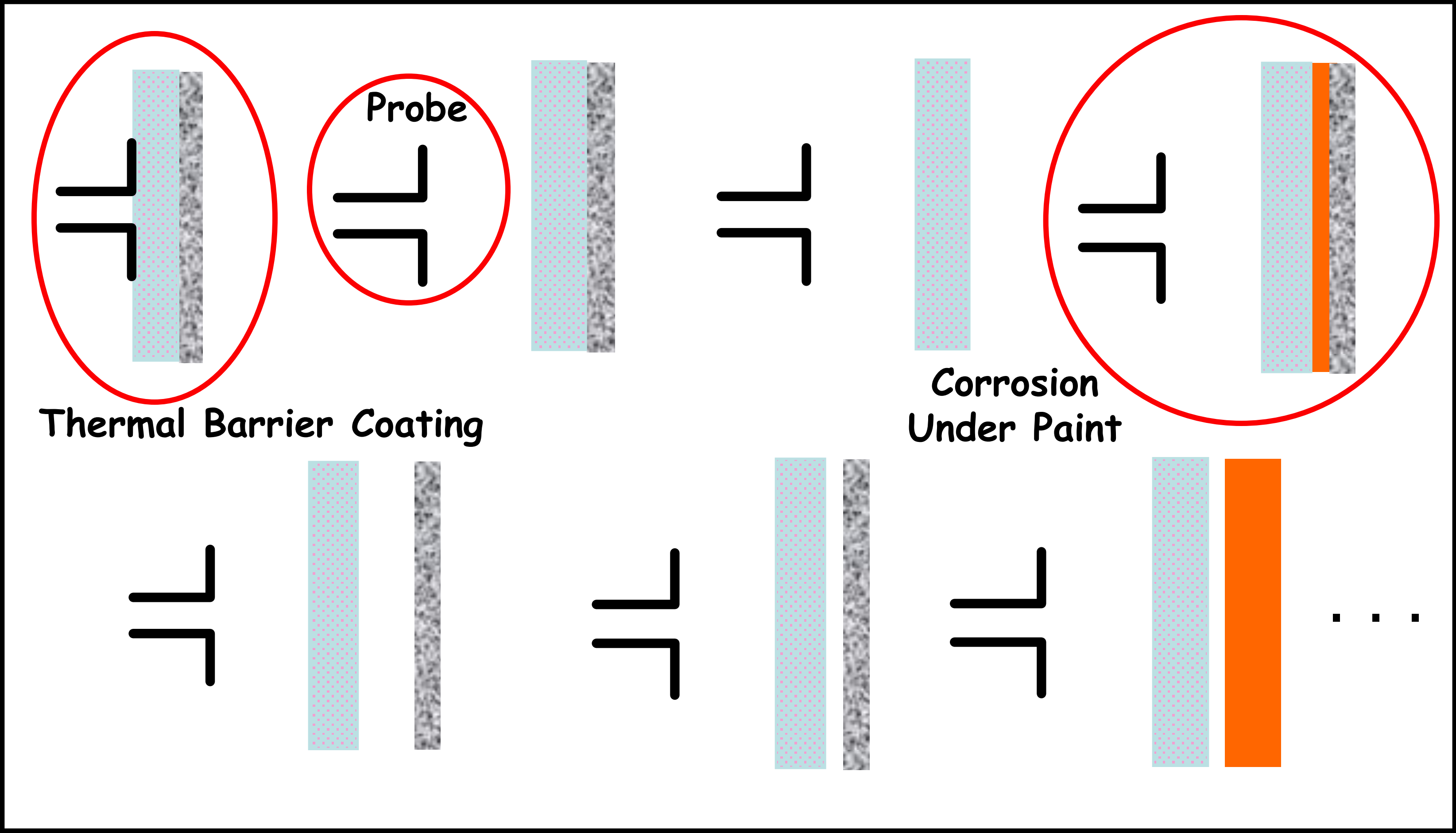
What Can Be Done?

- Material characterization - evaluation of dielectric properties of materials.
- Evaluation of moisture in composites.
- Cure-state monitoring.
- Relating microwave properties to physical & mechanical properties of materials.
- Comprehensive inspection of thick composite materials and structures.
- Dielectric coating evaluation.
- Thickness variation/quality control.
- Detection and evaluation of disbond, delamination, void & porosity.

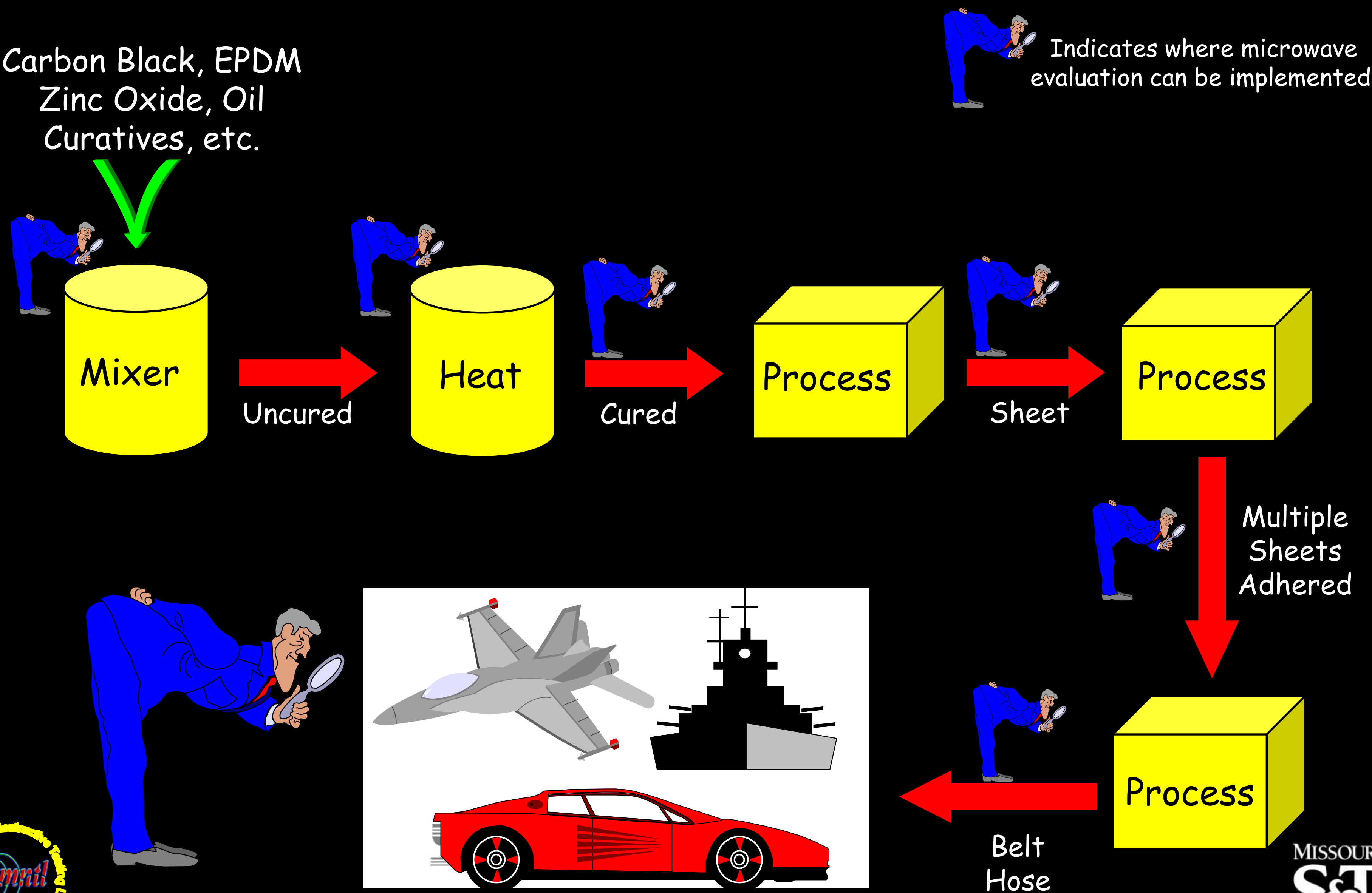
What Can Be Done?

- Detection of defect/inhomogeneity in dielectric composites.
- Evaluation of defect size and properties.
- Production of high-resolution defect images.
- Detection and evaluation of properties of surface cracks, anomalies & perturbations (impact damage) in metals and graphite composites.
- Conductor & dielectric sheet surface profiling.
- Detection and evaluation of corrosion and precursor pitting under coatings.

Stratified Composites - Examples



Life-Cycle Inspection – Rubber Products



MATERIAL CHARACTERIZATION

Material Characterization

- An insulating material becomes polarized in the presence of an electric field.
- Although the process occurs at atomic and molecular level, polarization vector is used to describe the process macroscopically through dielectric constant or properties.
- The ability of a material to store energy (microwave) is denoted by its (relative to free-space) permittivity, ε'_r.
- The ability of a material to absorb energy (microwave) is denoted by its (relative to free-space) loss factor, ε''_r.
- These two parameters are the basis for material characterization.

Material Characterization

$$\bar{p} = q\bar{d} \qquad (C \cdot m)$$

$$\bar{P} = \lim_{\Delta v \to 0}\left[\frac{1}{\Delta v}\sum_{i=1}^{n}\bar{p}\right] \qquad (C/m^2)$$

$$\varepsilon = \varepsilon_o(1+\chi_e) \qquad (F/m)$$

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon' - j\left(\frac{\sigma_e}{\omega}\right)$$

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} = \varepsilon'_r - j\varepsilon''_r$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'}$$

Material Characterization

- Determine a mixture constituent makeup via dielectric mixing models.
- Control mixture properties.
- Correlate measured dielectric properties to chemical, physical & mechanical properties.
- Cure-state monitoring.
- Determine porosity level in TBC, ceramics, refractory, plastics, etc.
- Determine moisture content in materials.

Material Characterization

- Measured dielectric properties, as a function of frequency, yields valuable information about material properties.
- For mixtures (i.e., porosity in TBC) various dielectric mixing models may be used to extract a particular information such as porosity level.

Material Characterization

- **Measurement considerations:**
  - ✓ Material type, i.e. liquid, solid, gas, etc.
  - ✓ On-line or off-line
  - ✓ Required measurement accuracy
  - ✓ Loss tangent of the material
  - ✓ Nondestructive vs. destructive
  - ✓ Non-contact vs. in-contact
  - ✓ Material geometry
  - ✓ Particular information sought

Measurement Methods

- Loaded transmission line:
  - ✓ Completely-filled waveguides.
  - ✓ Completely-filled coaxial lines.
  - ✓ Partially-filled waveguides.
  - ✓ Open-ended waveguides and coaxial lines into either finite-thickness or infinite half-space.
- Cavity resonators.
- Microstrip patches.
- Free-space transmission and/or reflection methods.

Porosity in Polymer

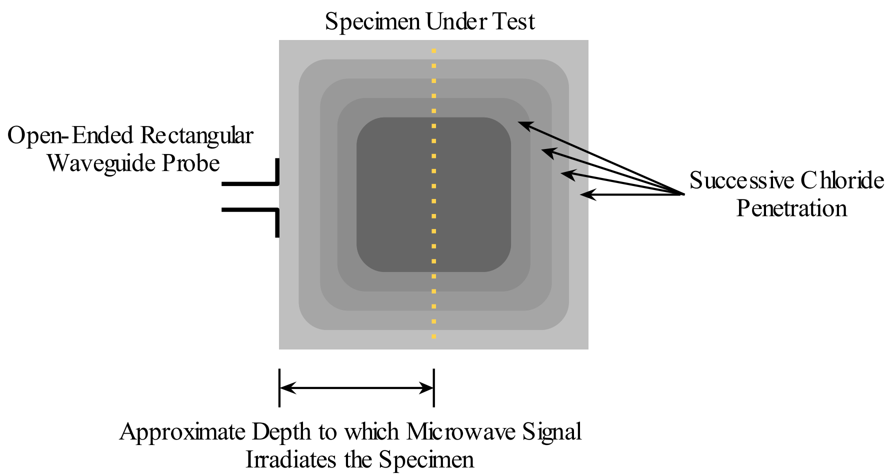
Relative Permittivity

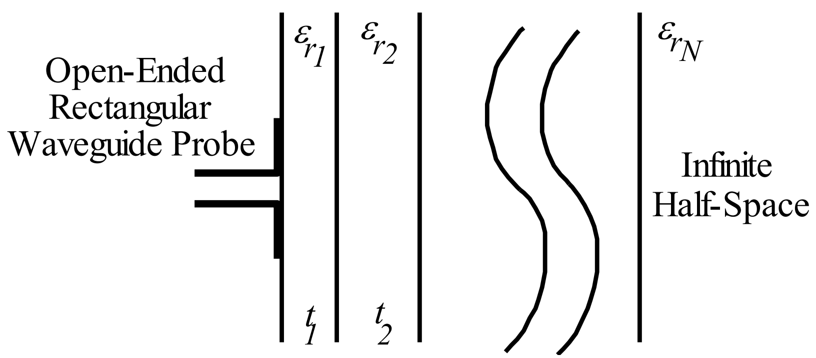
Frequency (GHz)	0%	48.9%	58.7%	68.5%
8.2	2.80	1.87	1.69	1.48
10	2.87	1.84	1.63	1.46
12	2.83	1.88	1.70	1.47
14	2.87	1.83	1.70	1.50
16	2.84	1.82	1.68	1.47
18	2.84	1.84	1.67	1.47

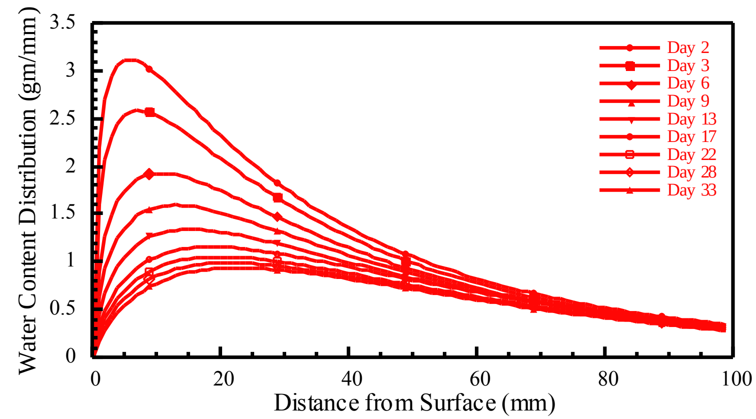
Relative Loss Factor

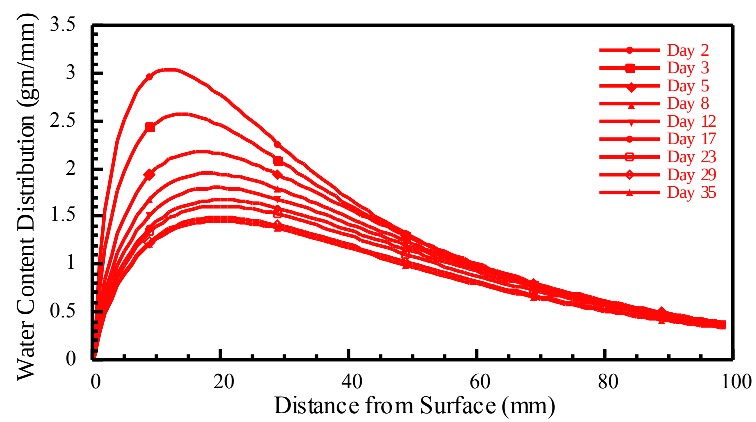
Frequency (GHz)	0%	48.9%	58.7%	68.5%
8.2	0.086	0.032	0.020	0.013
10	0.086	0.034	0.023	0.015
12	0.082	0.033	0.022	0.014
14	0.083	0.033	0.027	0.022
16	0.077	0.026	0.021	0.019
18	0.068	0.027	0.025	0.014

Salt Water Permeation in Mortar



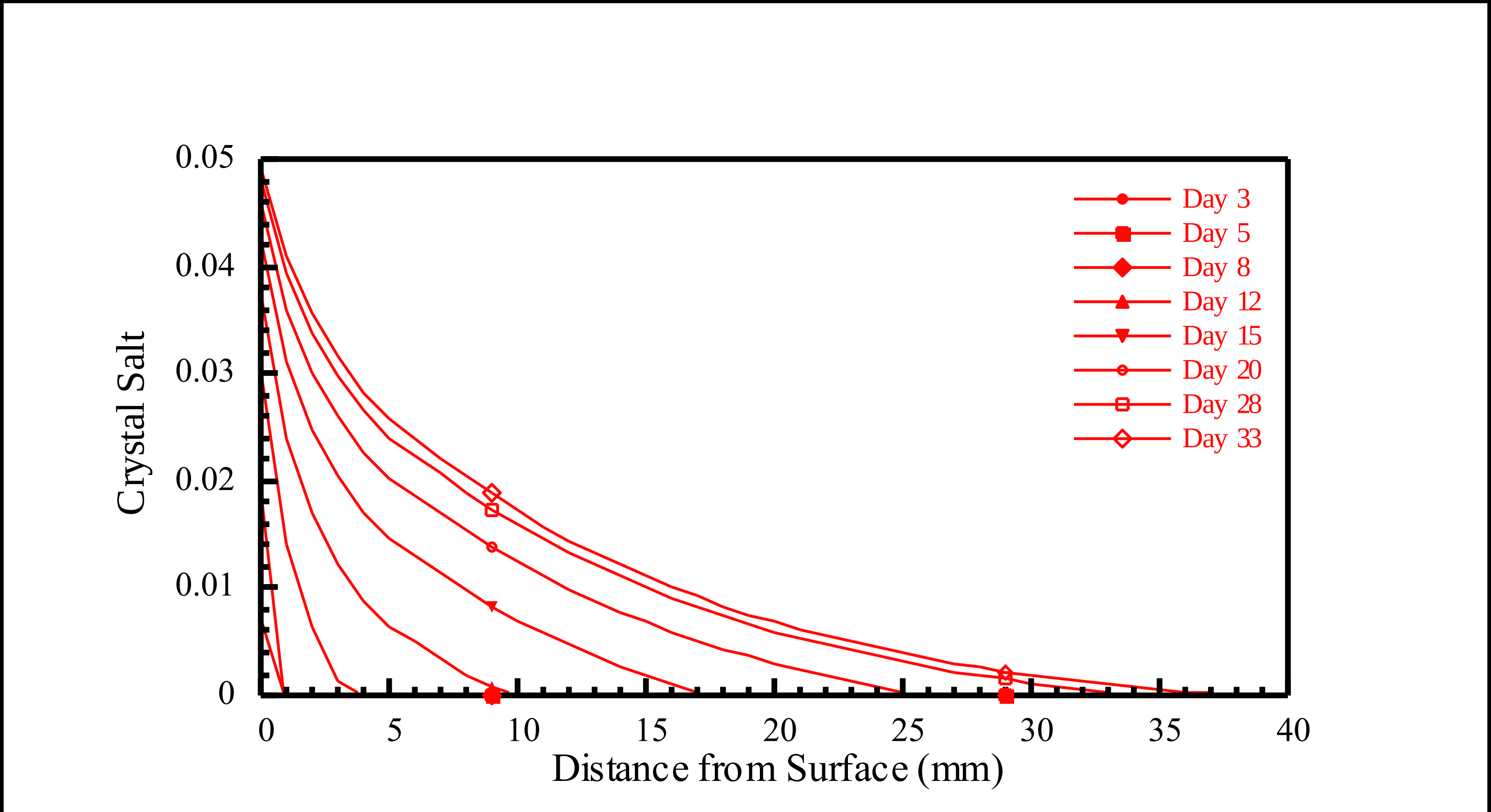






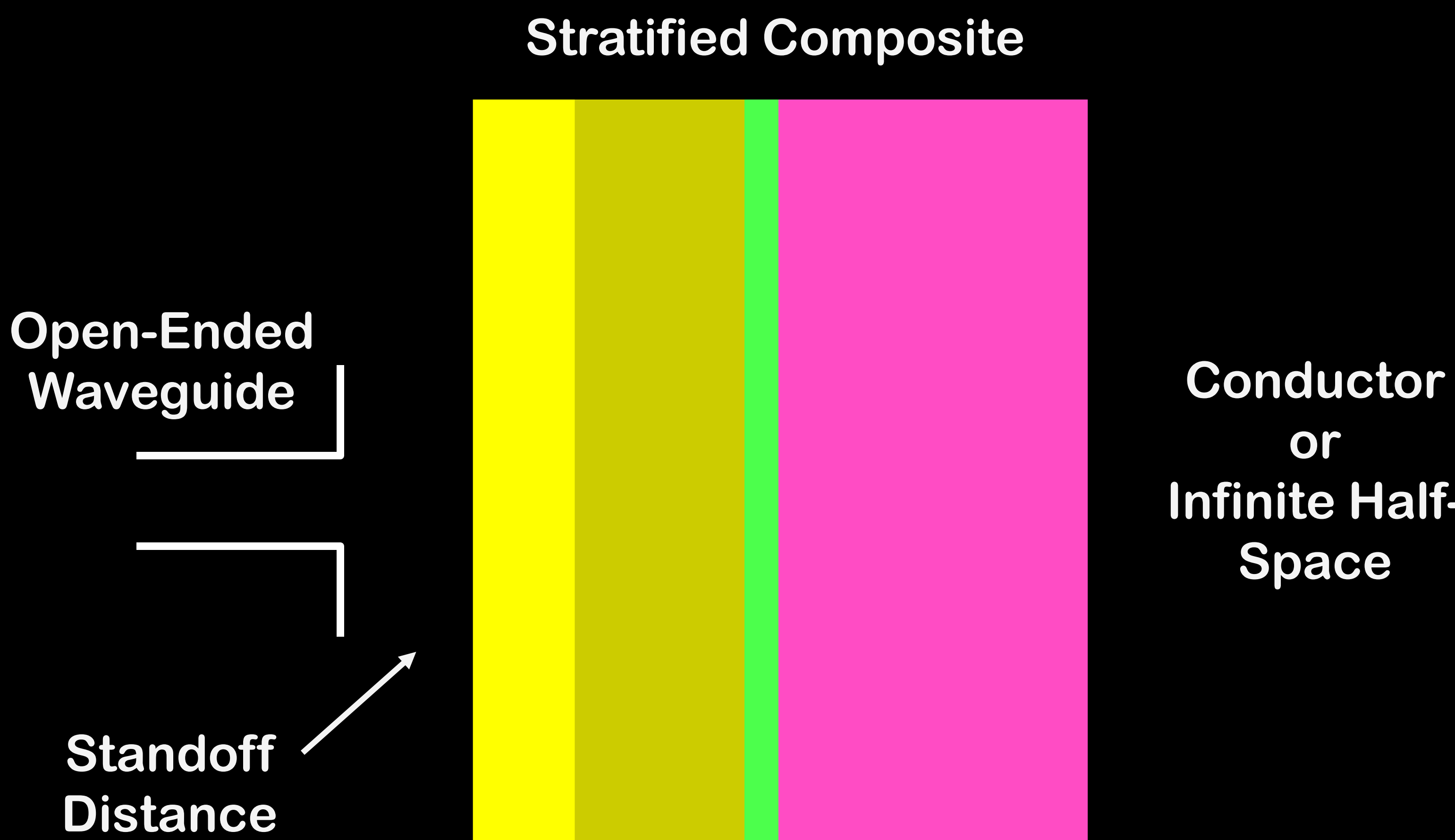
Salt Water Permeation in Mortar

Recalculation of Cyclical Crystal Salt Deposition in Mortar Blocks



GENERAL MULTI-LAYER COMPOSITES

General Multi-Layer Structure



General Multi-Layer Structure

$$\overline{E}(x,y,0) = V_{i_o}\overline{e}_o(x,y) + \sum_{n=0}^{\infty} V_{r_n}\overline{e}_n(x,y)$$

$$\overline{H}(x,y,0) = Y_o V_{i_o}\overline{h}_o(x,y) - \sum_{n=0}^{\infty} Y_n V_{r_n}\overline{h}_n(x,y)$$

$$V_{r_n} = \iint_S \overline{E}(x,y,0)\bullet\overline{e}_n(x,y)\,dxdy$$

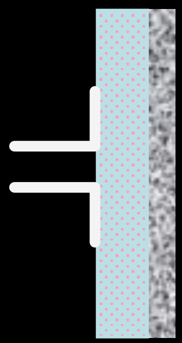
$$Y = G + jB = \frac{\iint_S \left[\overline{E}(x,y,0)\times\overline{W}(x,y,0)\right]\bullet\hat{a}_z\,dxdy}{\left[\iint_S \overline{E}(x,y,0)\bullet\overline{e}_o(x,y)\,dxdy\right]^2}$$

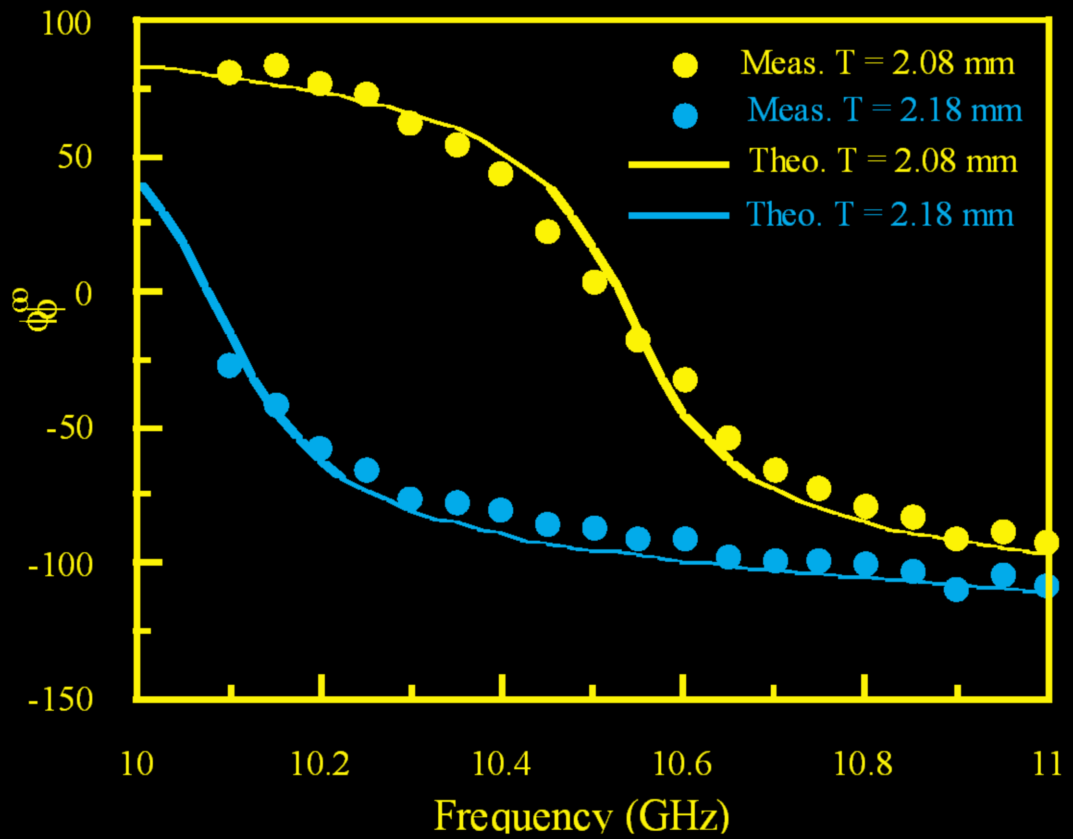
$$\overline{W}(x,y) = \overline{H}(x,y,0) + \sum_{n=0}^{\infty} Y_n\overline{h}_n(x,y)\iint_S \overline{E}(\eta,\zeta,0)\bullet\overline{e}_n(\eta,\zeta)\,d\eta\, d\zeta$$

$$\Gamma = |\Gamma| e^{j\phi} = \frac{1-Y}{1+Y}$$

Coating Thickness - Contact

Rubber with 12.4 - j2.4





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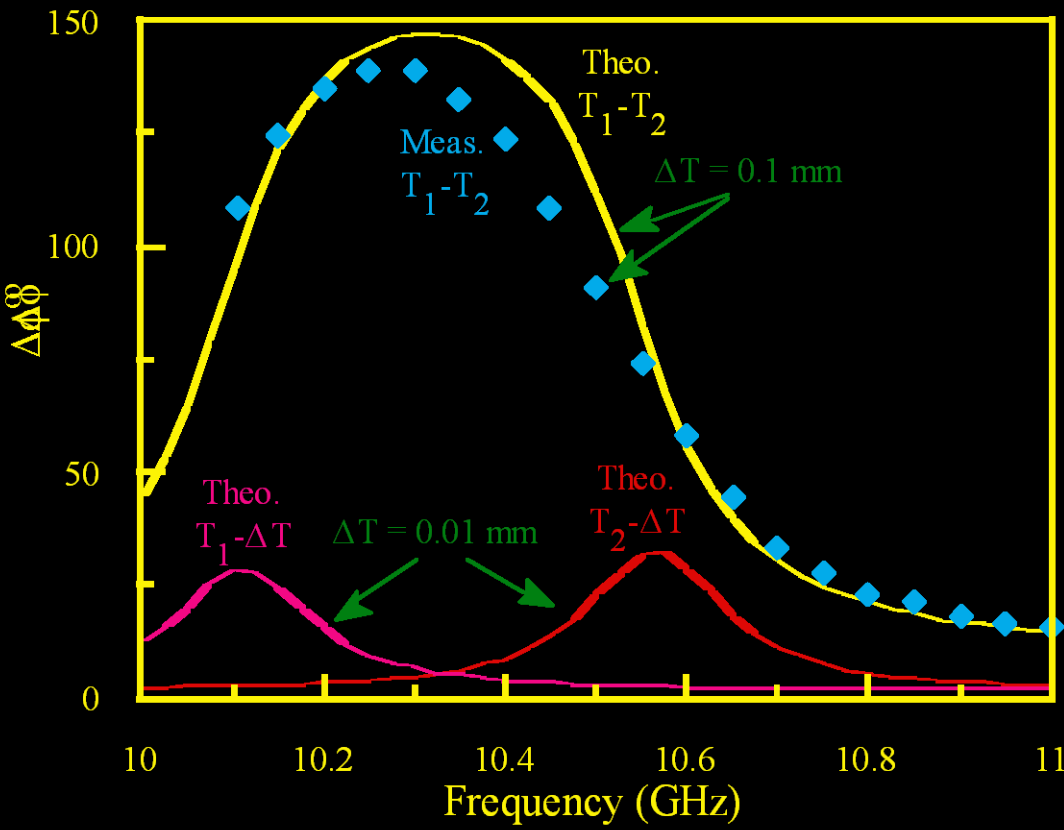
Coating Thickness



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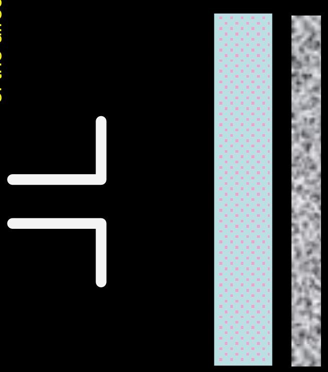
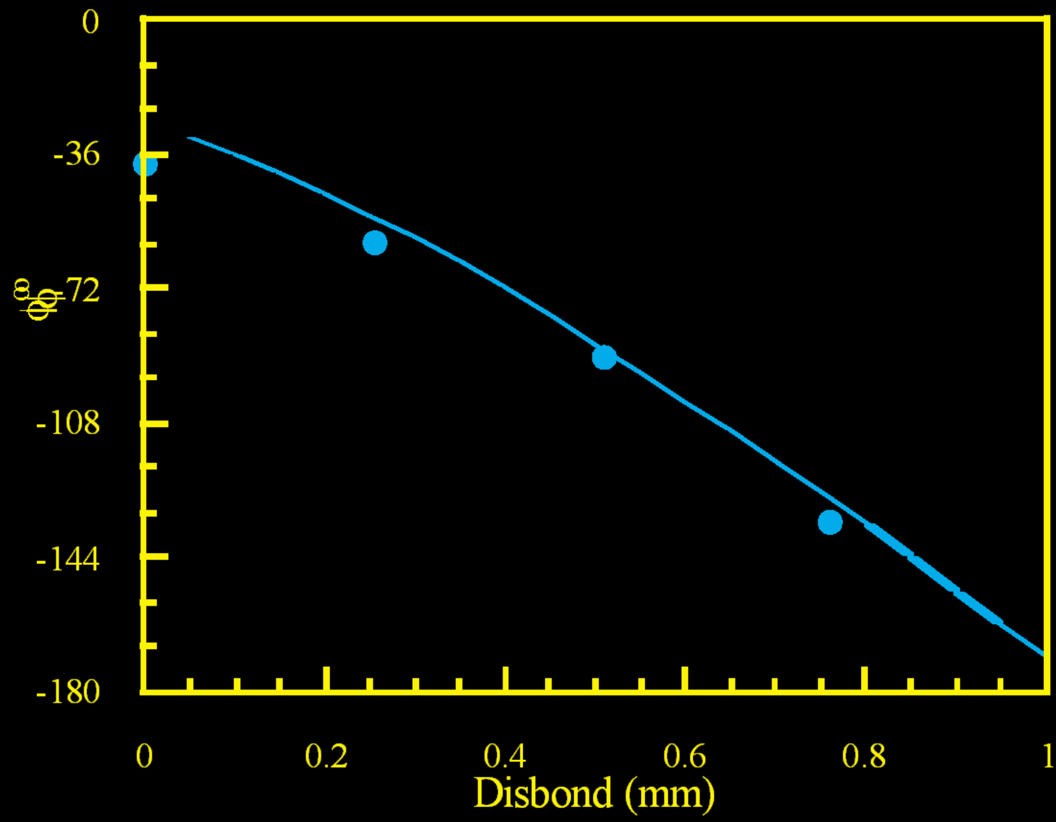
Non-Contact Disbond

7.55 mm-Thick Rubber with 8.4 - j0.9
10 GHz @ 5 mm Standoff





IMAGING FOR NDT&E

NDT&E Imaging Constraints

- You can simulate and measure changes in complex reflection and transmission coefficients and deduce much about the characteristics of a structure.
- This is generally time-consuming, off-line and not real-time.
- In many NDT applications it is first and foremost important to know whether something is wrong (i.e., NDT) and then maybe evaluate its properties (i.e., NDE).

NDT&E Imaging Constraints

- Operators and technicians need quick qualitative tools first – an image of a composite showing an area of potential damage.
- In some applications slight damage may not be tolerated, while in others it may be OK until the next inspection or when a threshold is crossed.
- Constraints on imaging capabilities and attributes vary widely in practice – corrosion in rebar vs. crack in aircraft fuselage, or disbond in a heat tile!

NDT&E Imaging Constraints

- Other important constraints include:
  - ✓ Cost
  - ✓ Ease of use
  - ✓ Portability
  - ✓ Rapid image production
  - ✓ Real-time image production
  - ✓ Resolution – spatial and depth
  - ✓ Personnel training
  - ✓ On-line needs
  - ✓ Level of technical comfort – commercial scanners, UT, EC, etc.

NEAR-FIELD TECHNIQUES

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Near-Field Methods

- **Near-field imaging using “standing-wave” or “single” reflectometers:**
  - ✓ Simple, inexpensive, small, handheld, portable
  - ✓ Commonly CW
  - ✓ High spatial resolution – resolution is probe size dependent
  - ✓ No depth resolution
  - ✓ Easily adaptable to commercially-available scanning platforms
  - ✓ Provides a great deal of information
  - ✓ Evaluation of properties not readily possible

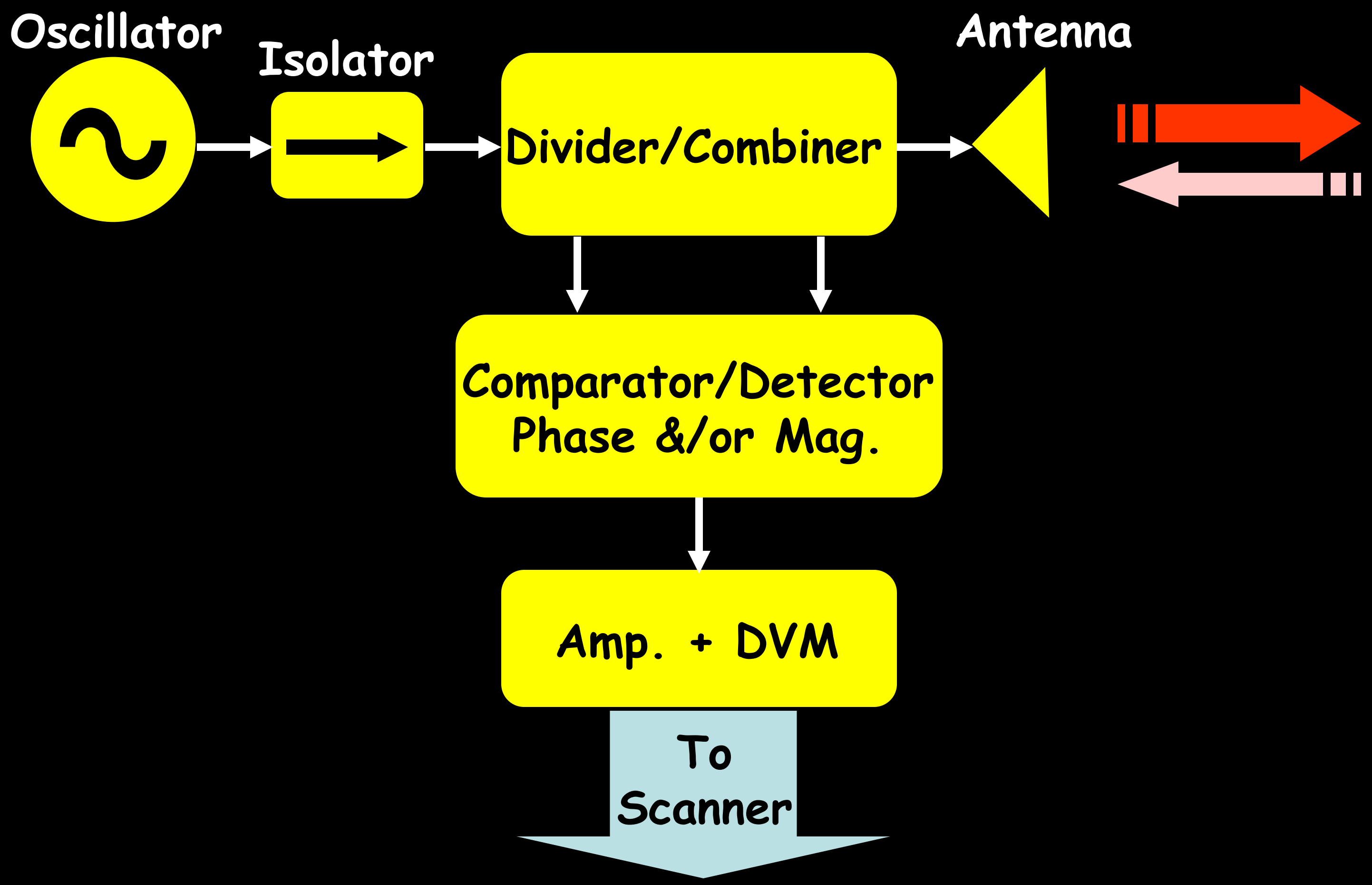
Near-Field Imaging

- **Near-field imaging using coherent imaging systems or reflectometers:**
  - ✓ Complex in design
  - ✓ Commonly CW but not always
  - ✓ High spatial resolution – resolution is probe size dependent and also synthetic aperture focusing is possible
  - ✓ Provides depth resolution
  - ✓ Relatively costly and larger
  - ✓ Generally not handheld, but yet portable
  - ✓ Not always easily adaptable to commercially-available scanning platforms
  - ✓ Evaluation of properties is possible using proper forward and inverse formulations.

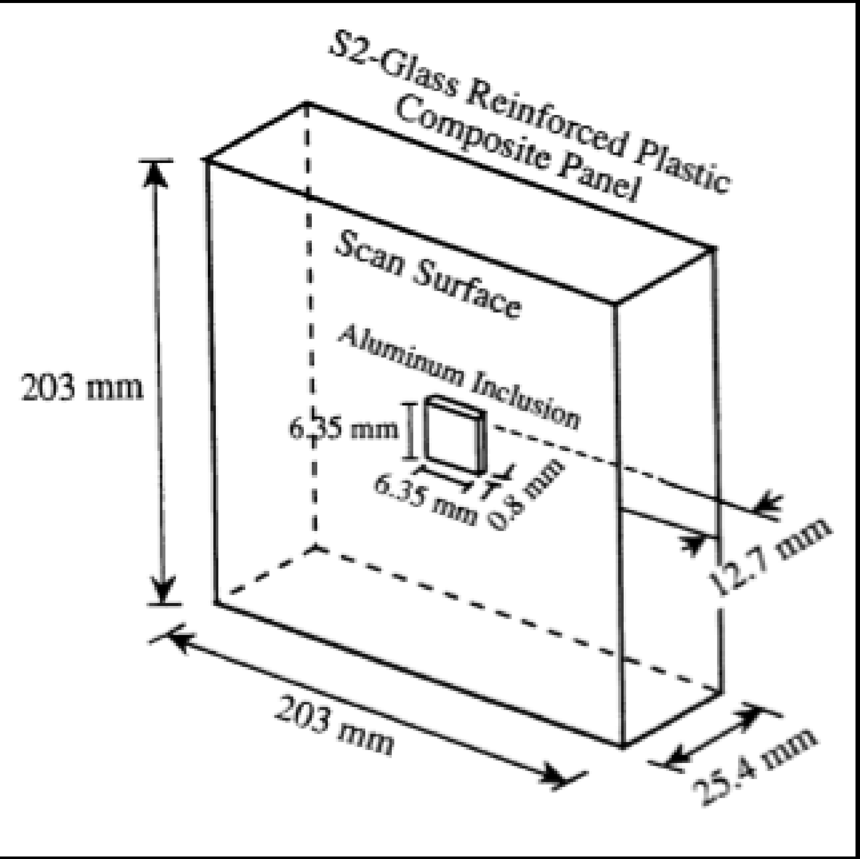
Near-Field Imaging

- Great usefulness for a variety of applications.
- Particularly suitable to inspect:
  - ✓ Dielectrics for embedded flaws
  - ✓ Metals for surface cracks
  - ✓ Stratified composite structures
  - ✓ Corrosion under paint

General Reflectometer Schematic

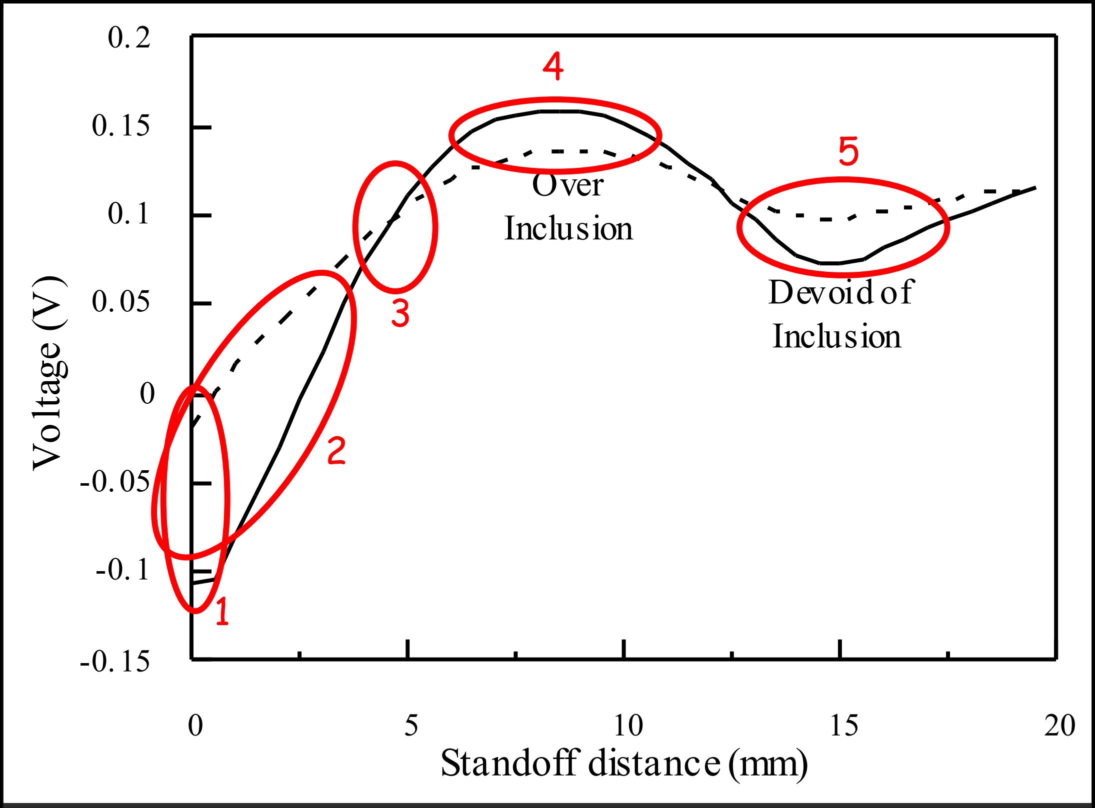


Glass with Aluminum Inclusion



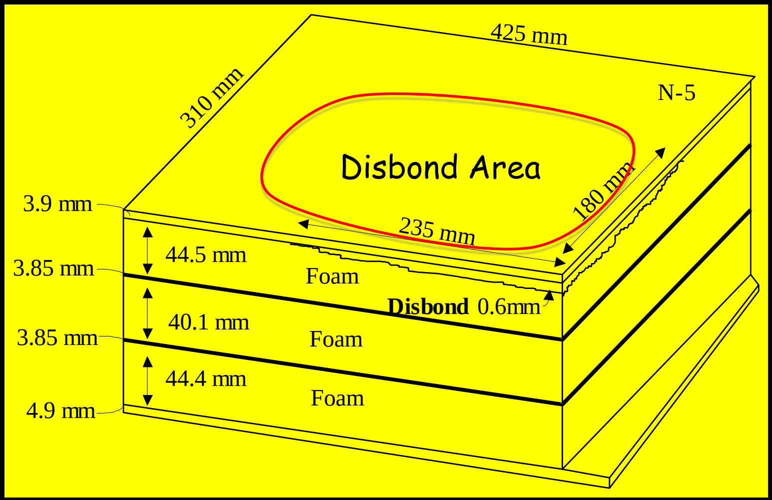
Standoff Distance Influence

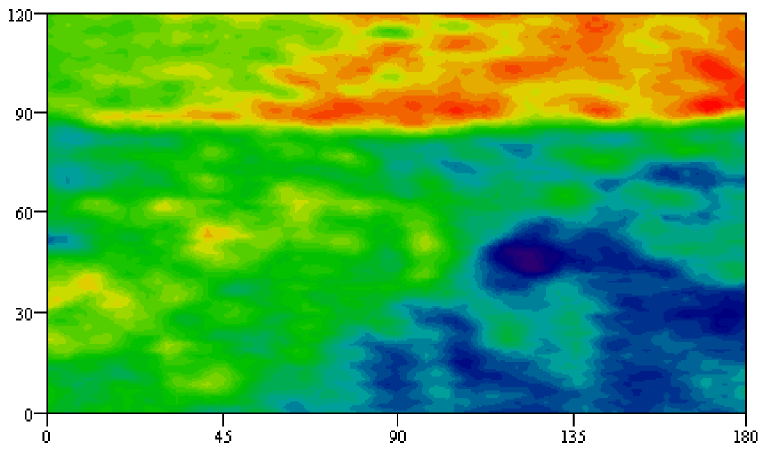
1. *Contact* measurement, max. signal difference.
2. High level of signal difference, but very sensitive to standoff distance change.
3. Crossover, no distinction between inclusion and no inclusion.
4. Sufficient signal difference while able to tolerate some standoff distance change.
5. Similar to 4, but image gray level flips.



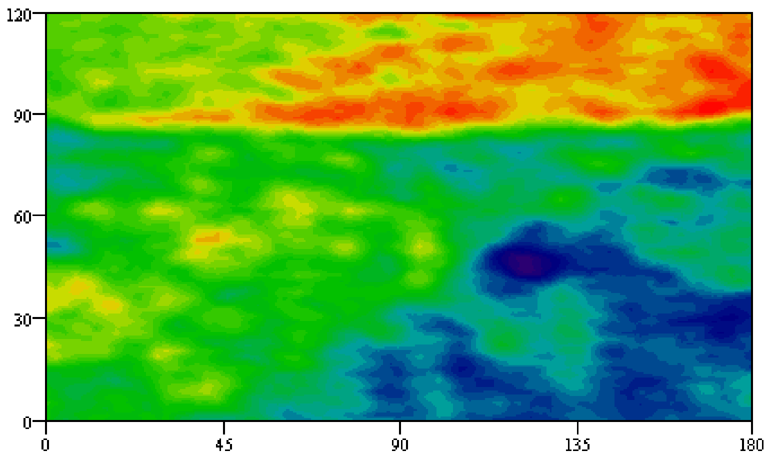
Disbond in Thick Composite

Using Standoff Distance Compensator and at Three Different Standoff Distances

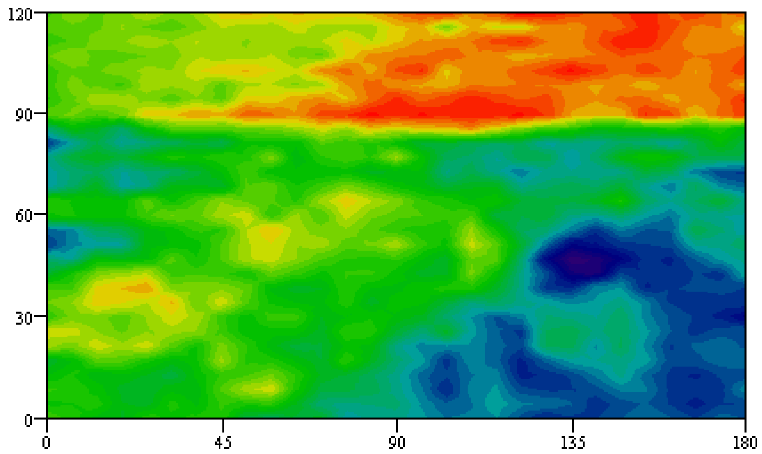




1.5 mm



3.5 mm



2.5 mm

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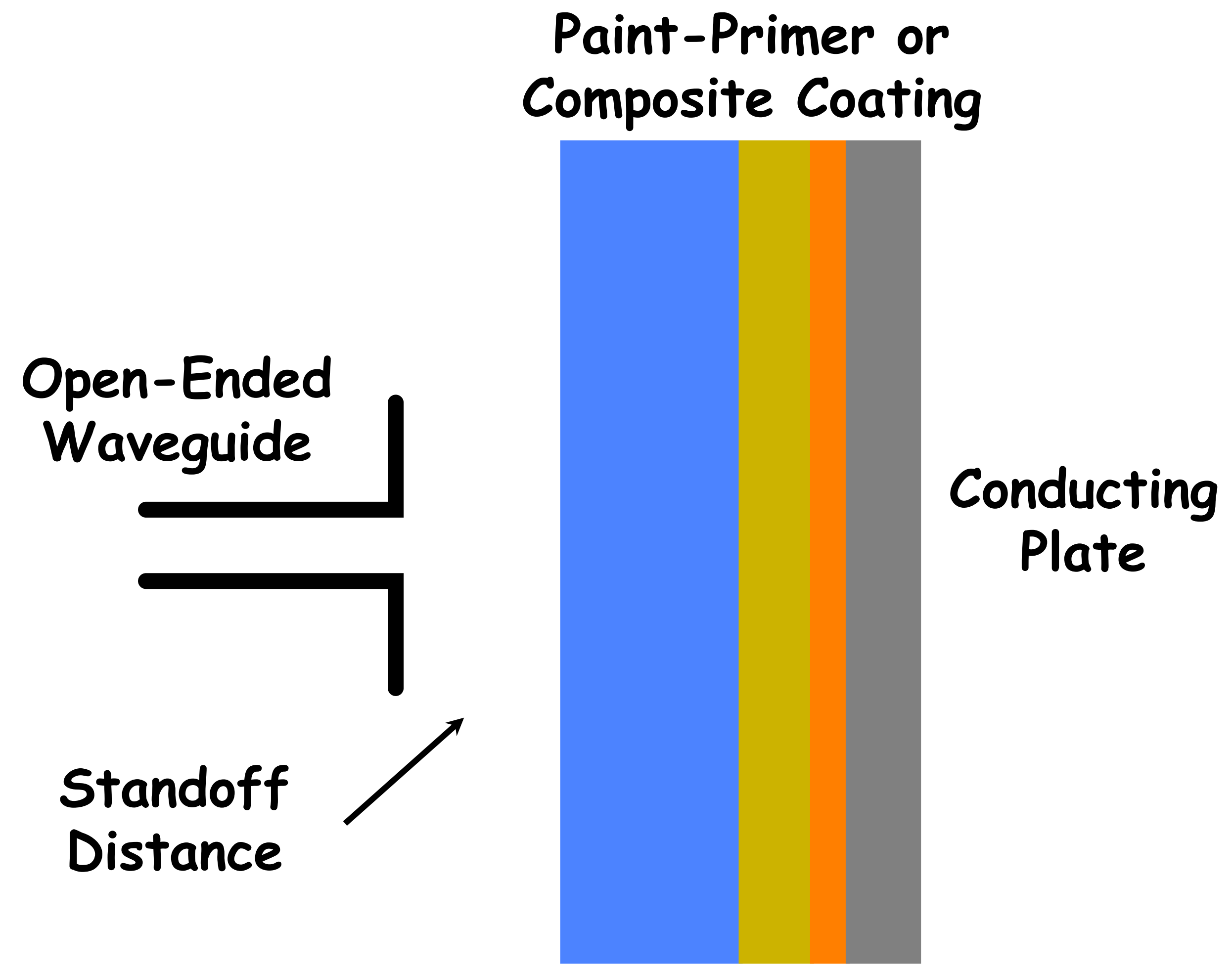
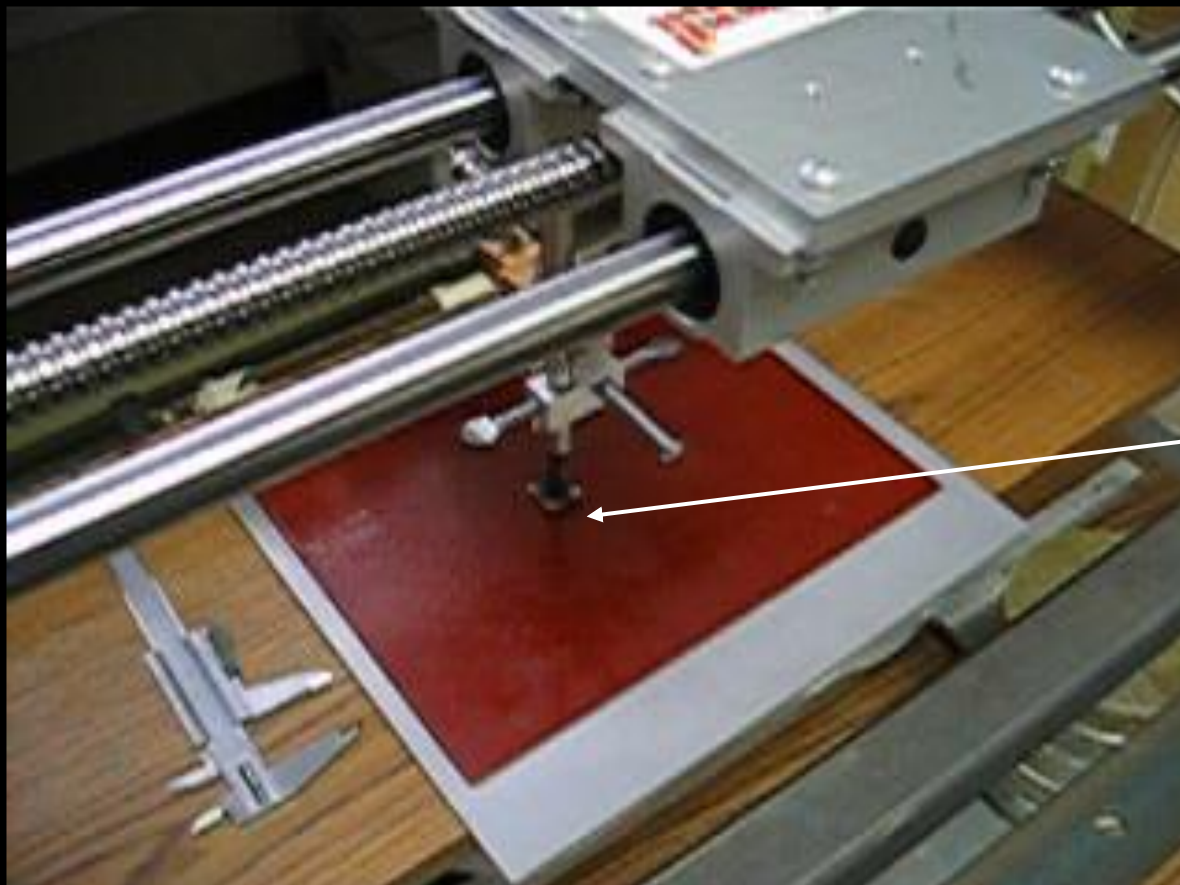
CORROSION and PRECURSOR PITTING

Background


Paint-Primer or
Composite Coating
Open-Ended
Waveguide
Conducting
Plate
Standoff
Distance

Corrosion under Paint



~2' by 2" Corrosion patch in steel plate (painted over several times in the picture to the left)

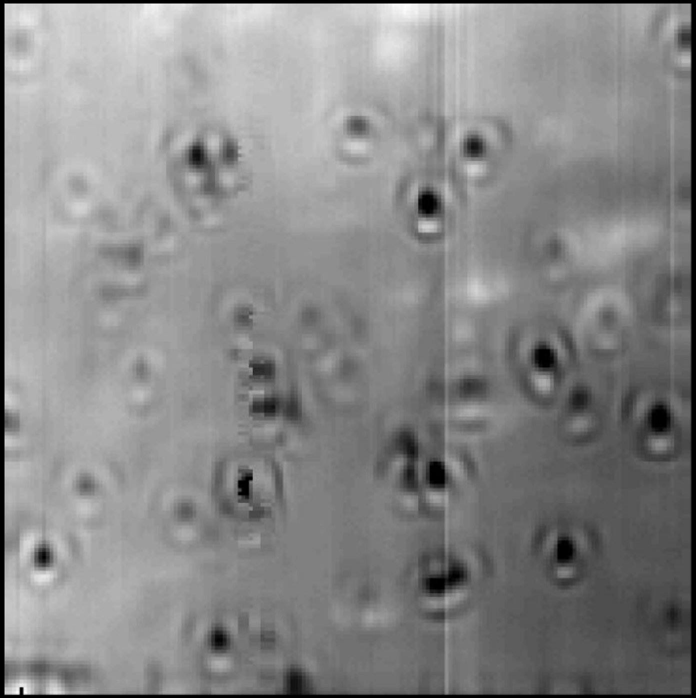
Click on the above picture to view video

Pitting

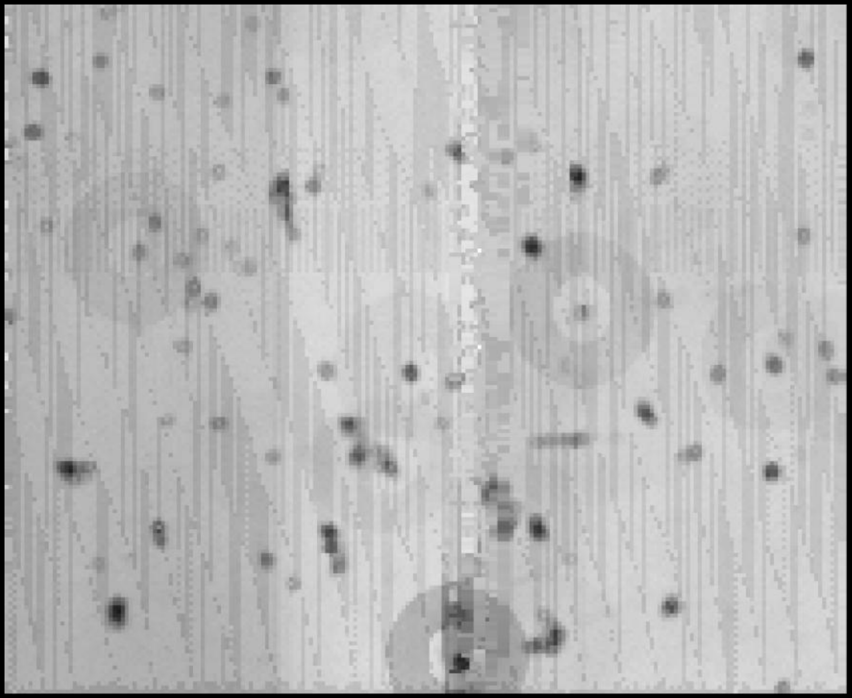
- Detection of corrosion precursor pit is important since if detected initiation of corrosion process is detected.
- Once a pit is detected its dimensions, and in particular information about its depth can be very useful maintenance decision process.
- In some applications, a pit can be "sanded off" to inhibit stress corrosion initiation.
- Pits are very small and hence difficult to detect when exposed and particularly under paint.

Pitting - Microwave & EC

Microwave



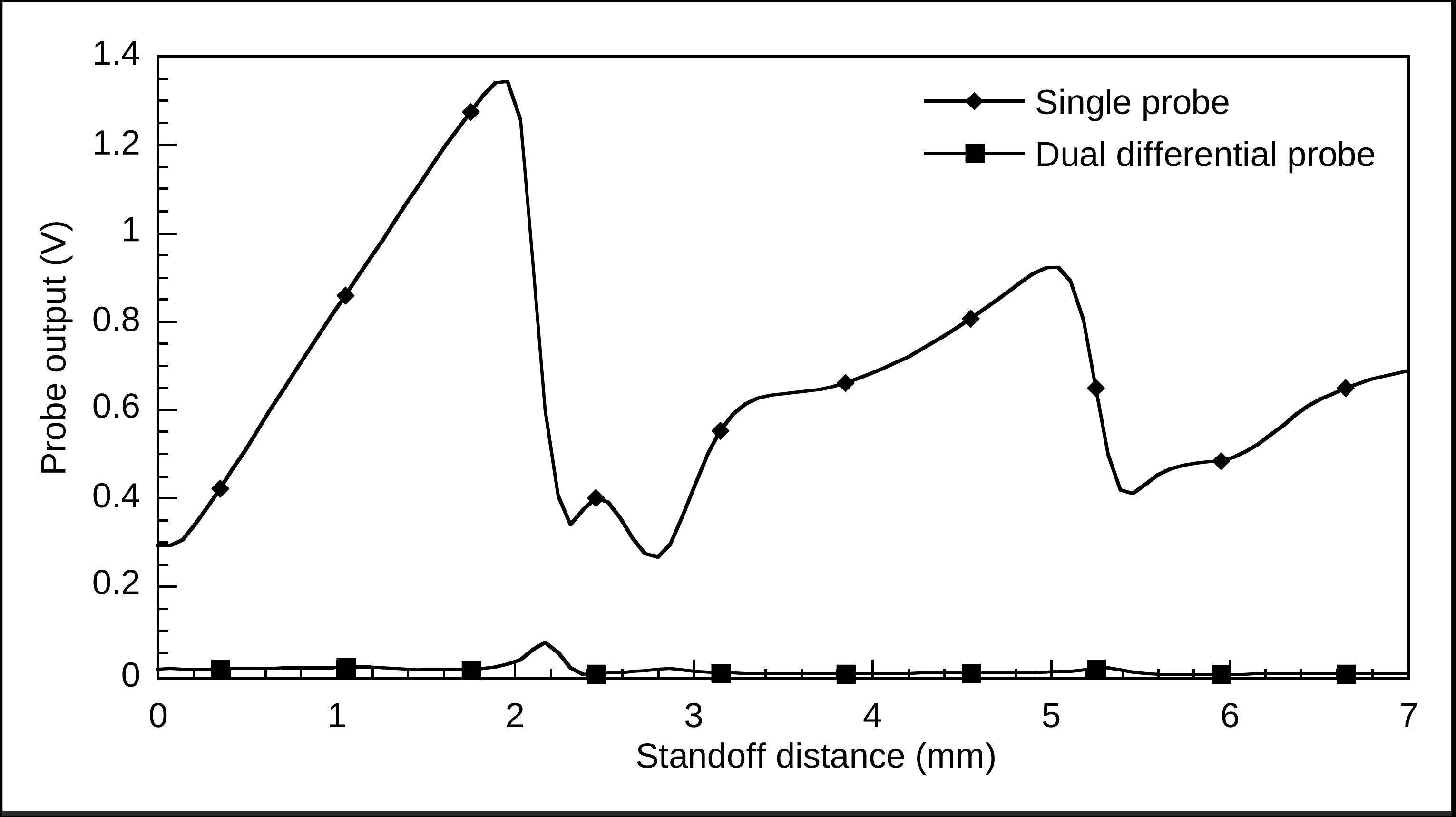
EC



Dual Differential Probe

- Capable of automatic removal of standoff distance variations.
- Sensitive to the presence of small anomalies.
- Produces image of boundaries of spatially extended anomalies.
- Indicates non-uniformity of spatially extended corrosion or anomaly.
- Simple, rugged and scanner adaptable.
- Pit sizing.

Standoff Removal



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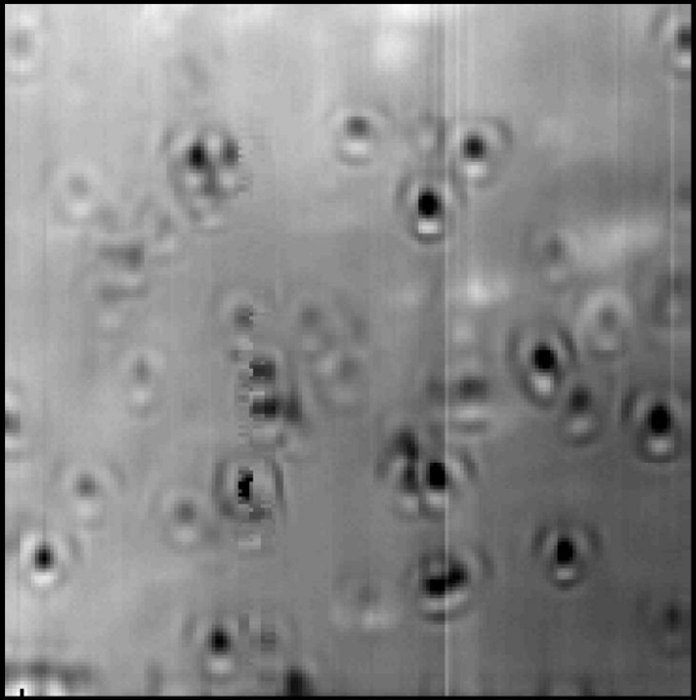
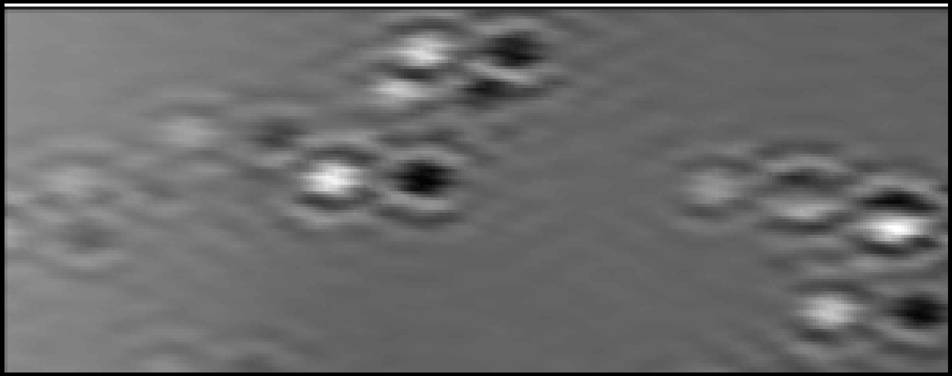
Dual Probe vs. Single Probe

Natural Pits
Ka-Band Single Probe

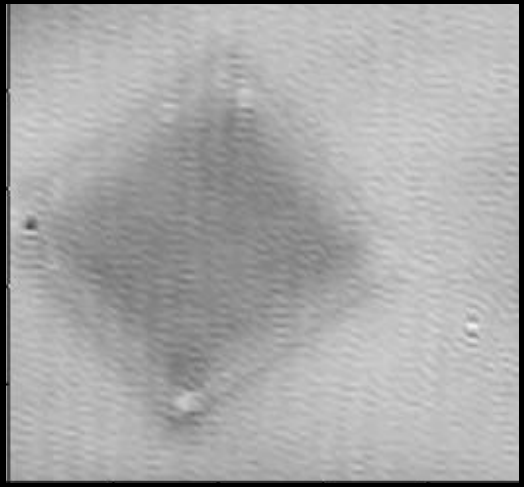


Natural Pits
V-Band Dual Probe

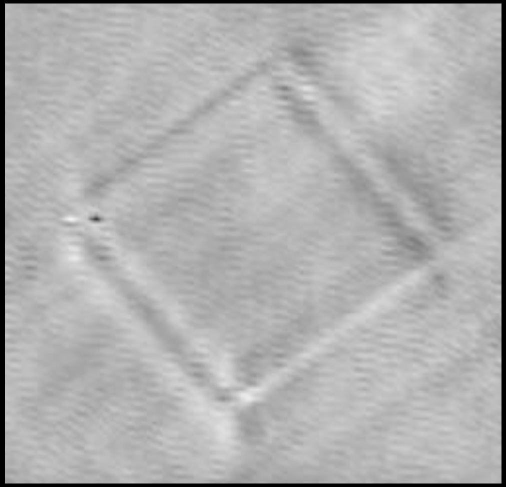


Corrosion under Paint

V-Band Single Probe



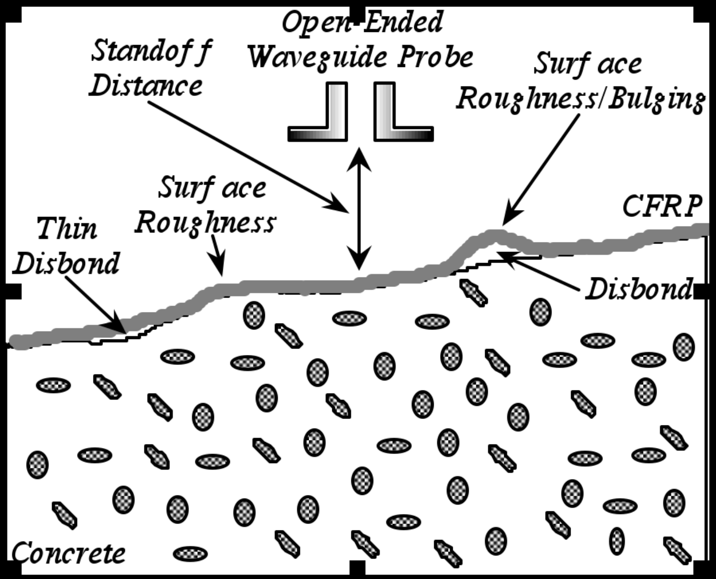
V-Band Dual Probe



DUAL POLARIZATION TECHNIQUE

CFRP-Strengthened Structures

- Concrete structures may be strengthened or rehabilitated with unidirectional CFRP sheets.
- Transmission through CFRP is highly polarization dependent.
- Two normal polarizations give different & useful information.
- Orthogonal polarization dependent of standoff and disbond.
- Parallel polarization data can be used to monitor and correct for standoff distance change.



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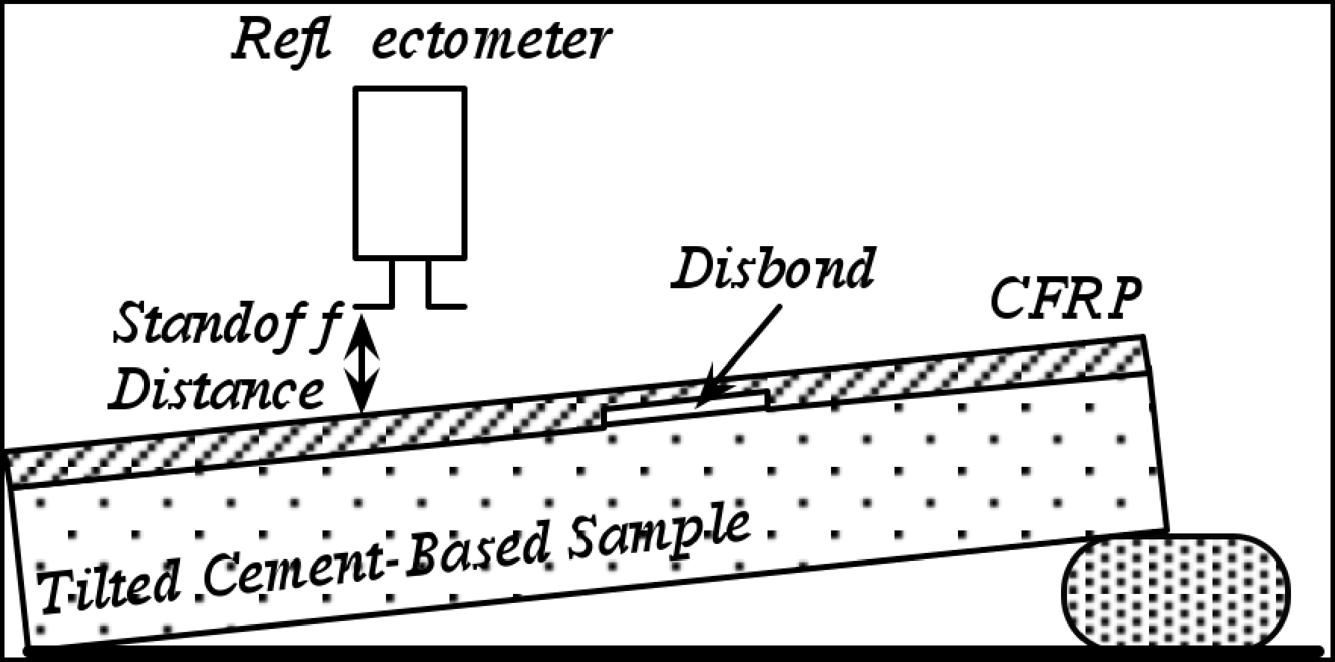
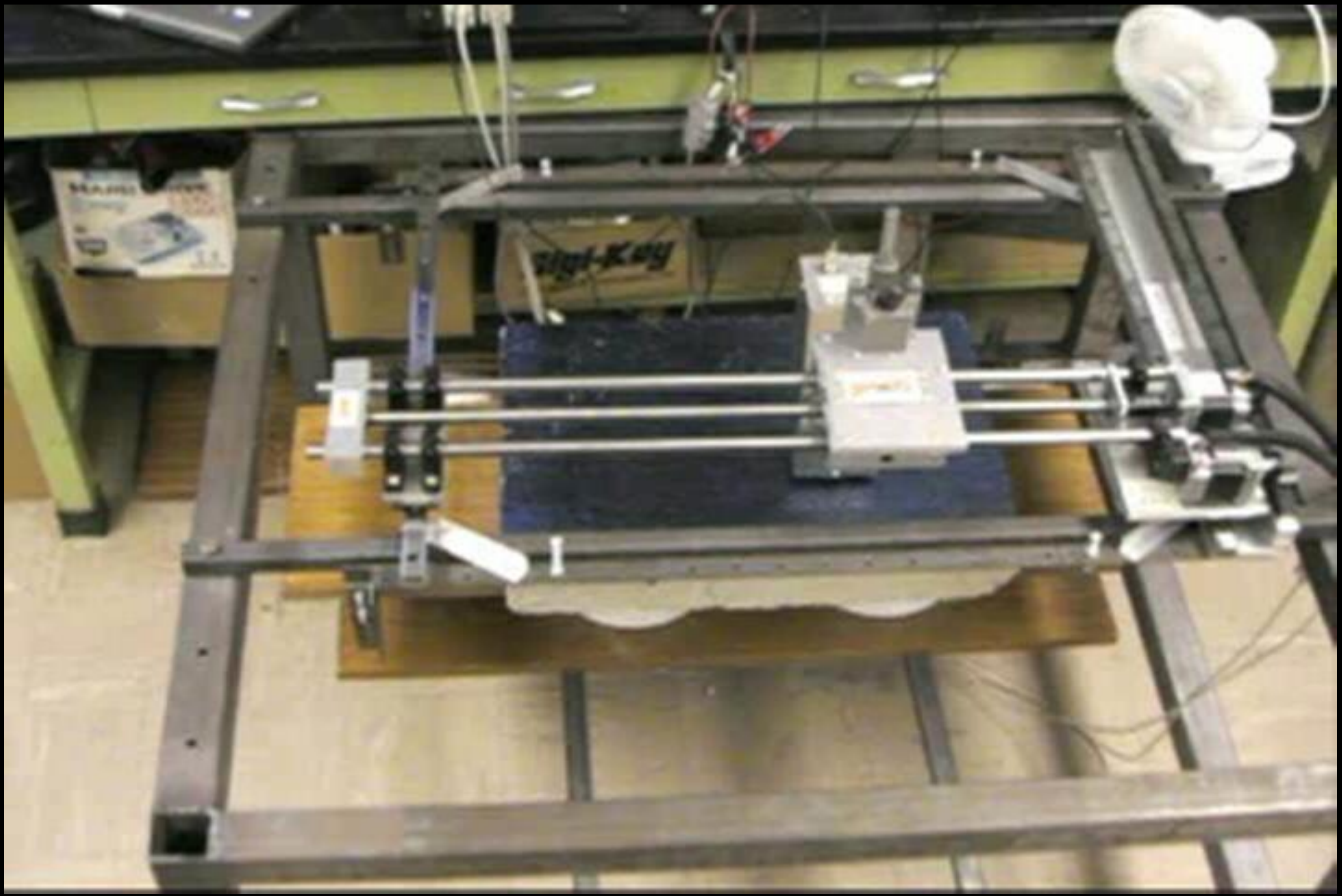
Dual Polarized Probe



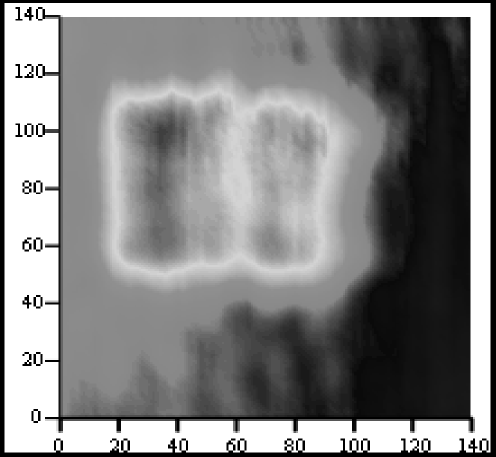
Dual Polarized Probe Video



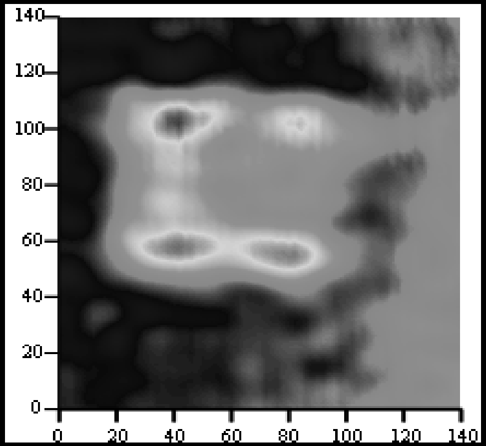
Click on the above picture to view video

Laboratory Results - Tilted

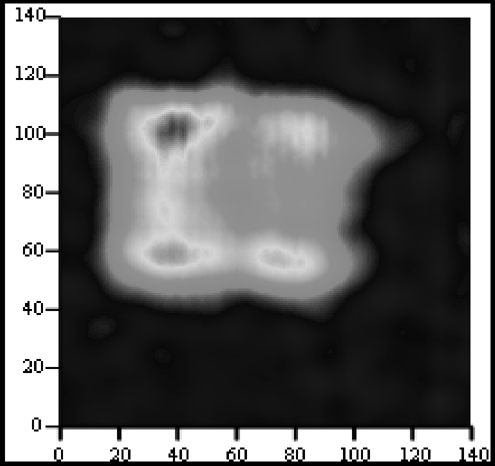
Parallel



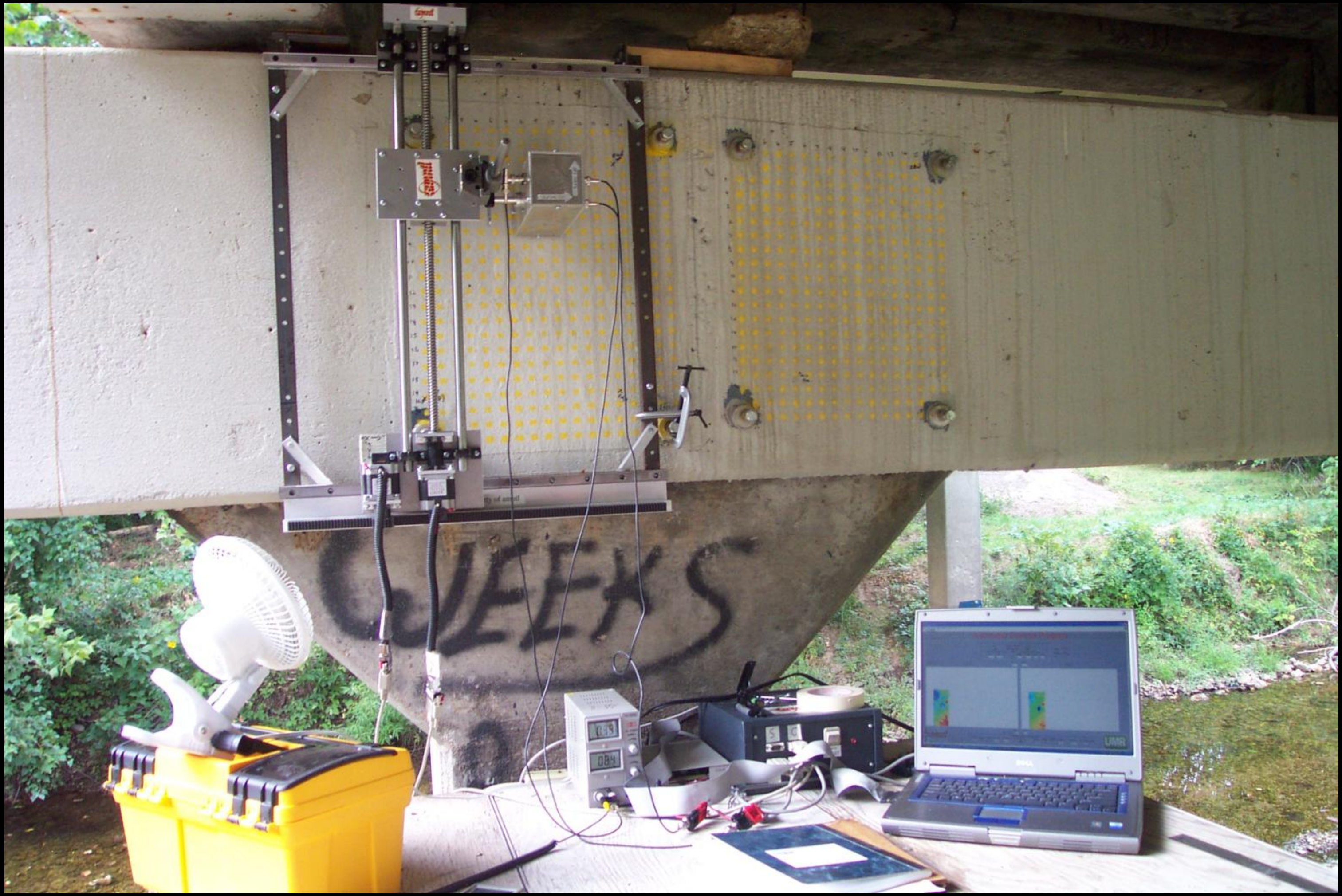
Perpendicular



Compensated

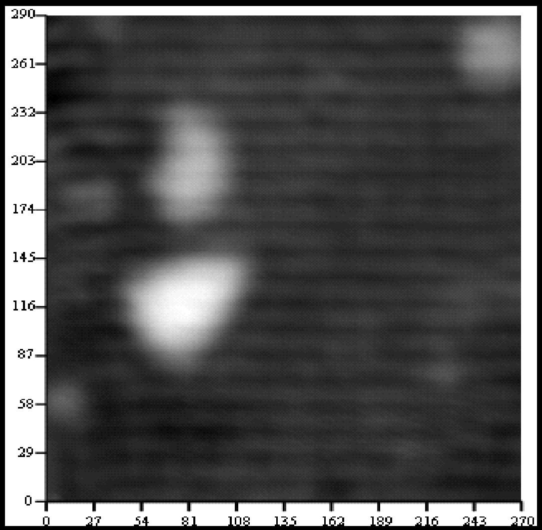


Dual Polarized Probe

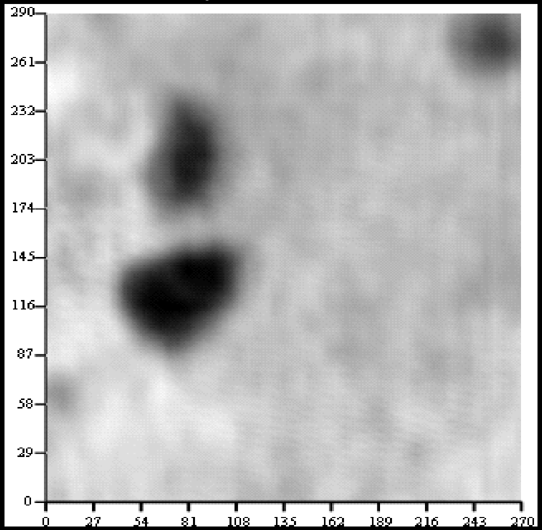


Field Results Abutment

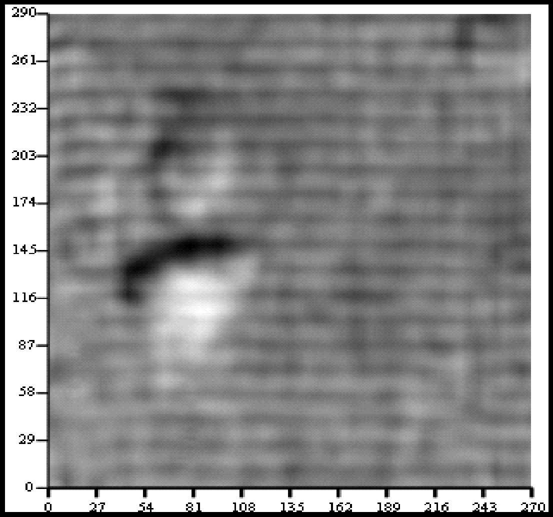
Parallel



Perpendicular



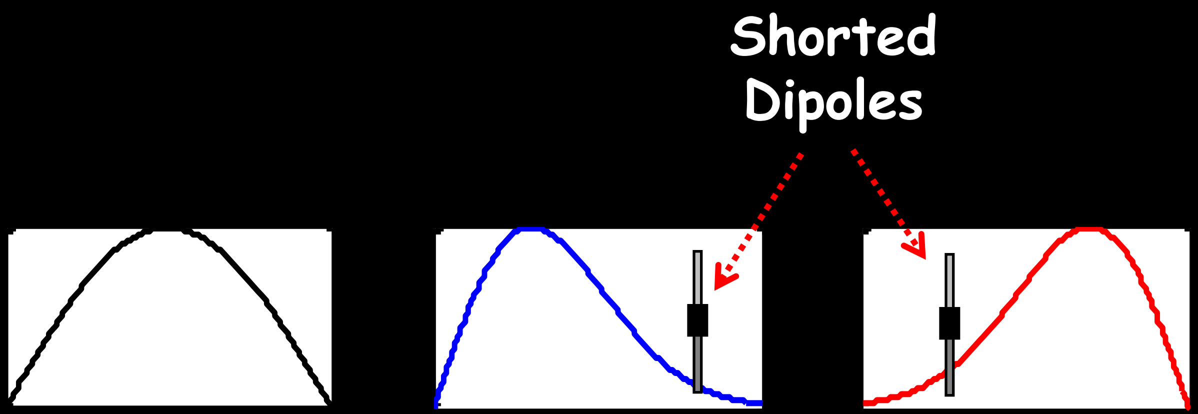
Compensated



DUAL MODULATED APERTURE TECHNIQUE

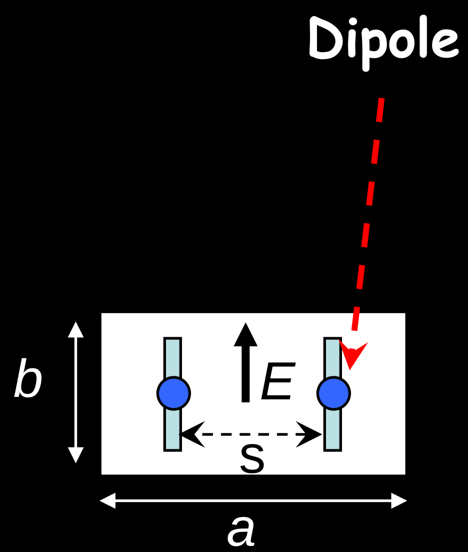
Foundation

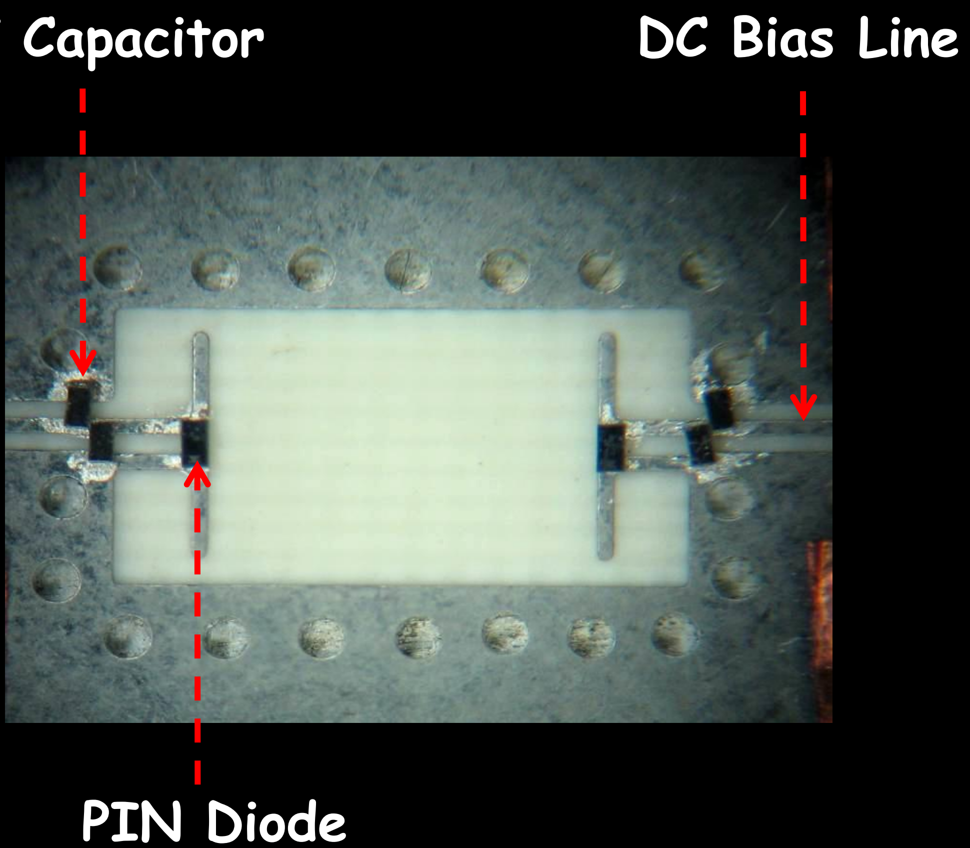
- Switch between two mirror electric field distributions synthesized over a single aperture.
- Both distributions interact with their surroundings in a similar manner.
- By making one of them ON at a time, two signals can be measured at any point.
- Standoff distance variation can be compensated for by subtracting the measured signals. These signals are measured non-coherently using a standing wave probe.



(a) (b) (c)

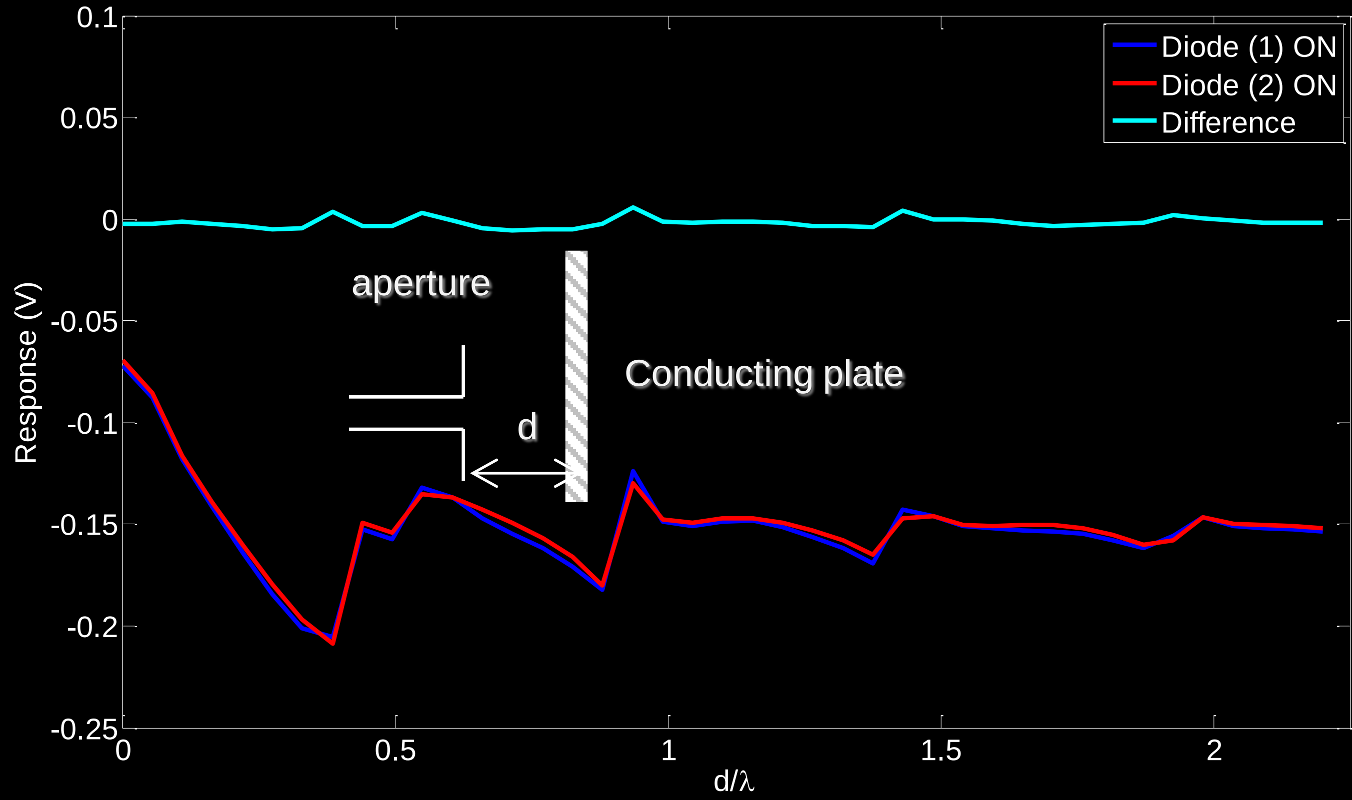
Prototype Probe Aperture





Dipole Length ~3mm and Dipole Interspacing ~5.3 mm

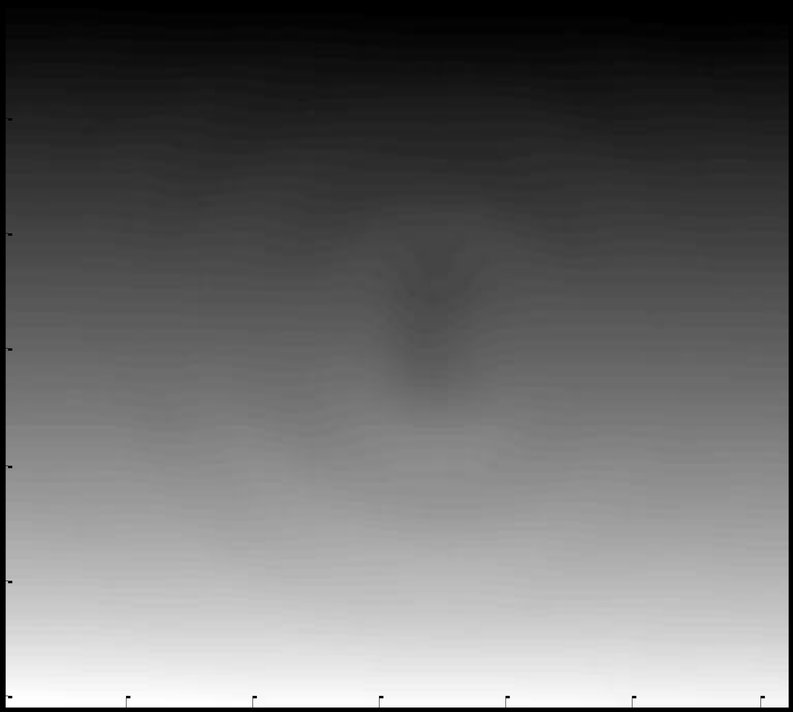
Standoff Distance Response



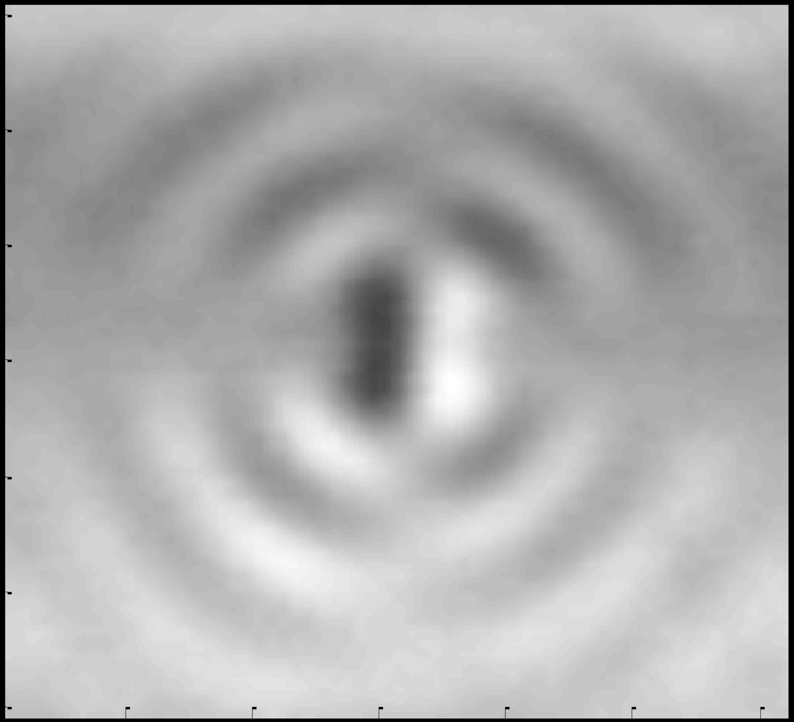
Missouri S&T

2D Image – Tilted Panel

Single Aperture Probe



Dual Modulated Aperture Probe



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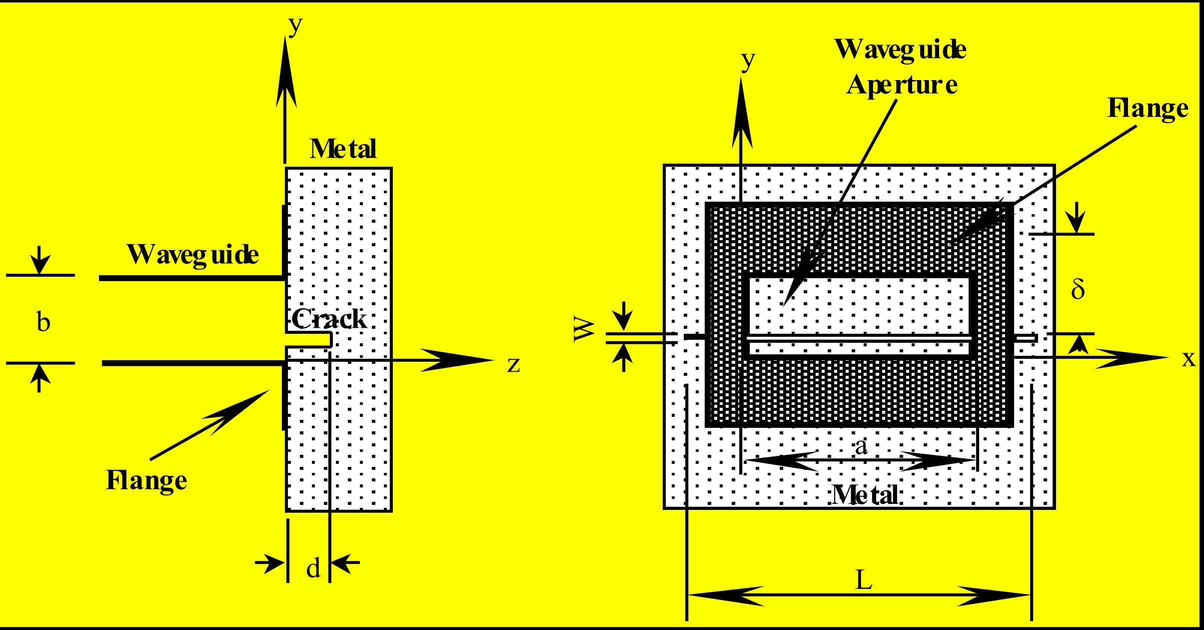
SURFACE CRACK DETECTION and EVALUATION

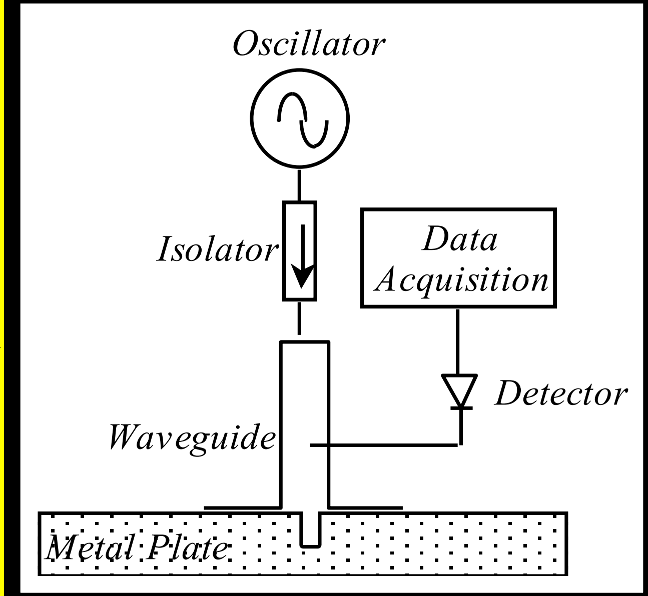
Foundation

- Metals terminating an open-ended probe aperture, cause total reflection of signal.
- Surface cracks perturb induced surface currents, thereby changing the reflection properties of the surface.
- Detection of changes in the reflection properties yields the presence of a crack.
- Characteristics of the reflection properties yield geometrical information.
- Can detect filled cracks and those under coatings.
- Detection is metal type independent.

Foundation



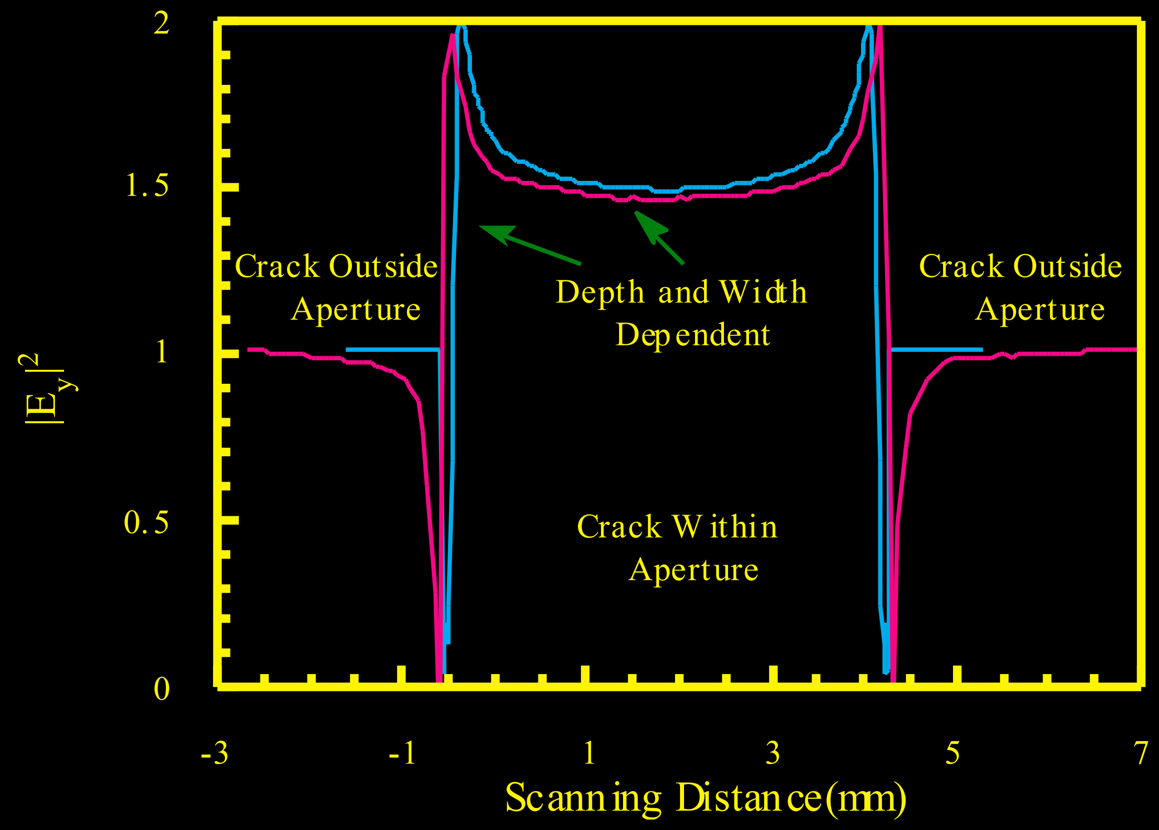
y
Metal
Waveguide
b
Crack
z
Flange
d
y
Waveguide Aperture
Flange
δ
W
x
a
Metal
L



Oscillator
Isolator
Data Acquisition
Detector
Waveguide
Metal Plate

Results

W = 0.55 mm, D = 2.5 mm @ 24 GHz



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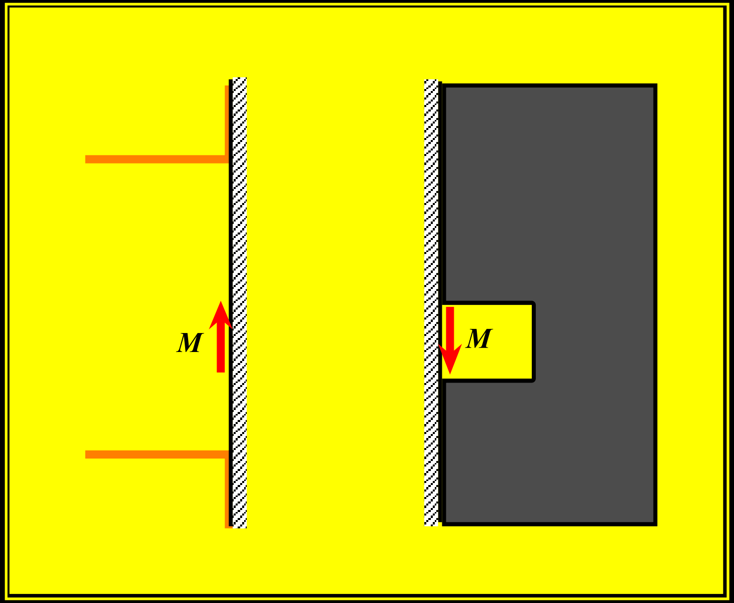
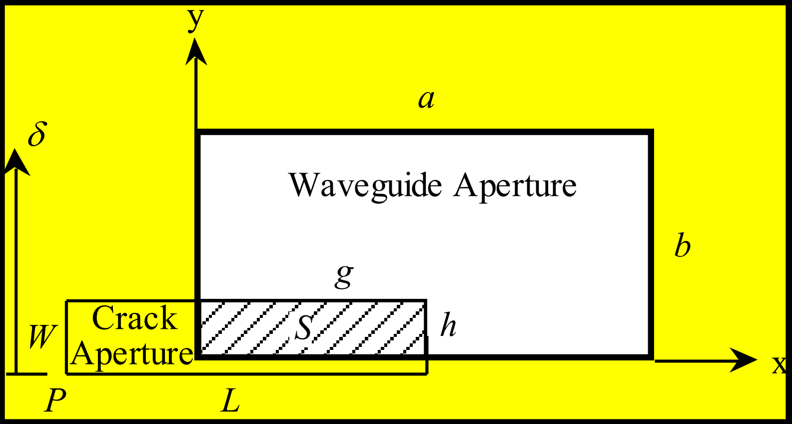
Modeling Approaches

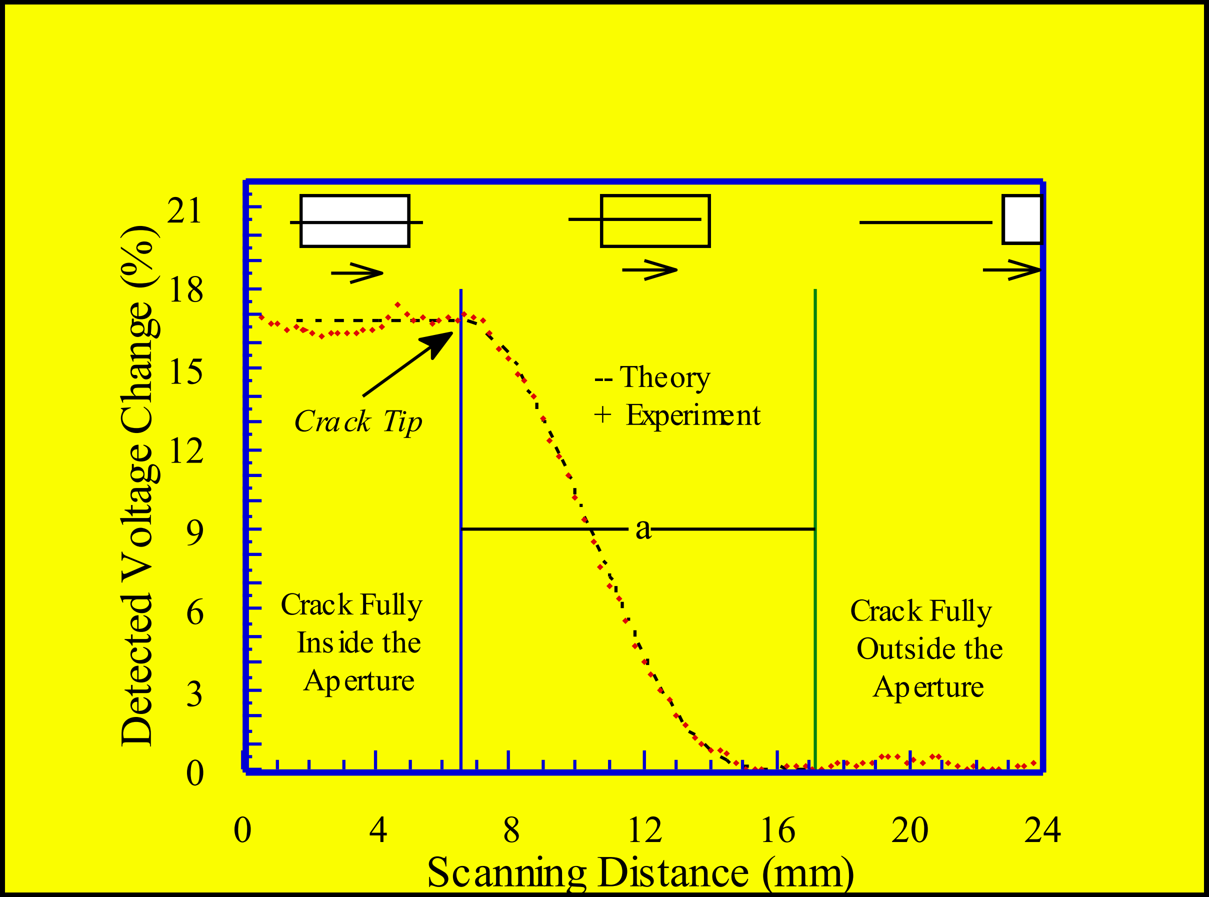
- Fourier boundary matching.
- Equivalent magnetic current density.
  - ✓ Model the junction by introducing and equivalent magnetic current density.
  - ✓ Use a moment solution.
  - ✓ Formulate the generalized scattering matrix (reflection coefficient).
  - ✓ Analyze the standing wave properties inside the waveguide at strategic locations.



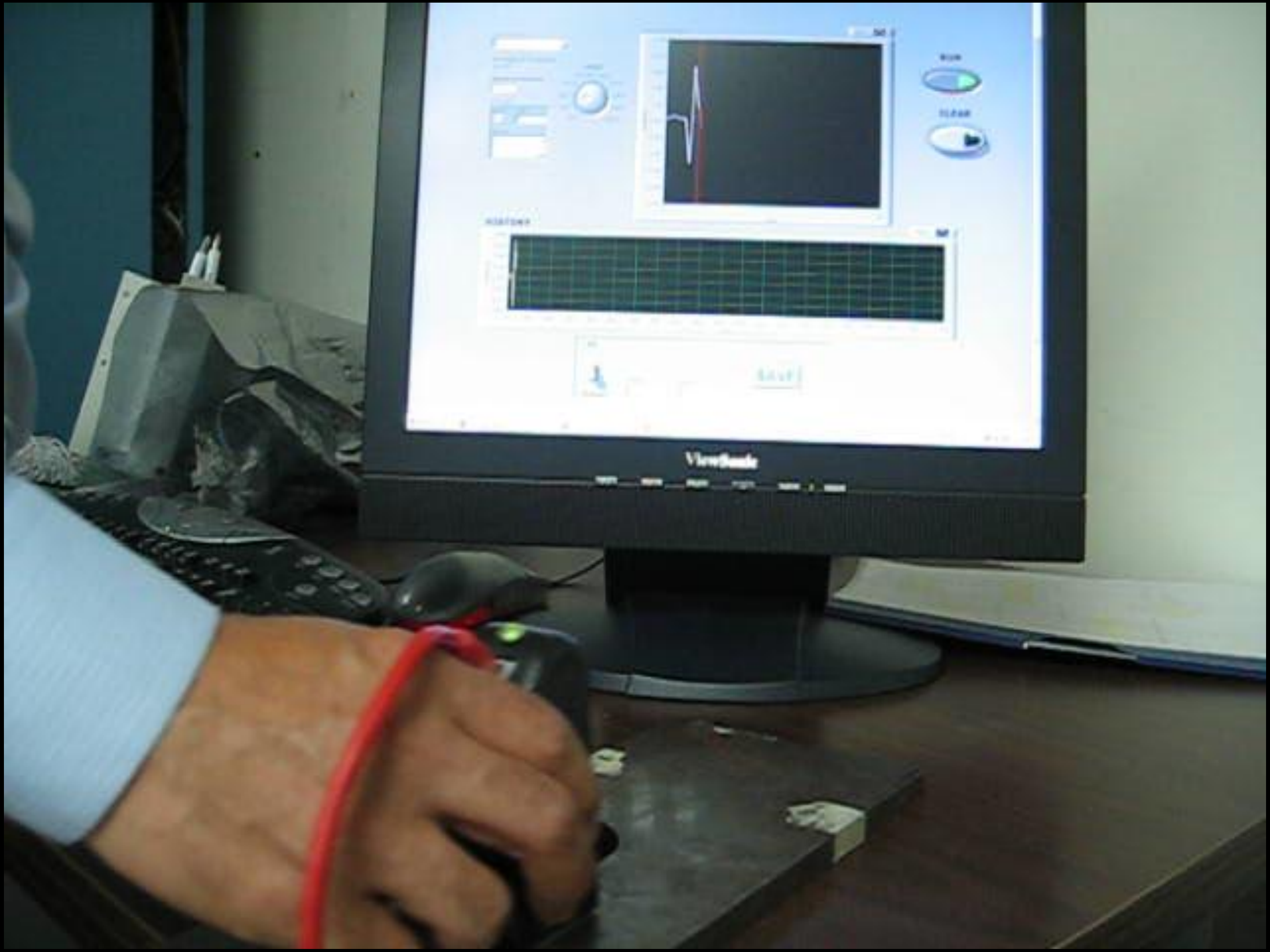


Crack Tip

W = 0.51 mm, D = 1.5 mm @ 24 GHz

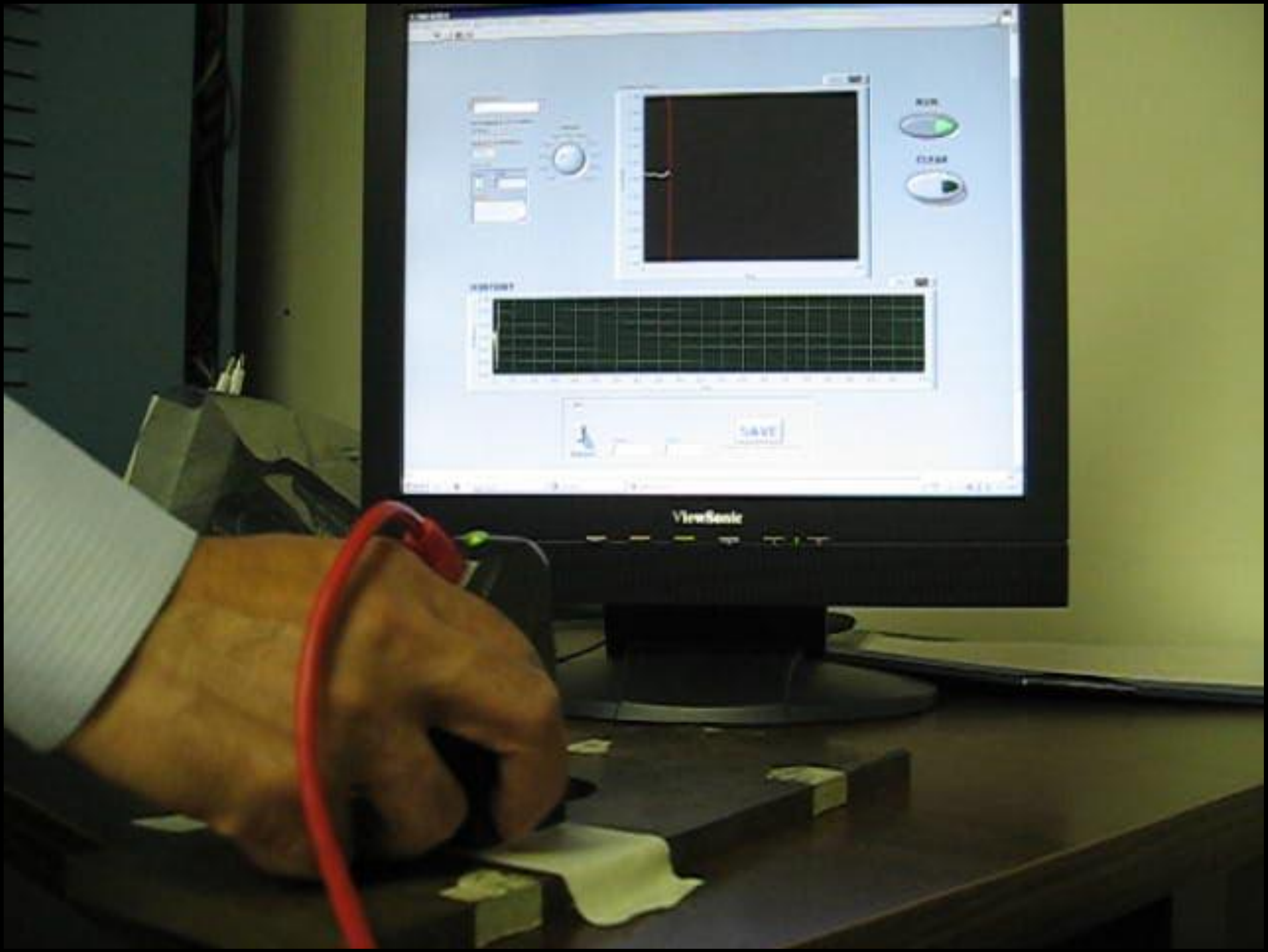


Exposed Crack



Click on the above picture to view video

Covered Crack



Click on the above picture to view video

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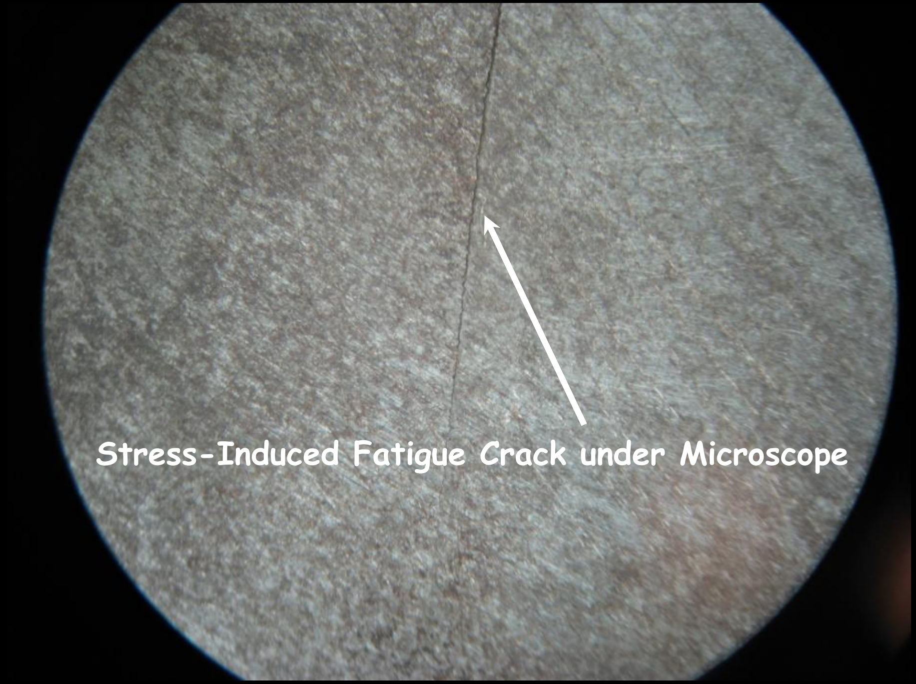
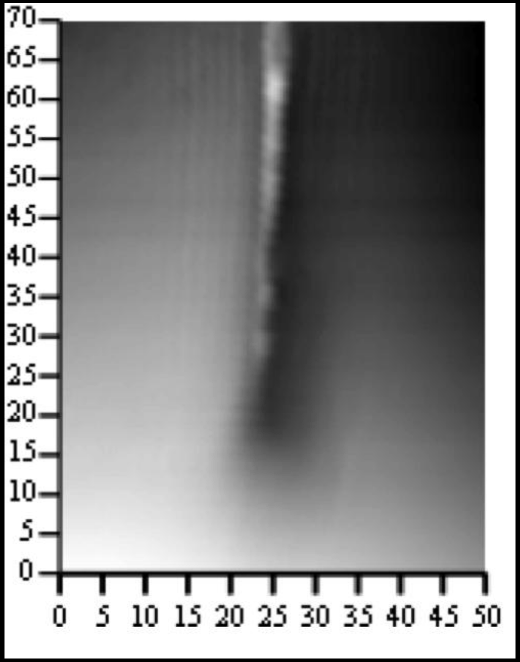
Fatigue Crack Image

Liftoff of 1.8 mm @ 90 GHz





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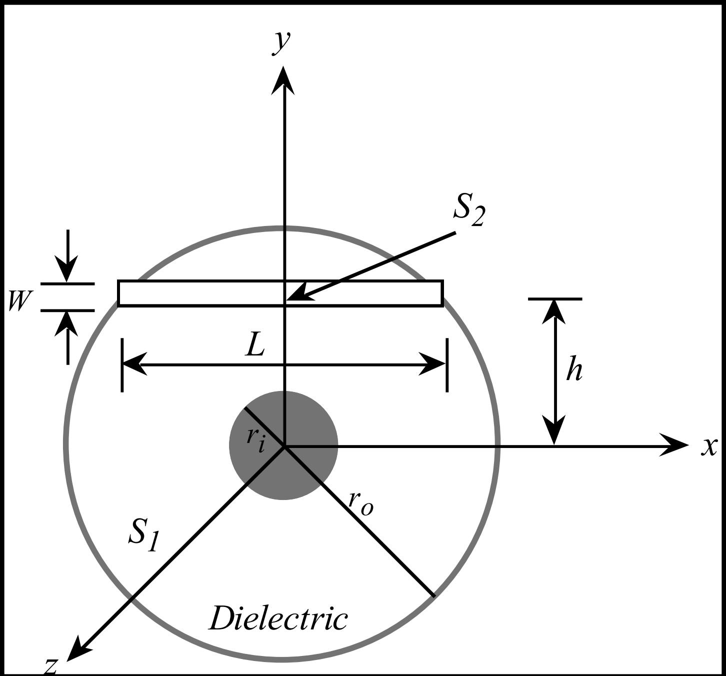
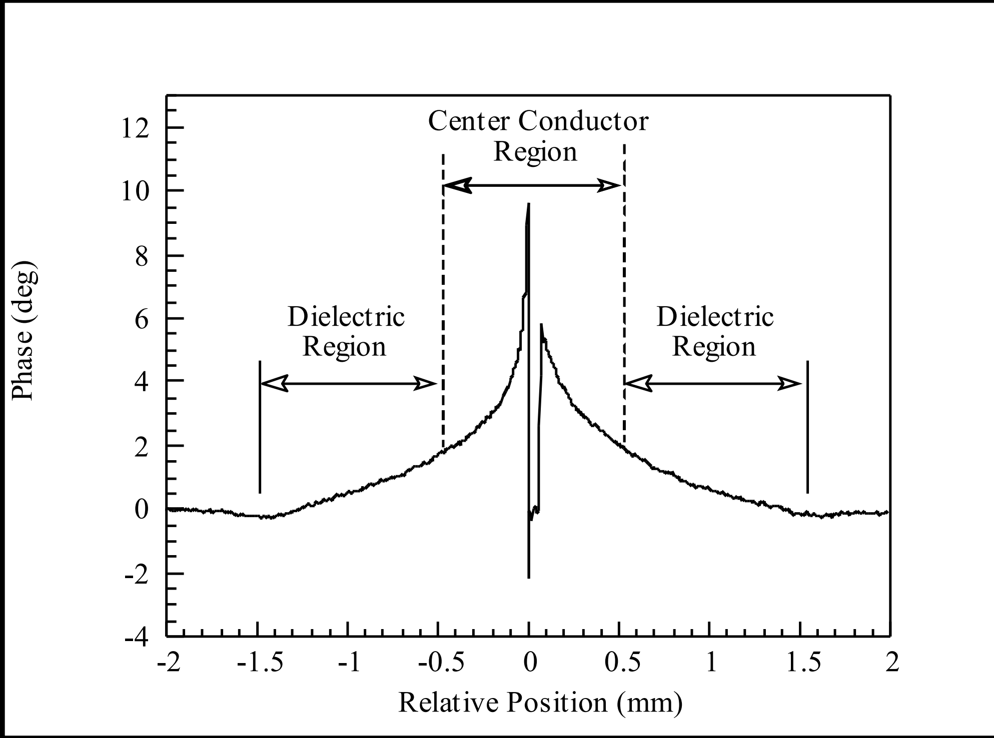
Coaxial Probe - Results

W = 0.152 mm, D = 1 mm @ 10 GHz





COMPOSITE INSPECTION & IMAGING

Foundation

- Robust imaging capabilities since:
  - ✓ Wavelength in mm range
  - ✓ Probes are small
  - ✓ Different "focusing techniques"
  - ✓ Different "image reconstruction" techniques
- No need for a separate transmitter and receiver (i.e., mono-static systems).
- No need for pulsed systems.

Foundation

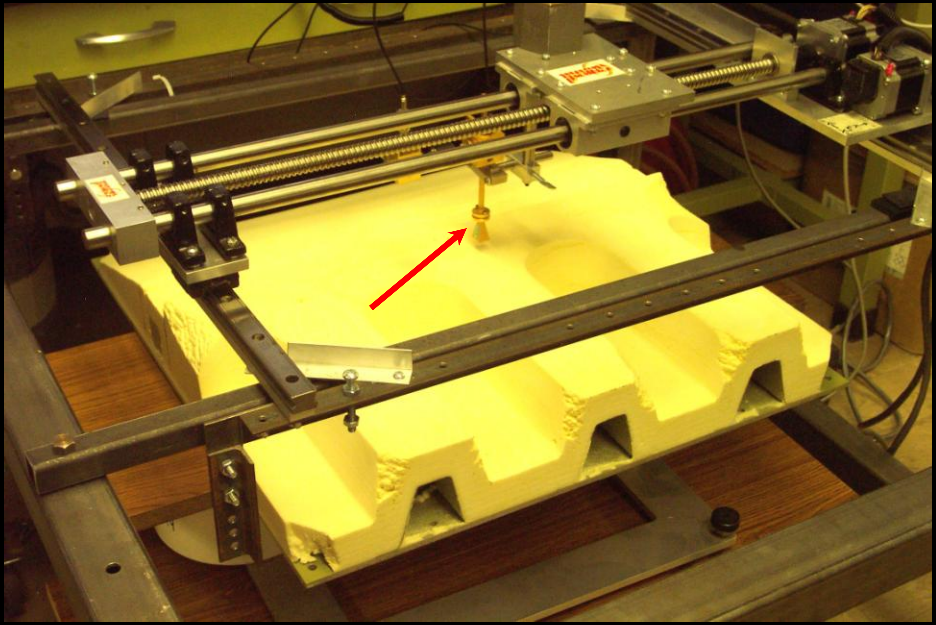
- Obtain high spatial-resolution images:
  - ✓ real and synthetic aperture methods.
- For real-aperture focused systems the "focusing" characteristics may be manipulated to accommodate a particular measurement.
- For synthetic aperture focusing methods, the measurements are conducted once and the processing to produce high resolution images takes only a few seconds.

Real-Aperture Focusing

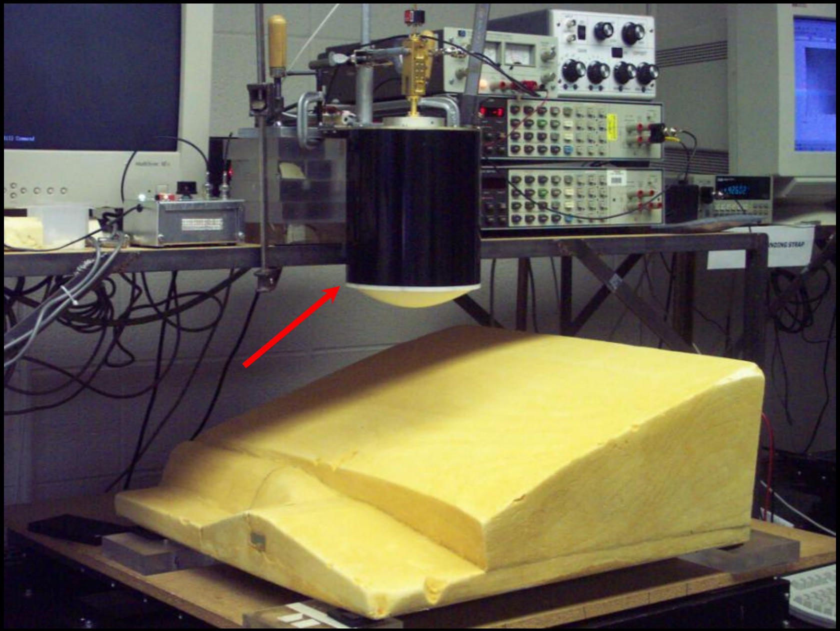
- Near-field imaging produces high-spatial resolution images - Resolution a function of probe size and not wavelength.
- Horn antennas focus a beam:
  - ✓ Near-field and far-field use.
- Lens antennas focus a beam into a small footprint.

Real-Aperture Focusing

100 GHz



150 GHz



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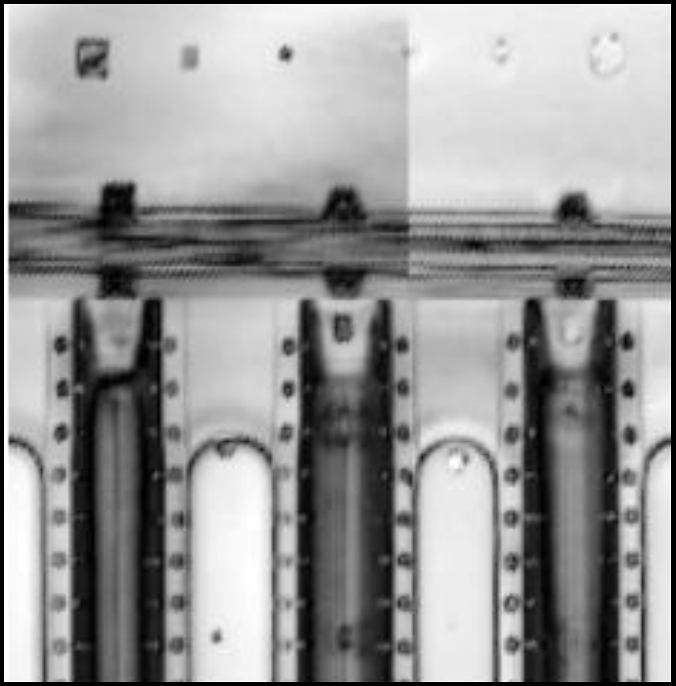
POD Panel Schematic

POD Panel - 100 GHz

Lens (0.25") Focused at Substrate

Perpendicular

Parallel



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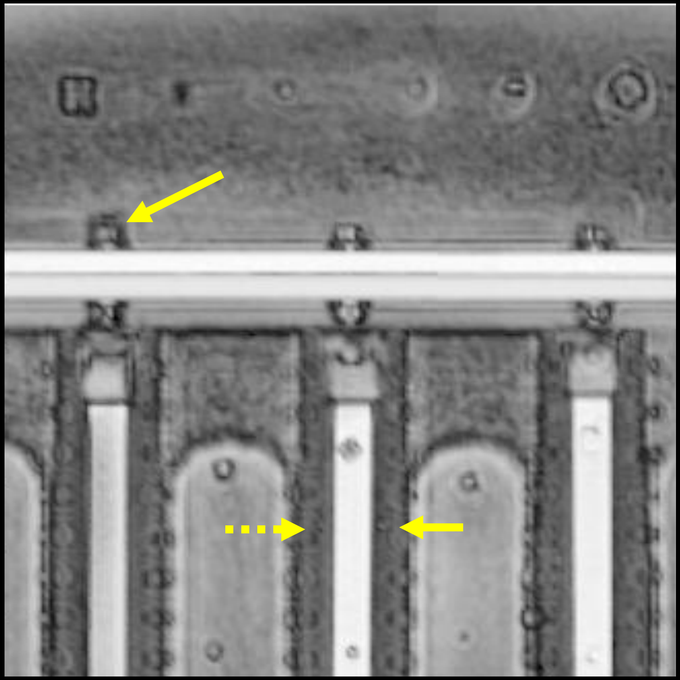
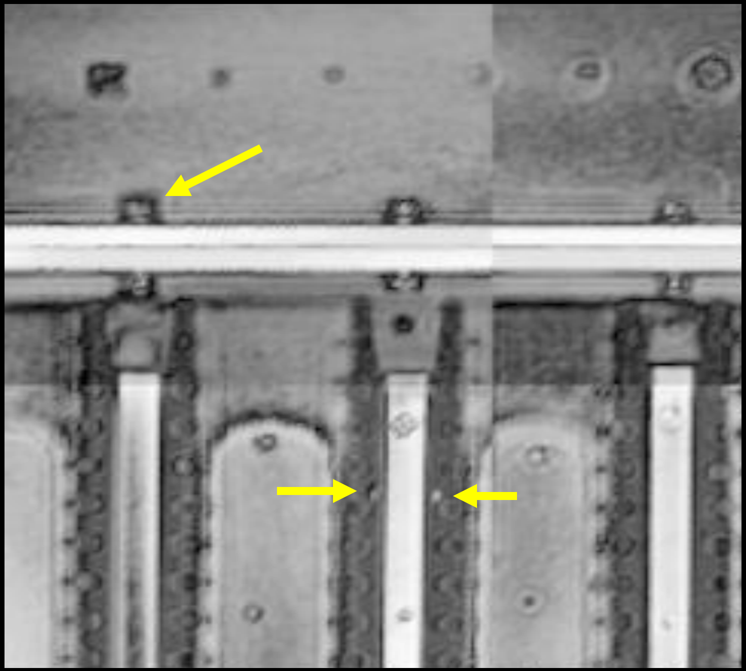
POD Panel - 100 GHz

Lens (0.25") Focused at Top of Stringers

Perpendicular



Parallel



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Acreage Heat Tiles

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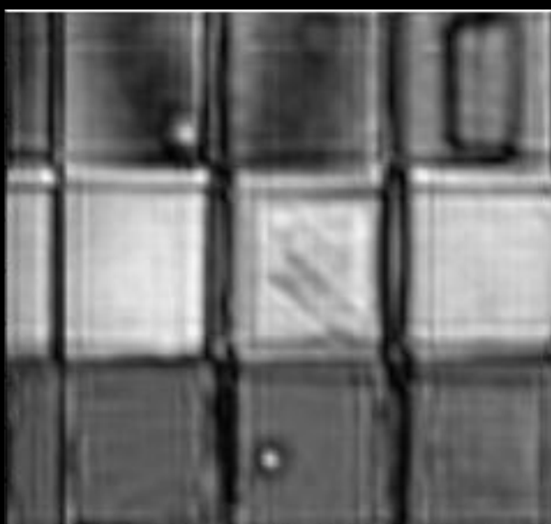
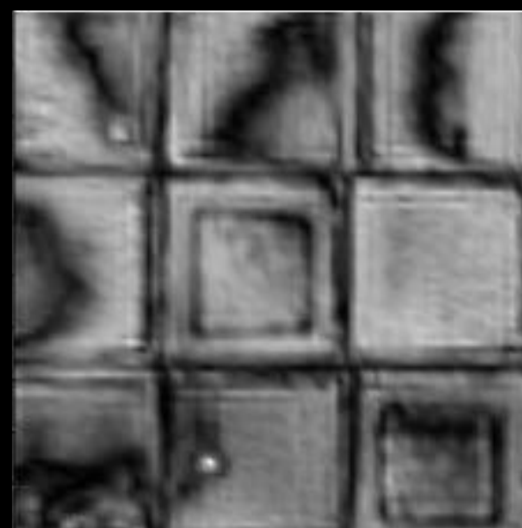
Acreage Heat Tiles

Near-Field Using Horn Antennas

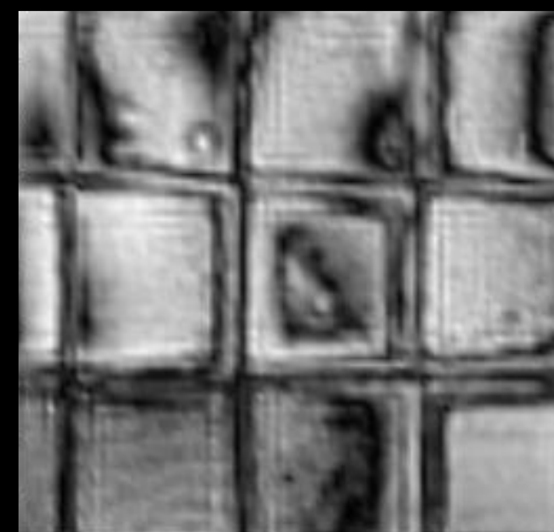
Ka-Band
33.5 GHz



V-Band
67 GHz



V-band
70 GHz



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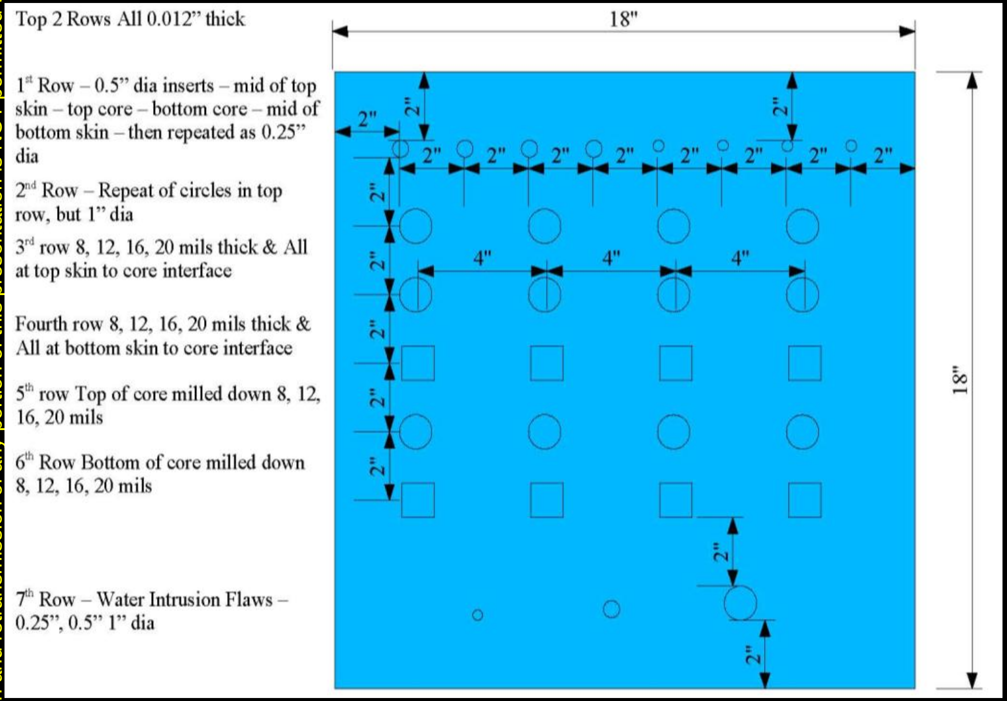
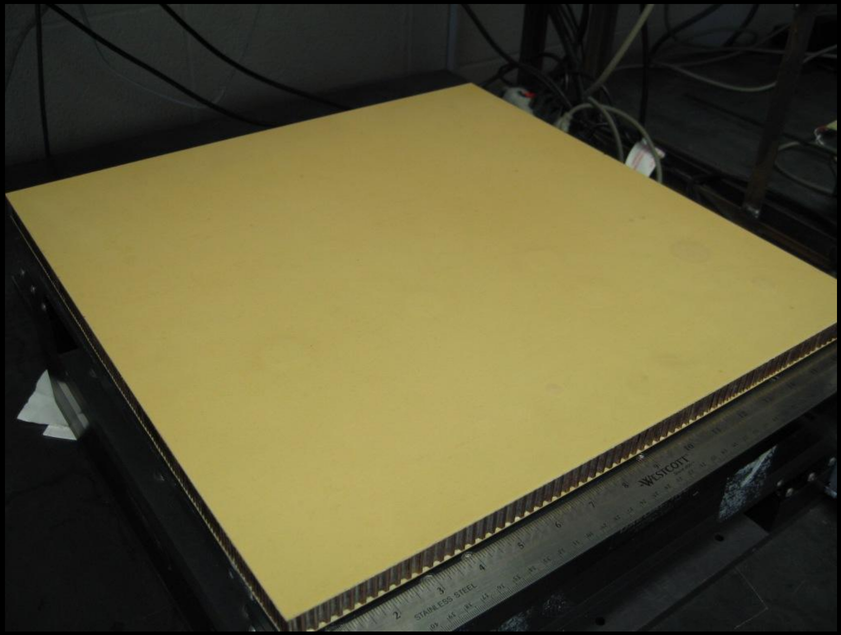
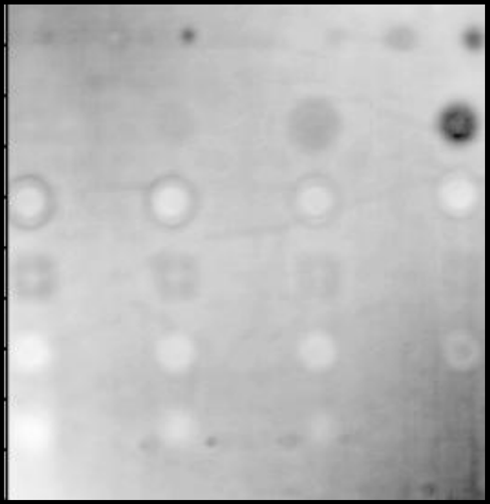
Panel Description



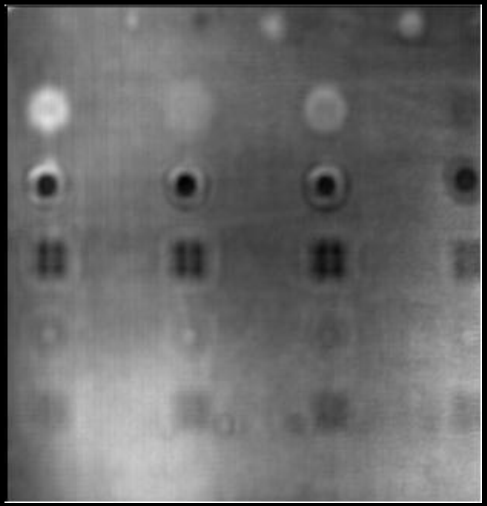


Near-Field Imaging Results

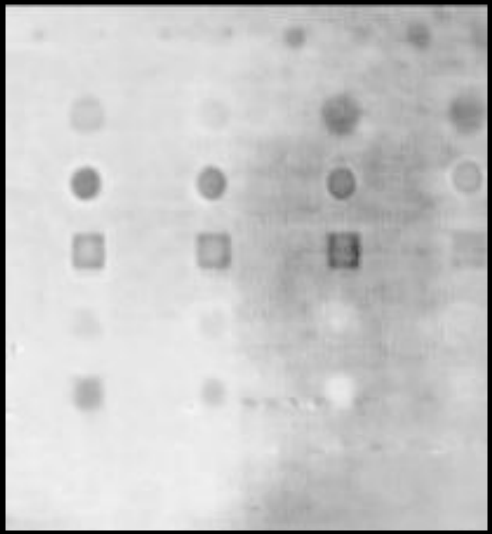
33 GHz (Open-Ended Waveguide)



73 GHz (Horn)



100 GHz (Lens)



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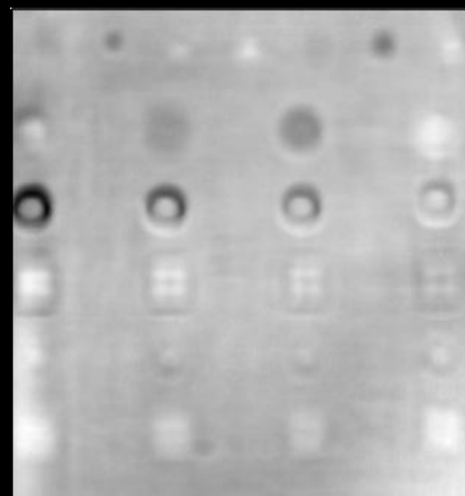
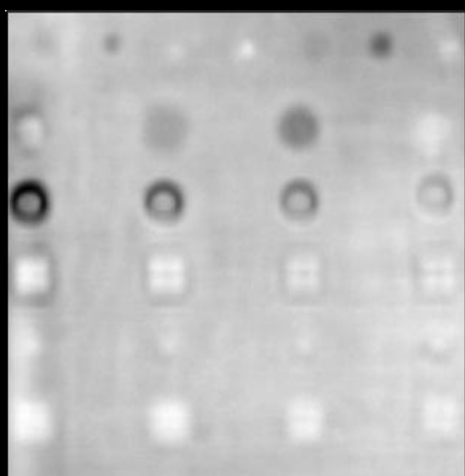
Near-Field Imaging Results - 67 GHz

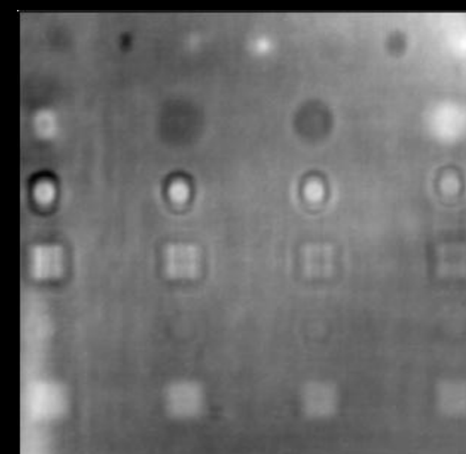
1.5 mm Standoff



3.5 mm Standoff



5 mm Standoff



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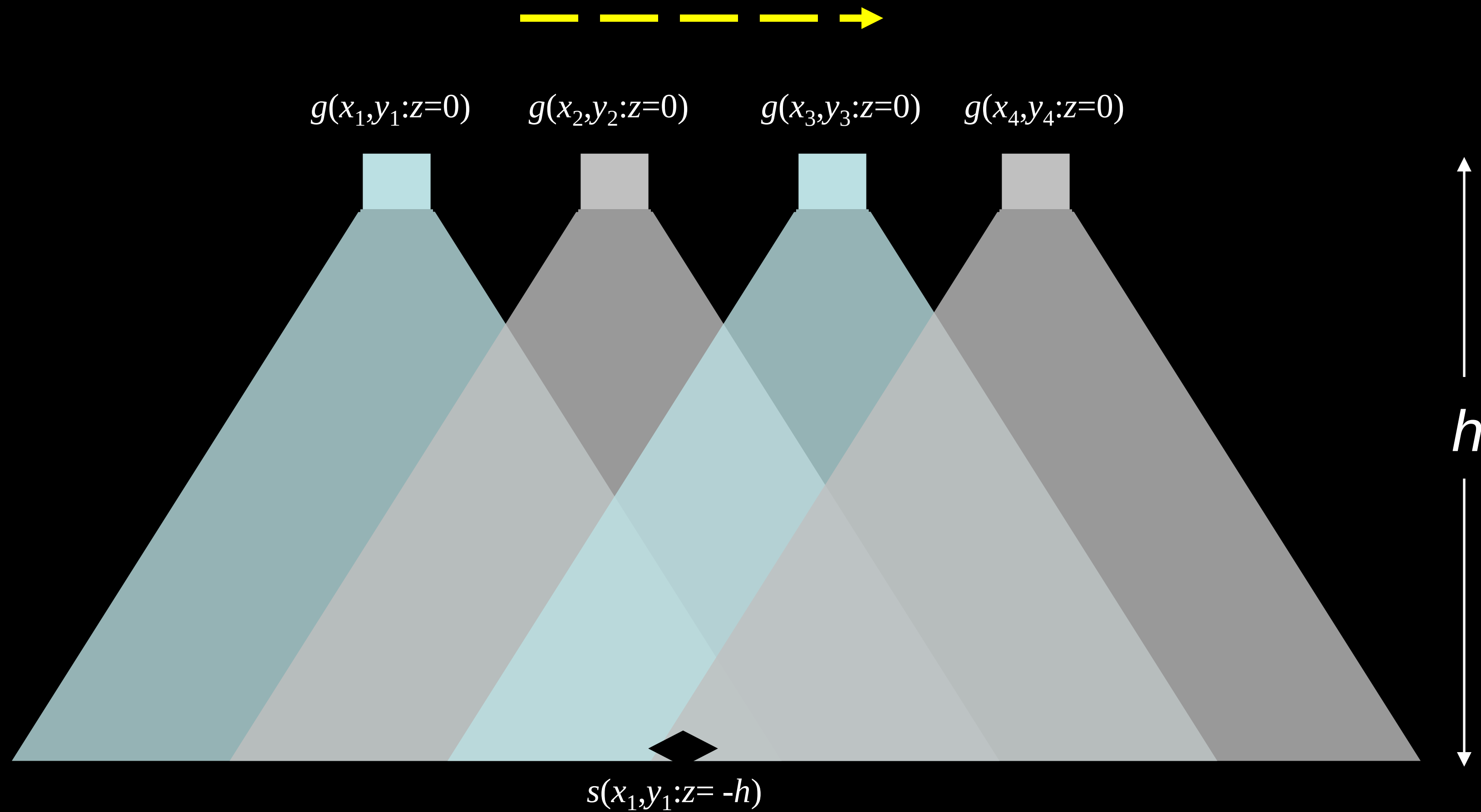
Synthetic Aperture Focusing

- A well-known imaging technique capable of producing high-spatial resolution images (on the order of half of the antenna real dimensions and independent of antenna height).
- Based on phase correction as an antenna moves along a path – uniform motion is not required.
- At 70 GHz (V-band) using open-ended rectangular waveguides or a small horn, images with resolution in the range of a few millimeters can be achieved.

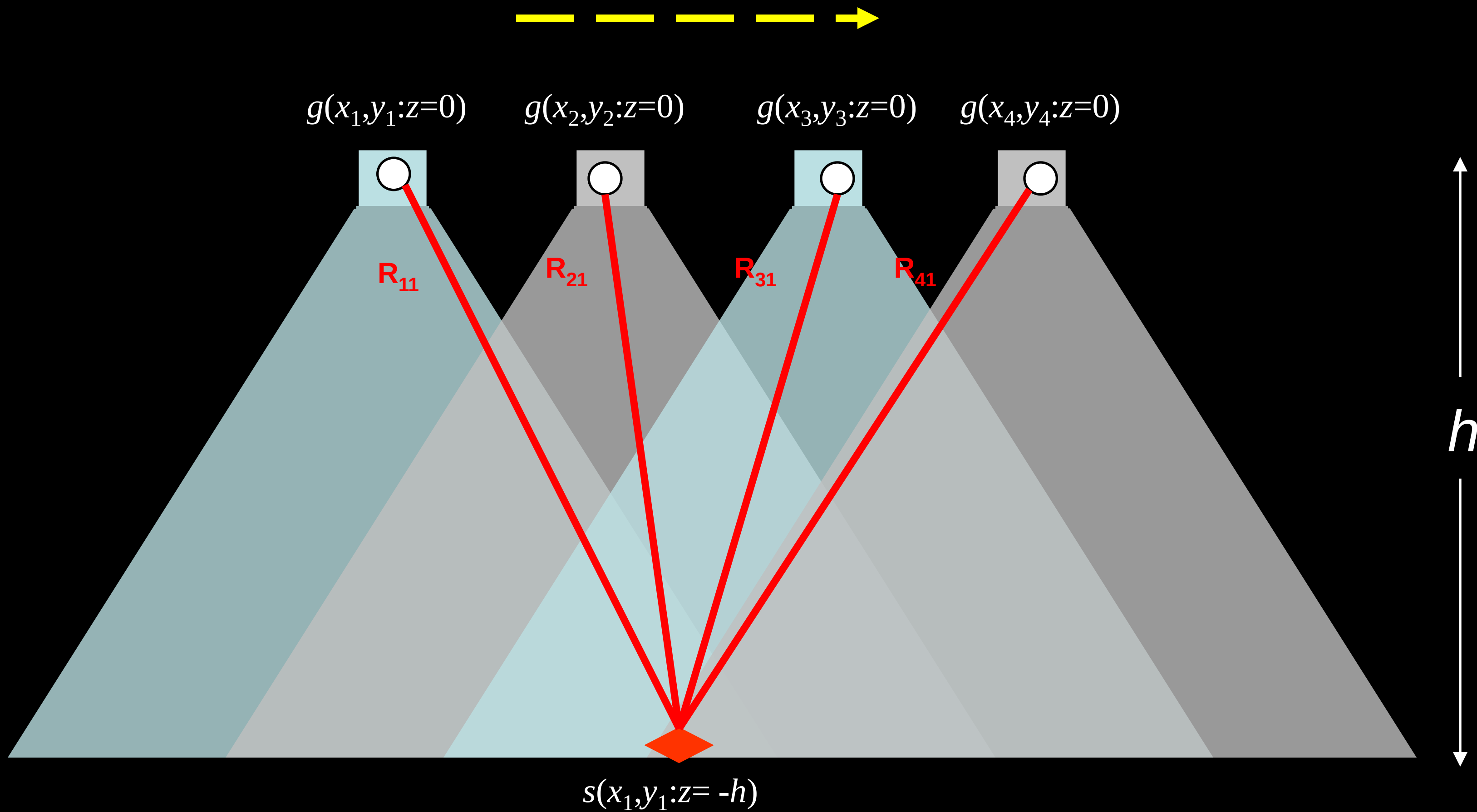
Synthetic Aperture Focusing

Antenna Motion Direction

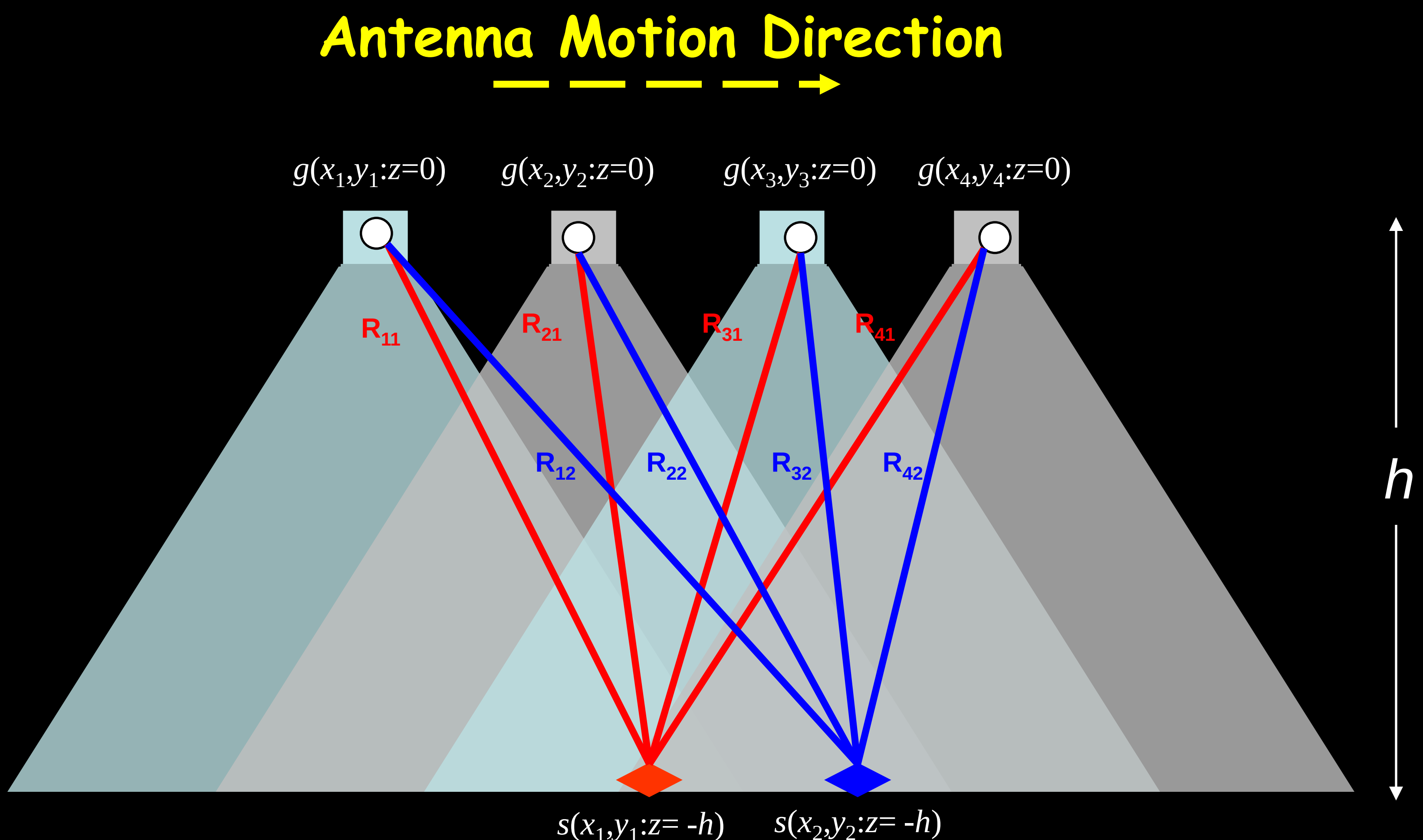


Synthetic Aperture Focusing

Antenna Motion Direction



Synthetic Aperture Focusing

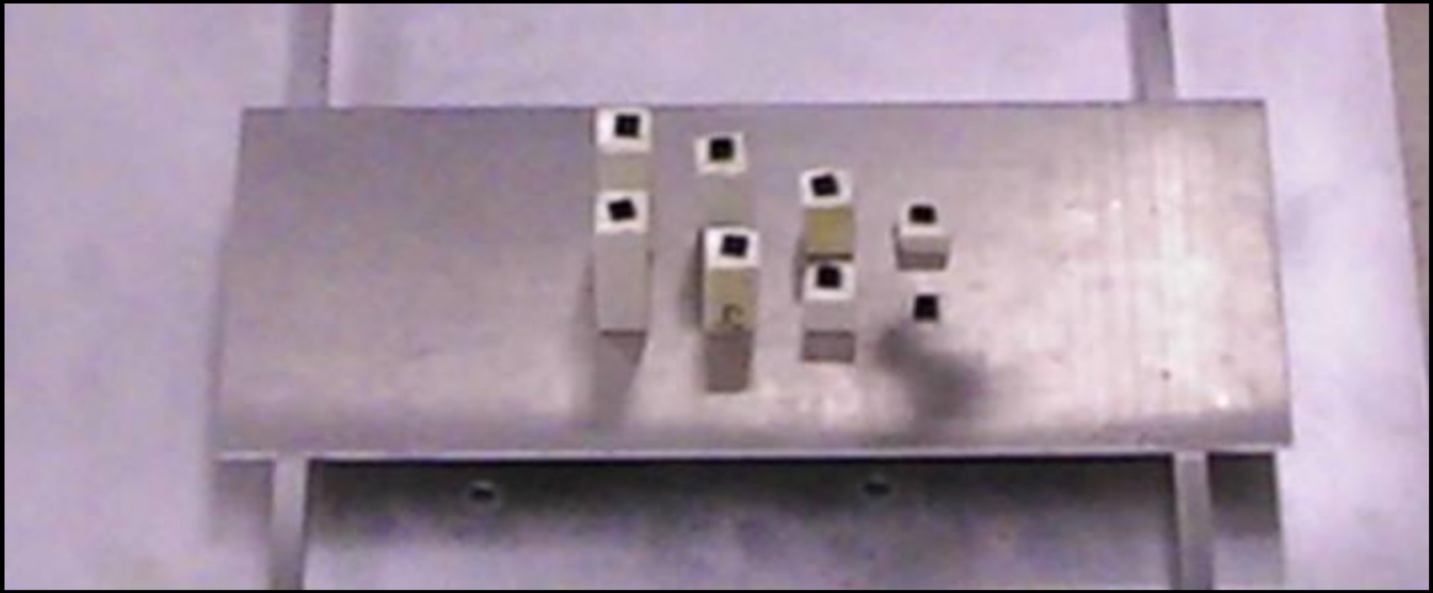


$$s\left(x_n, y_n : z = -h\right) = \sum_{i=1}^{4} g\left(x_m, y_m : z = 0\right) \exp\left(j2kR_{mn}\right)$$

mm- Wave Holography (3D Imaging)

- Swept frequency measurements, at mm-waves where large bandwidths are available, can be used to produce images with high-range (i.e., depth) resolution.
- This way one may obtain high resolution 3D images.

Sample for 3D Imaging Demo.

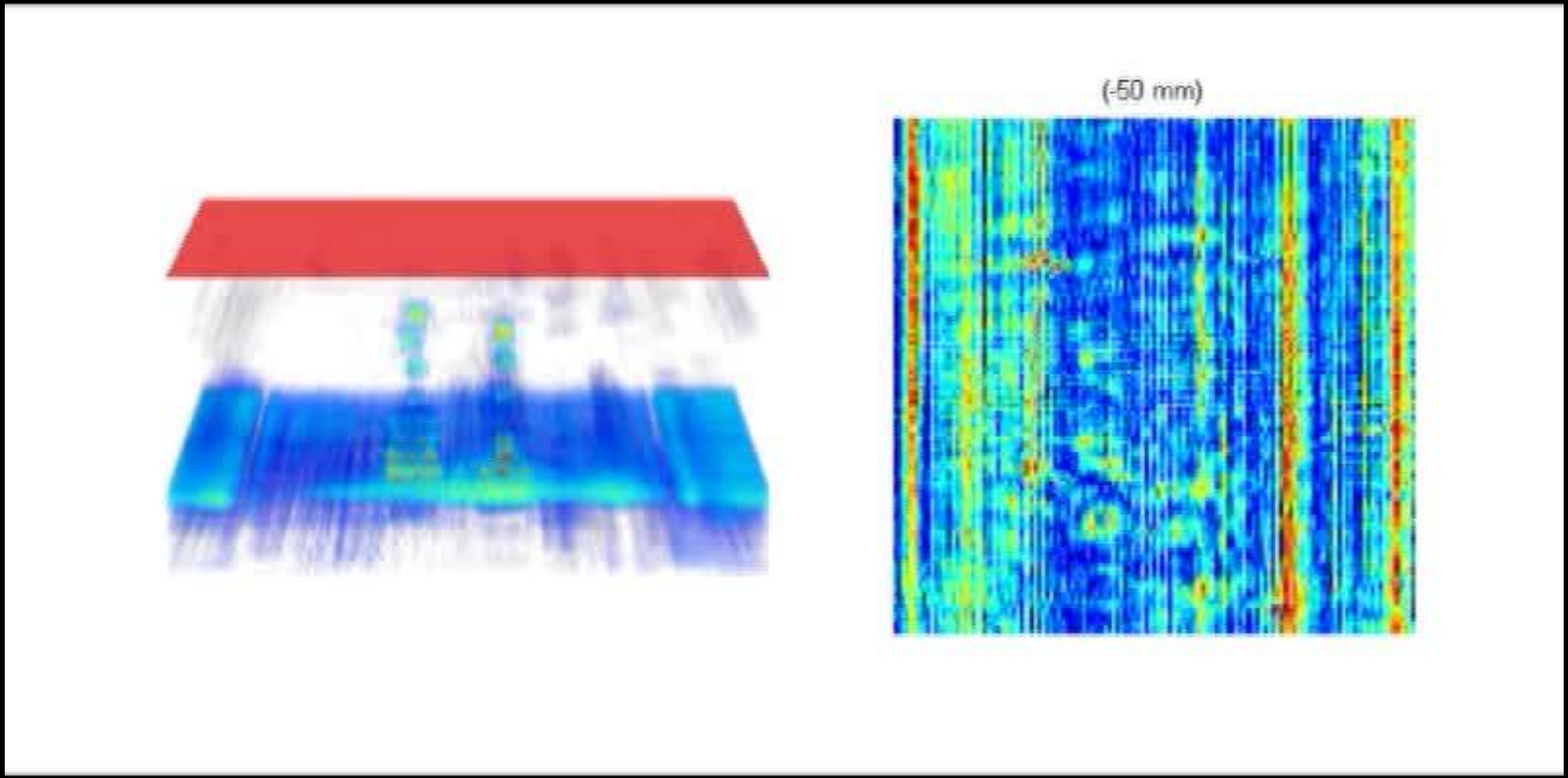


Missouri S&T

3D Imaging Results (Q-Band)

Click on the above picture to view video

SAFT Demonstration



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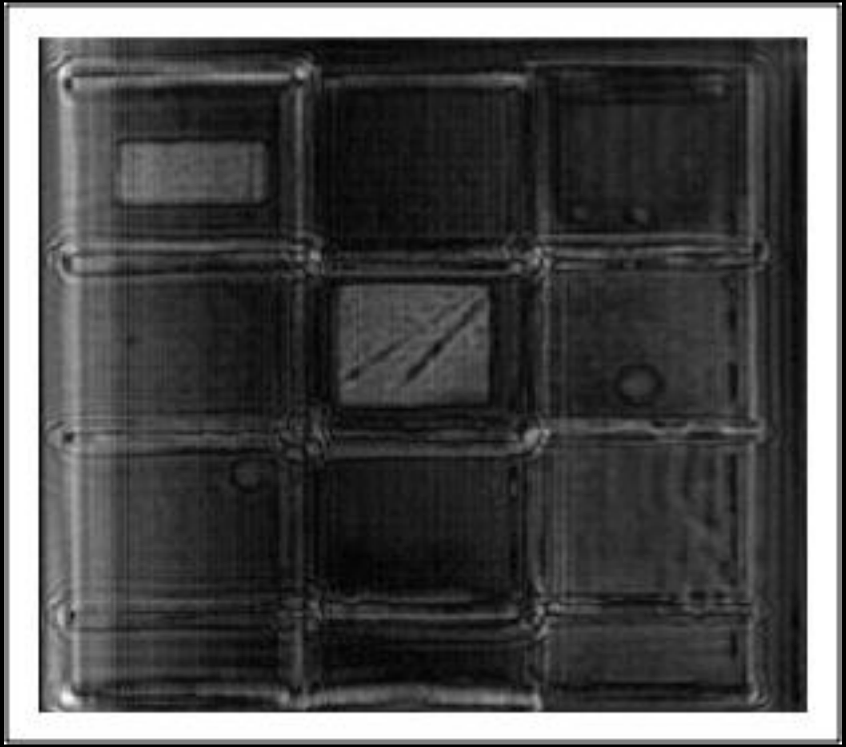
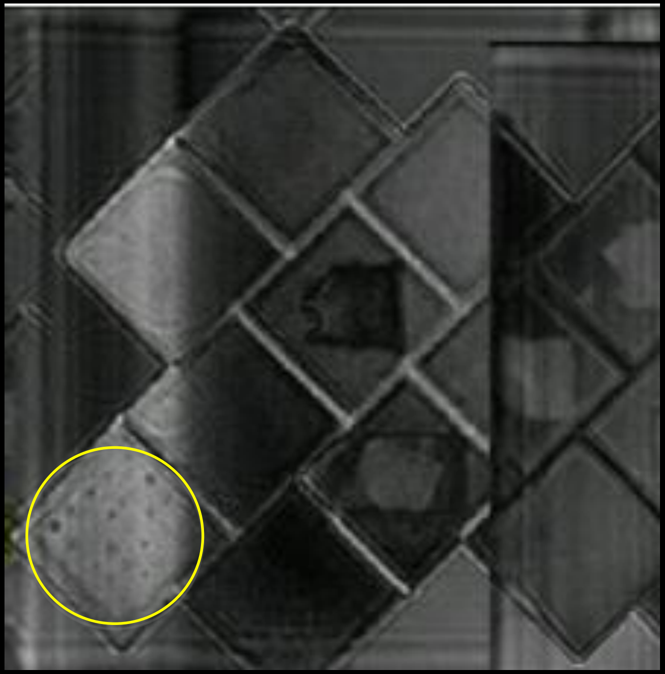
Embedded Flaws in Heat Tile

Q-Band Hologram Slice



Corrosion under Heat Tile

Q-Band Hologram Slice



RAPID COHERENT IMAGING USING ROTARY SCANNER

Rapid Imaging Systems

- Generally refers to the scanning platform using different imaging systems.
- Speed becomes a function of frequency through step size, probe size, CW or swept-frequency mode and frequency step size.

Rapid Imaging

- Conventional raster scanning a 2' by 2' area may take in excess of several hours.
- Scanning speed constraint becomes more significant as the scan area increases.
- Rotational scanning format eliminates stop-go action all together.
- Critical design issues to consider:
  - ✓ Linear signal polarization
  - ✓ Control and synchronization vs. spatial data acquisition
  - ✓ Variable speed vs. changing scan radius

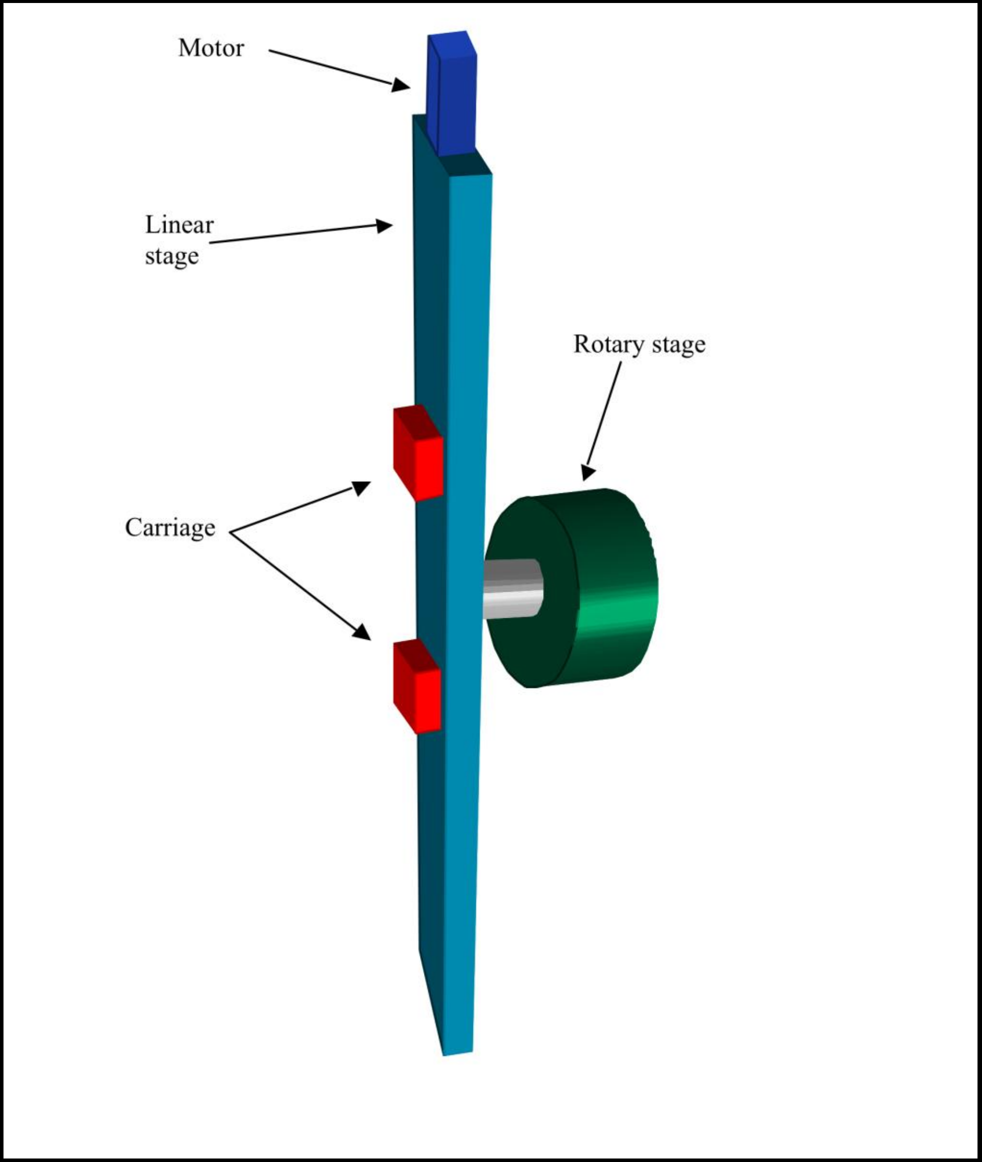
Q-band System

- Wideband system requirements:
  - ✓ Q-band (33-50 GHz): 35-45 GHz transceiver
  - ✓ High-resolution images
  - ✓ Coherent reflection measurement – SAFT
- SAFT image production.

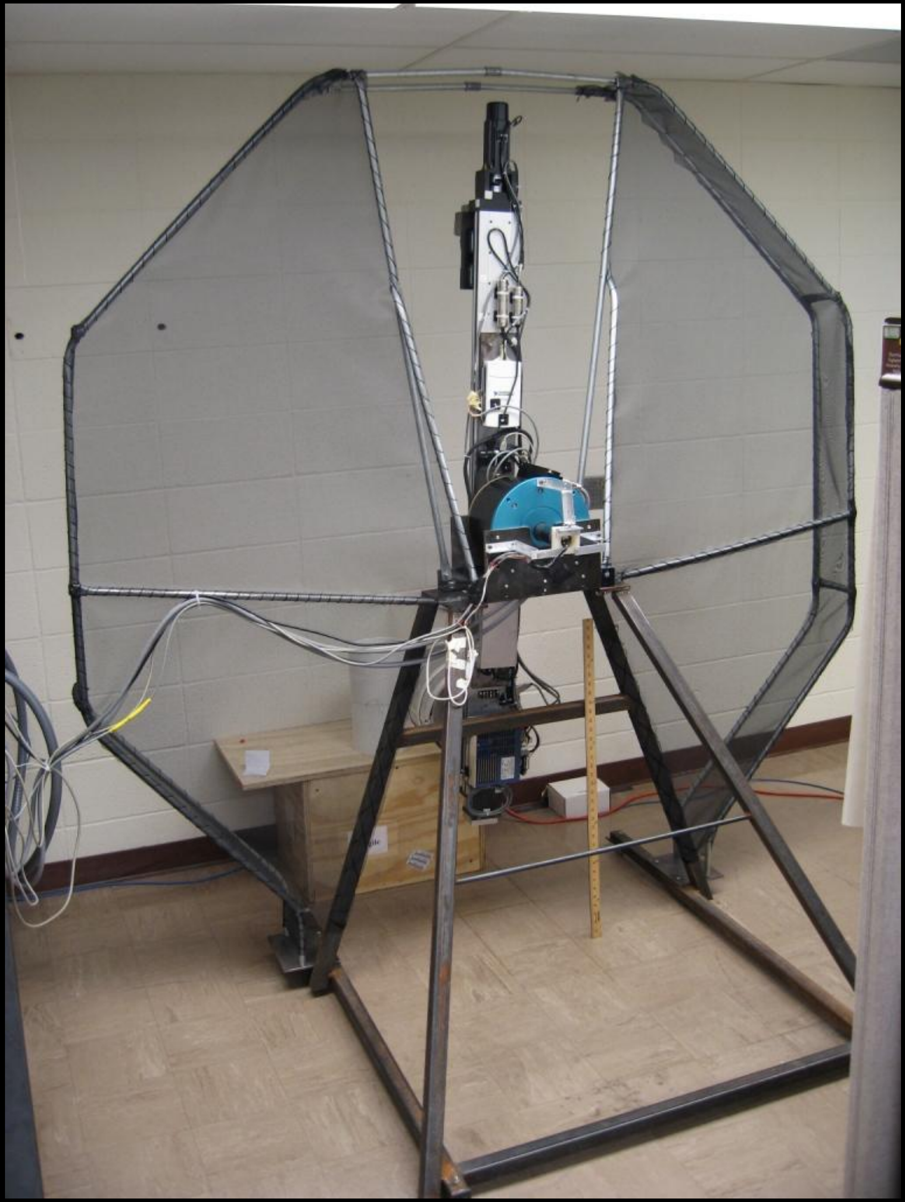
Main Components

- Mechanical components:
  - ✓ Linear dual-action positioning arm
  - ✓ Direct-drive motor
- Q-band coherent transceiver.
- Control and communications interface software.
- Polarization transforming and polar SAFT software.

Scanner Schematic



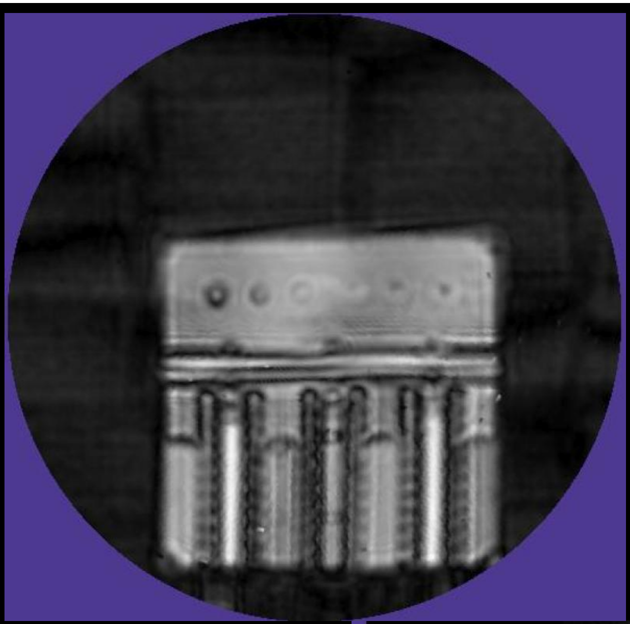
Final System

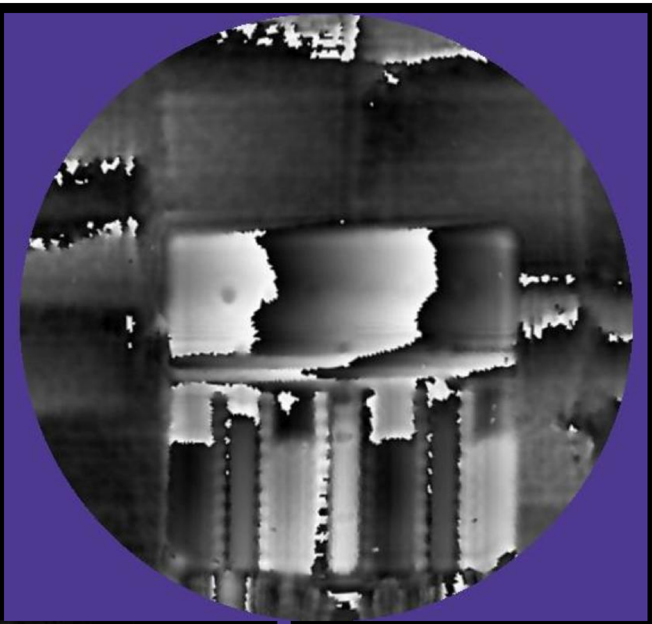


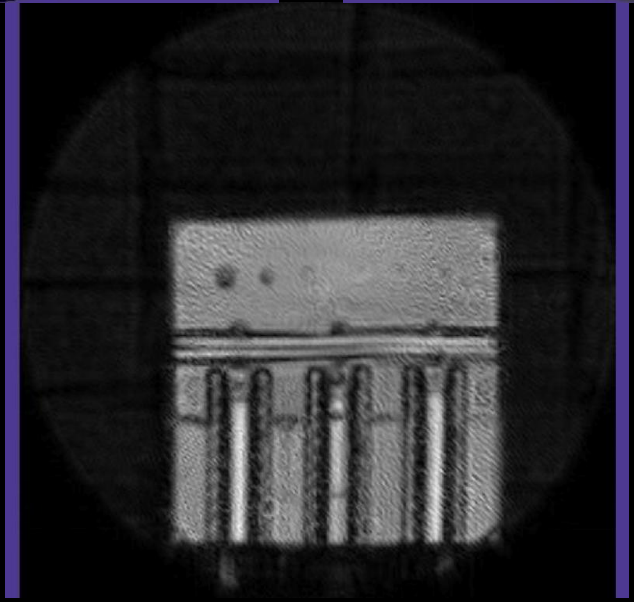
Video

Click on the above picture to view video

POD Panel – 45 GHz

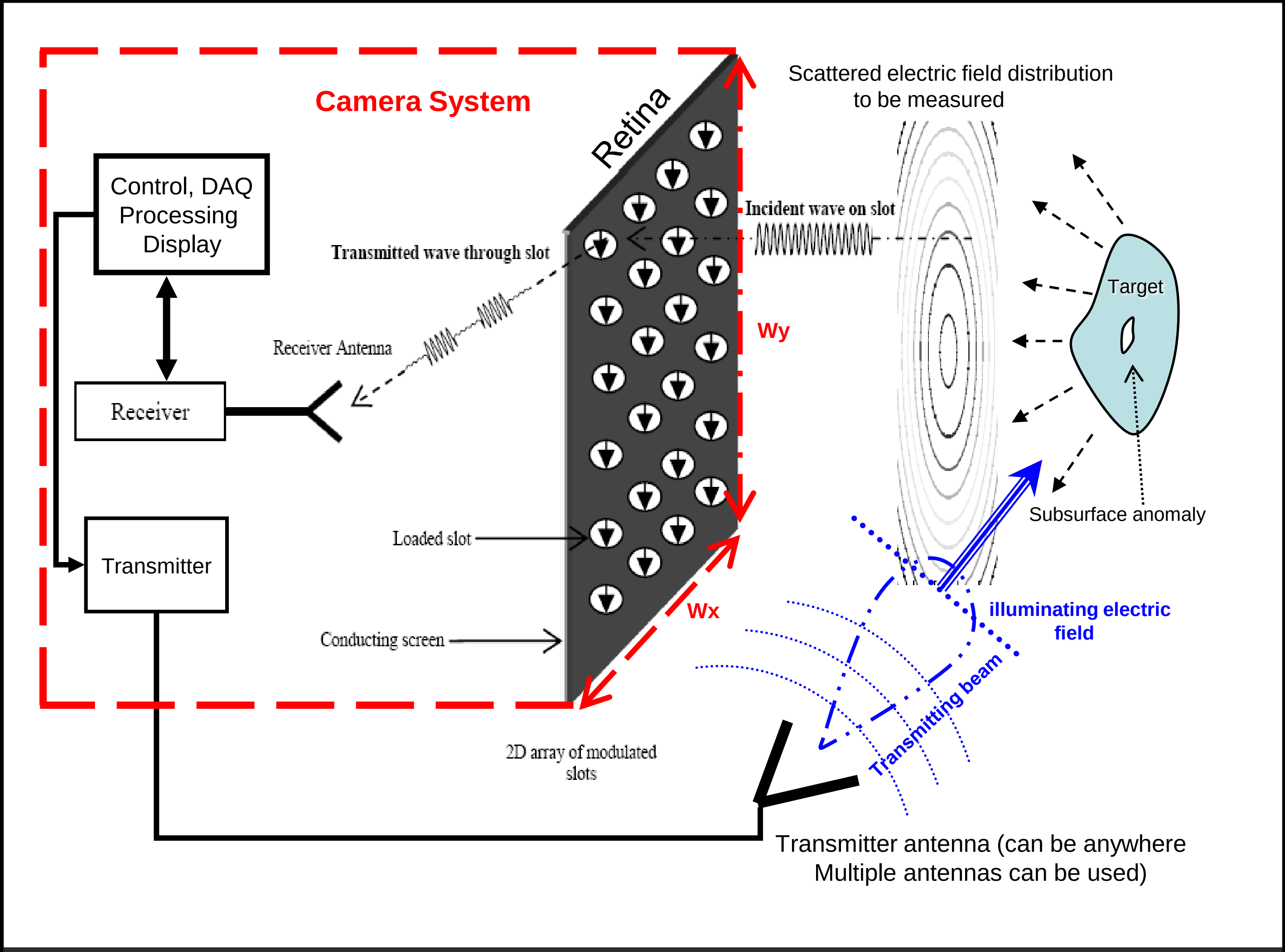






REAL-TIME TECHNIQUES

Basic Schematic



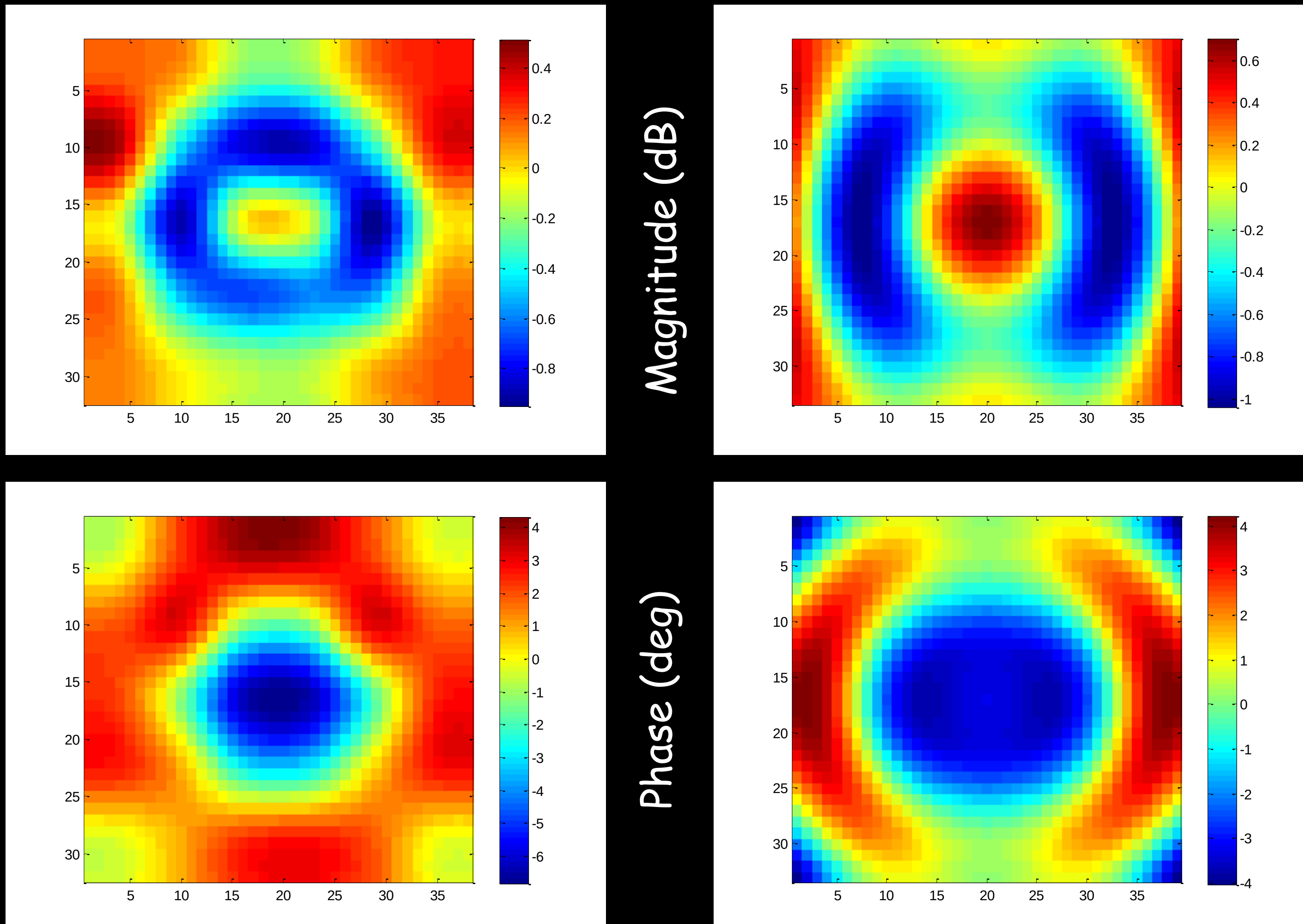
MISSOURI S&T

Improvement Considerations

- An array of modulated probes provides for coherent electric field distribution over the desired 2D space.
- Traditional, minimally perturbing elements result in a compact array for field sampling and measurement, however they suffer from several drawbacks.
  - ✓ Inefficiency of the sub-resonant dipoles, places their scattered signal very close to the noise floor.
  - ✓ Mutual coupling among the dipoles can significantly limit system dynamic range.
- These problems become even more significant and challenging at higher frequencies.
- Alternative antenna is a high-Q compact resonant slot loaded with a PIN diode.

K-Band Initial Prototype

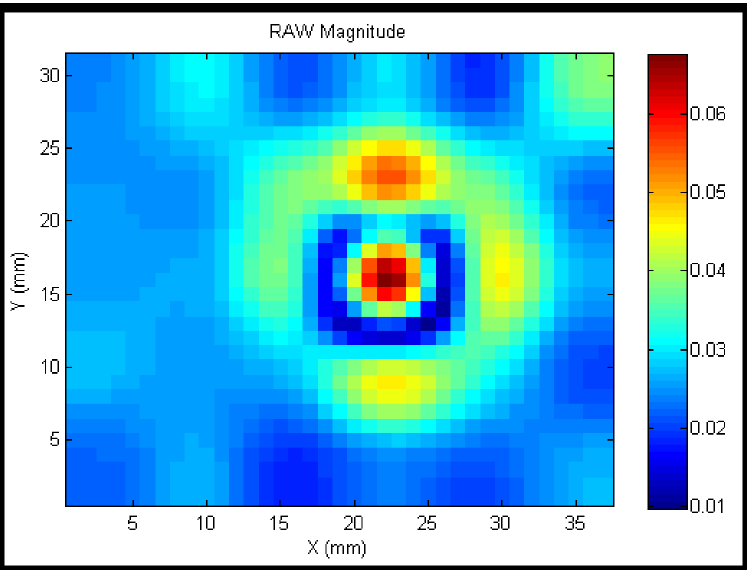
Measurement vs. Simulations (12 mm)

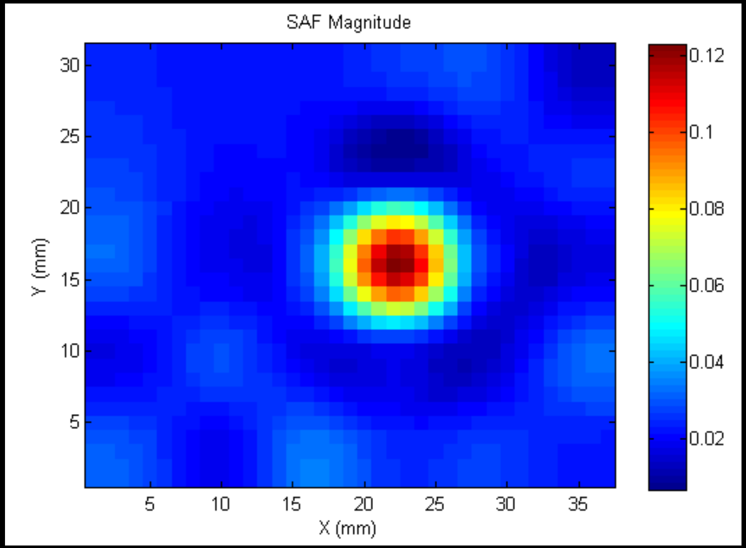


Measurement Simulated

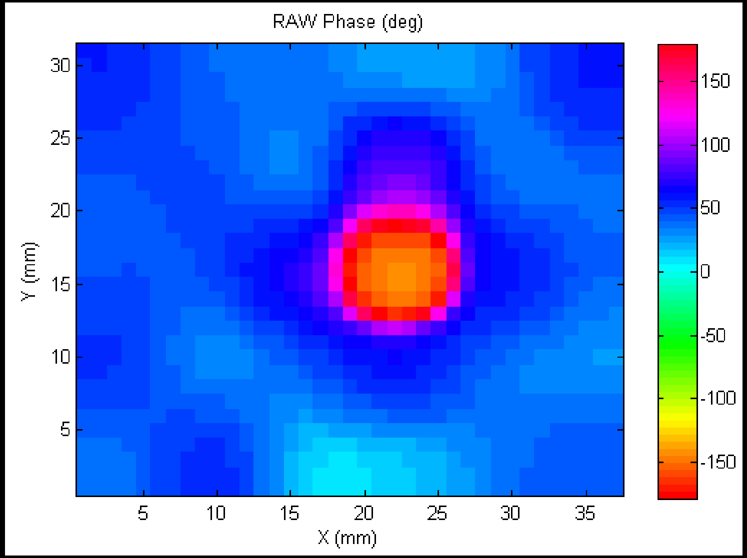
Reflection Mode – Reflection Mode

- Object
  - ✓ 10mm-diameter metallic sphere
- Distance to retina
  - ✓ 10mm
- X6.25 super-sampled



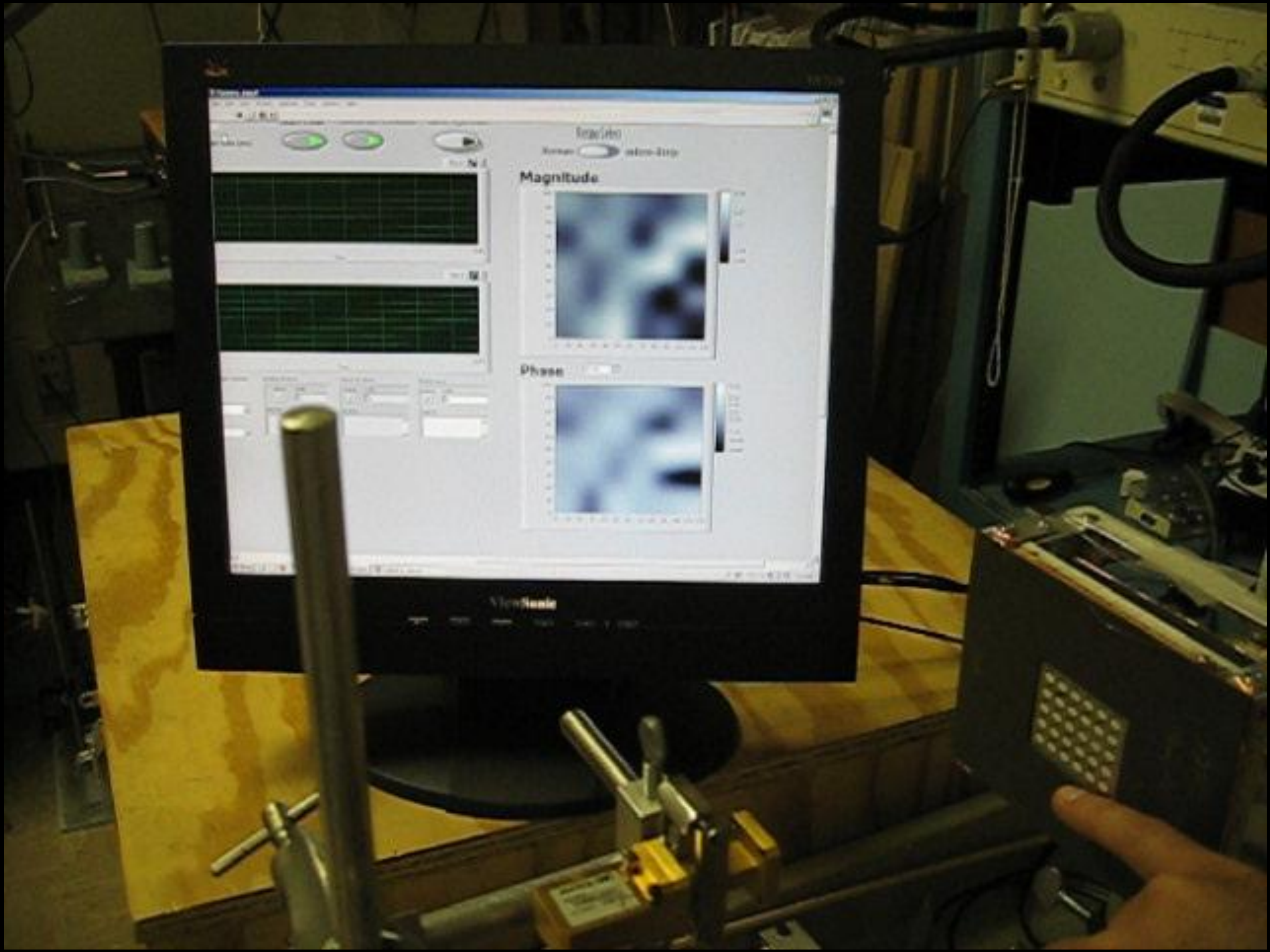


Synthetic Aperture Focused



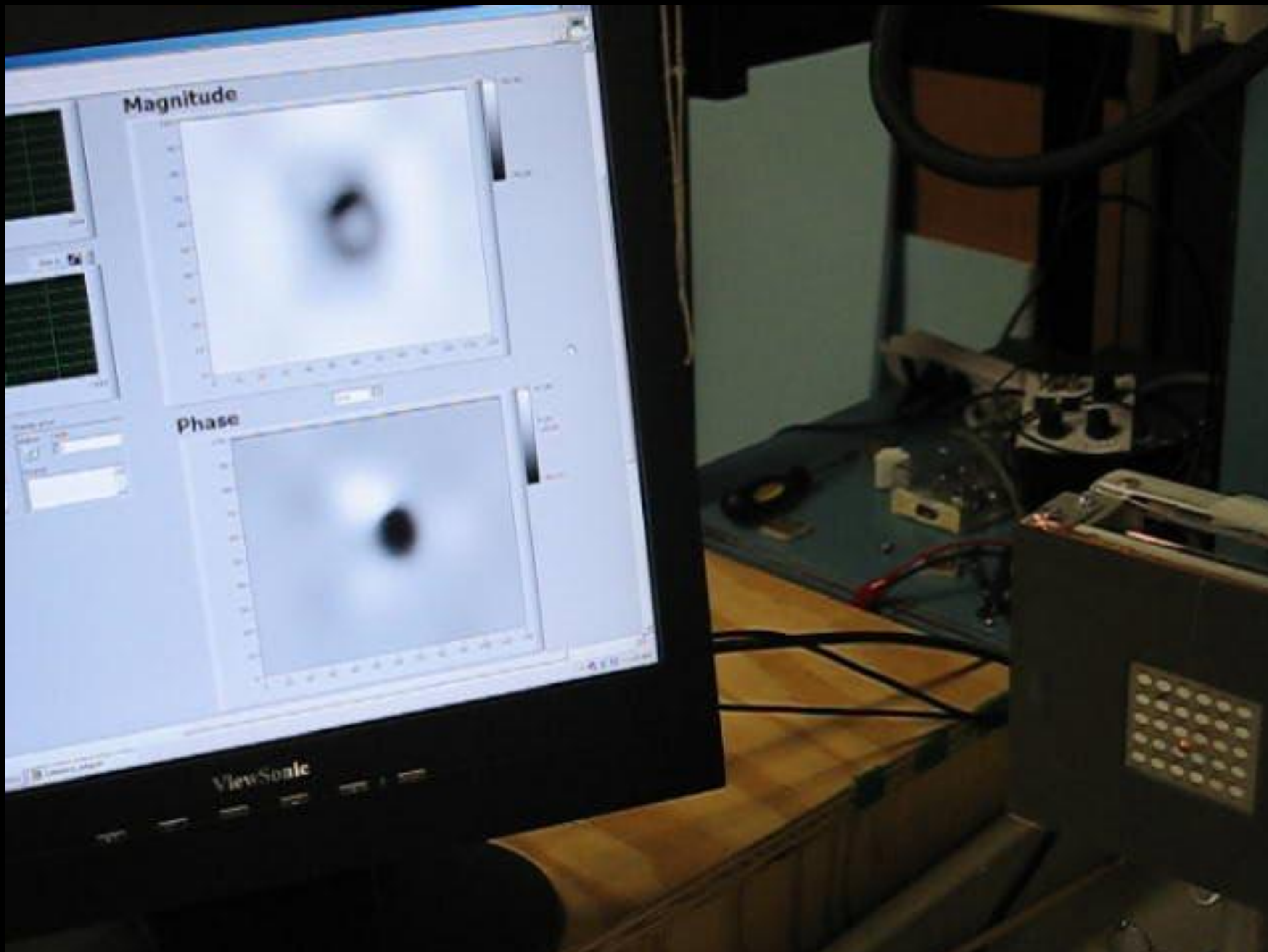
Raw Magnitude & Phase

Real-Time Imaging – Transmission Mode



Click on the above picture to view video

Real-Time Imaging



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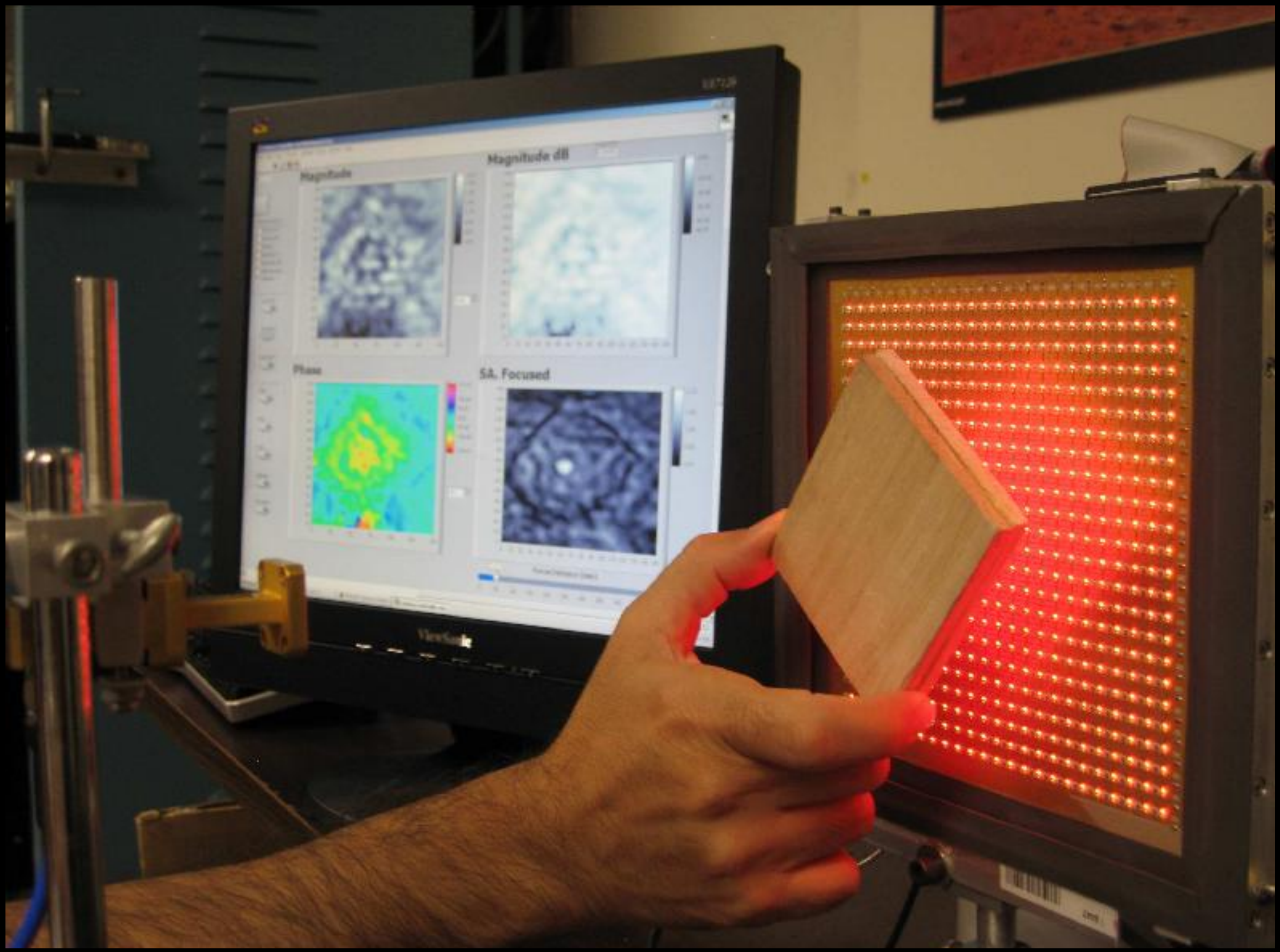
MISSOURI S&T

Current K-Band Camera



Click on the above picture to view video

Future

- The limitations associated with the "standard" techniques require a fresh look into the utility of other methodologies.
- The ever-increasing utilization of dielectric composites will contribute to the more widespread use of these methods.
- Wide range of critical applications.

Future

- Recent applications & prototype developments have shown some myths about the following to be unfounded:
  - ✓ Cost
  - ✓ Design complexity
  - ✓ Resolution
  - ✓ Measurement sensitivity
  - ✓ Operator unfriendliness
  - ✓ Radiation hazard
  - ✓ Need for extensive signal processing
  - ✓ etc.

Future

- Lack of off-the-shelf component and testing devices has traditionally been considered a significant limitation.
- However, recent advances in wireless communications have resulted in the availability of many components at microwave and millimeter wave frequencies.
- Need for standardization for these techniques.
- Sensor/data FUSION will bring microwave sensors along side other sensors.
- Real-time and one-shot imaging "camera".

Future

- Development of imaging and inspection systems per a given application.
- Transceiver dynamic range and sensitivity improvement as a result of better devices becoming commercially available.
- More significant developments in real-time, high-resolution and one-shot imaging.