

## ***High Resolution Millimeter Wave Inspecting of the Orbiter Acreage Heat Tiles of the Space Shuttle***

*J.T. Case<sup>1</sup>, S. Kharkovsky<sup>1</sup>, R. Zoughi<sup>1</sup> and F. Hepburn<sup>2</sup>*

*<sup>1</sup>Applied Microwave Nondestructive Testing Laboratory (amntl)  
Electrical and Computer Engineering Department  
University of Missouri-Rolla  
Rolla, Missouri 65409*

*<sup>2</sup>NASA Marshall Space Flight Center  
Marshall Space Flight Center, AL 35812*

**Keywords** – millimeter waves, high resolution, nondestructive inspecting, space shuttle, heat tiles

### **INTRODUCTION**

Presence of defects such as disbonds, delaminations, impact damage, in thermal protection systems can significantly reduce safety of the Space Shuttle and its crew. The physical cause of Space Shuttle Columbia's catastrophic failure was a breach in its thermal protection system, caused by a piece of external tank insulating foam separating from the external tank and striking the leading edge of the left wing of the orbiter. There is an urgent need for a rapid, robust and life-cycle oriented nondestructive testing (NDT) technique capable of inspecting the external tank insulating foam as well as the orbiter's protective (acreage) heat tiles and its fuselage prior and subsequent to a launch. Such a comprehensive inspection technique enables NASA to perform life-cycle inspection on critical components of the orbiter and its supporting hardware. Consequently, NASA Marshall Space Flight Center initiated an investigation into several potentially viable NDT techniques for this purpose. Microwave and millimeter wave NDT methods have shown great potential to achieve these goals [1-4]. These methods have been successfully used to produce images of the interior of various complex, thick and thin external tank insulating foam structures for real focused reflectometer at operating frequency from 50-100 GHz [1-2] and for synthetic aperture techniques at Ku-band (12-18 GHz) and K-band (18-26 GHz) [3-4]. Preliminary results of inspecting heat tile specimens show that increasing resolution of the measurement system is an important issue [2]. This paper presents recent results of an investigation for the purpose of detecting anomalies such as debonds and corrosion in metal substrate in complex multi-sectioned protective heat tile specimens using a real focused 150 GHz (D-band) reflectometer and wide-band millimeter wave holography at 33-50 GHz (Q-band).

### **APPROACHES**

The acreage heat tiles are multi-layered structures composed of a variety of ceramic-like materials capable of insulating the fuselage of the space shuttle from the extreme heat encountered during its re-entry into the atmosphere. The heat tiles are in the family of low loss dielectric materials but with higher relative permittivity than spray on foam insulation. One of the acreage heat tile specimens used in this investigation is shown in Figure 1a. It was composed of nine individual square tiles with an approximate area of 150 mm by 150 mm with varying

thicknesses in the range of 15 mm to 30 mm (even within a given tile) and three rectangular tiles with an approximate area of 75 mm by 150 mm. Aluminum substrate of this specimen had two square and one rectangular thin pockets. Various anomalies representing thin debonds of different shapes and poor bonds between the tiles and substrate as well as circular repair regions inside the tiles were embedded in these specimen.

In this investigation, two high resolution inspecting approaches were used namely, a real focusing millimeter wave approach using lens antennas and wide-band millimeter wave holography using low-gain (non-focused) antennas. For both approaches the heat tile specimens were placed on a 2D automated scanning table. The reflectometers were held at a fixed position above the specimens while the table moved the specimen underneath the reflectometers.

The real focused millimeter wave reflectometer systems that have been used at V-band (50-57 GHz), W-band (75-110 GHz) and D-band (110-170 GHz) incorporated lens antennas so that the radiating beam could be focused at a small footprint. The systems operating at 100 GHz and 150 GHz have been very successful in detecting the various anomalies mentioned above. However, the 150 GHz reflectometer system provided for a smaller footprint of approximately 2 mm in diameter. In addition, given the nature of the heat tile it is expected that at frequencies much above 150 GHz the signal will experience significant reflection from the surface of the tiles and scattering within the specimen. At this frequency, 2D raster scanned images of the specimens were produced at different standoff distances (e.g., the distance between the lens and the surface of a specimen). A DC voltage, proportional to the reflected signal from the specimen under test was then measured at each location and recorded in a matrix corresponding to the scanning area. Subsequently, the measured voltages in this matrix were normalized (with respect to the highest voltage value) and a gray-scale or color image of the specimen was produced.

Wide-band millimeter wave holography is capable of producing relatively high-resolution 2D and 3D images of the interior of the specimen without necessitating a physically large antenna to produce a small illumination size [5]. Instead, a large antenna is synthesized through the movement of a small antenna rendering a synthetically produced antenna array (i.e., antenna with a narrow beam), which results in measurements with high spatial resolution. The measurement time for one scan of the specimen by this method is comparable to measuring with the lens antenna and subsequent processing and rendering time is less than one minute. The advantage of this method is that the 3D images of the specimen (or 2D images of the specimen at different depths) can be generated from data obtained in one scan. For the purpose of inspecting heat tile specimens, measurements of the complex reflection coefficient were taken every 2 mm with 201 sampled frequency points using an Agilent E8361A Network Analyzer in conjunction with a Q-band (33-50 GHz) open-ended rectangular waveguide probe.

## RESULTS

Figures 1 shows the millimeter wave images of the heat tile specimen composed of twelve individual tiles obtained using the 150 GHz reflectometer with a lens antenna (Fig. 1b), and the wide-band holography at 33-50 GHz (Fig. 1a). It must be noted that the image shown in Figure 1a is the raw image and no signal/image processing was applied to it. This is significant since it shows the effectiveness of this millimeter wave NDT method for producing rapid and informative images about the interior of the heat tile specimen. The debonds of different shapes (marked by red arrows) under six of the tiles as well as the two circular repair regions (marked by yellow arrows) are clearly evident. The image shown in Figure 1b also shows a number of

unknown indications which shape allows making a conclusion that these are indications of poor bonds and non-uniformities in the adhesive layer between the tiles and the substrate.

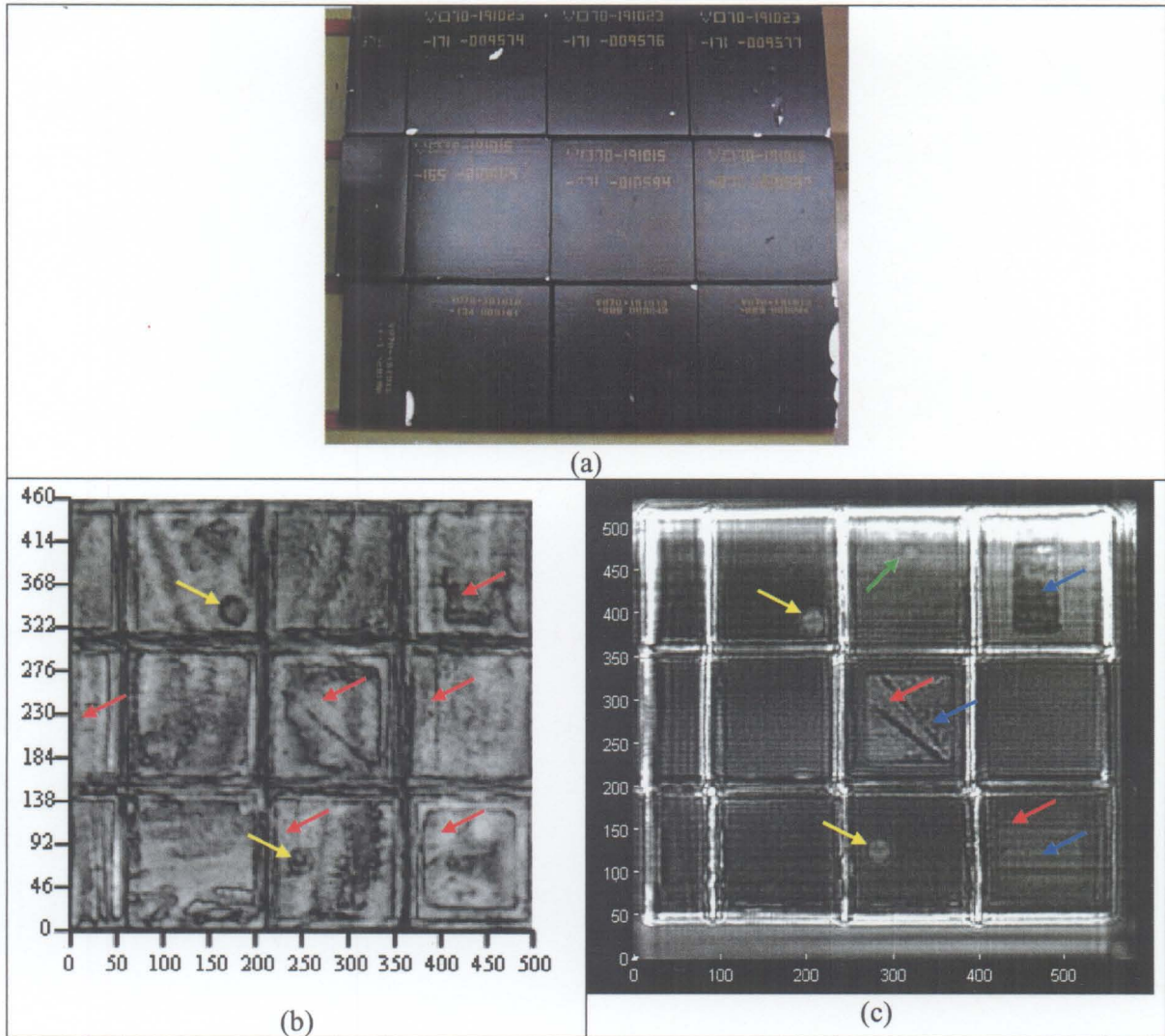


Figure1: (a) Picture of heat tile specimen, and millimeter wave images of this specimen, obtained using (b) 150 GHz reflectometer with a lens antenna and (c) wide-band holography at 33-50 GHz (dimensions are in mm).

Figure 1c shows the hologram viewed from above, and this view/image of the specimen demonstrates very clear indications of some debonds (marked by red arrows), repair regions (marked by yellow arrows) as well as the pockets in the substrate (marked by blue arrows) with sharp boundaries. The image of the middle square tile possessing diagonal debond clearly shows the debond and its respective spatial extents. Three indications of the pockets in the substrate are visible more clearly than those in the image obtained with the 150 GHz reflectometer. The unknown anomaly (marked by green arrow) was also clearly detected. Other images of the

specimens with indications of other anomalies and structural features of the specimen obtained from the hologram shown in Figure 1c will be presented in the paper.

## SUMMARY

Anomalies such as debonds and poor bonds between the heat tiles and substrate in the thermal protective system of the orbiter can significantly reduce its insulating effectiveness. Additionally, these anomalies may cause complete separation of the heat tiles from the fuselage exposing it to extreme heat. The results of these investigations clearly show the utility of millimeter wave NDT methods for detecting anomalies in heat tiles specimens similar to those used in the space shuttle. The real focused 150 GHz reflectometer produces high resolution images of the specimen without the need for image processing algorithms. The wide-band millimeter wave holography at 33-50 GHz provides high-resolution images of the specimen at different depths using data of one scan and relatively simple processing algorithm. Both methods provide a significant amount of information about the nature of an anomaly (e.g., size, location, etc.). This paper will also present the results of detection of anomalies including corrosion areas on the surface of the substrate under heat tiles in other heat tile specimens.

*Acknowledgement:* Funding for this work has been provided by the NASA Marshall Space Flight Center, Huntsville, Alabama.

## REFERENCES

1. S. Kharkovsky, J.T. Case, M. A. Abou-Khousa, R. Zoughi and F. Hepburn, Millimeter Wave Detection of Localized Anomalies in the Space Shuttle External Fuel Tank Insulating Foam, *IEEE Transactions on Instrumentation and Measurement*, vol. 55, No 4, Aug. 2006, pp. 1250-1257.
2. R. Zoughi, S. Kharkovsky and F. Hepburn, Microwave and Millimeter Wave Testing for the Inspection of the Space Shuttle Spray on Foam Insulation (SOFI) and the Acreage Heat Tiles, *Proceedings of the Thirty Second Annual Review of Progress in Quantitative Nondestructive Evaluation*, vol. 25A, pp. 439-446, Brunswick, Maine, July 31- August 5, 2005.
3. J.T Case, F. Hepburn, and R. Zoughi, Inspection of Spray on Foam Insulation (SOFI) Using Synthetic Aperture Focusing and Holography, *Proceedings of the IEEE Instrumentation and Measurement Technology Conference*, pp.2148-2153, Sorrento, Italy, 2006.
4. J.T Case, J. Robbins, S. Kharkovsky, R. Zoughi and F. Hepburn, Microwave and Millimeter Wave Imaging of the Space Shuttle External Tank Spray on Foam Insulation (SOFI) Using Synthetic Aperture Focusing Techniques (SAFT), *Proceedings of the Thirty Second Annual Review of Progress in Quantitative Nondestructive Evaluation*, vol. 25B, pp. 1546-1553, Brunswick, Maine, July 31- August 5, 2005.
5. D.M. Sheen, D.L. McMakin, T.E. Hall, "Three-Dimensional Millimeter-Wave Imaging for Concealed Weapon Detection," *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, No 9, Sept. 2001. pp. 1581-1592.



---

# **High-Resolution Millimeter Wave Inspecting of the Orbiter Acreage heat Tiles of the Space Shuttle**





---

# **J.T. Case, S. Kharkovsky and R. Zoughi**

Applied Microwave Nondestructive Testing  
Laboratory (*amntl*)  
Electrical and Computer Engineering Department  
University of Missouri-Rolla (UMR)  
Rolla, MO, USA





# Collaborators

---

**F.L. Hephburn**

NASA Marshall Space Flight Center (MSFC)

Huntsville, AL, USA





# Acknowledgment

---

This work was supported by a  
Cooperative Agreement from  
NASA Marshall Space Flight Center.





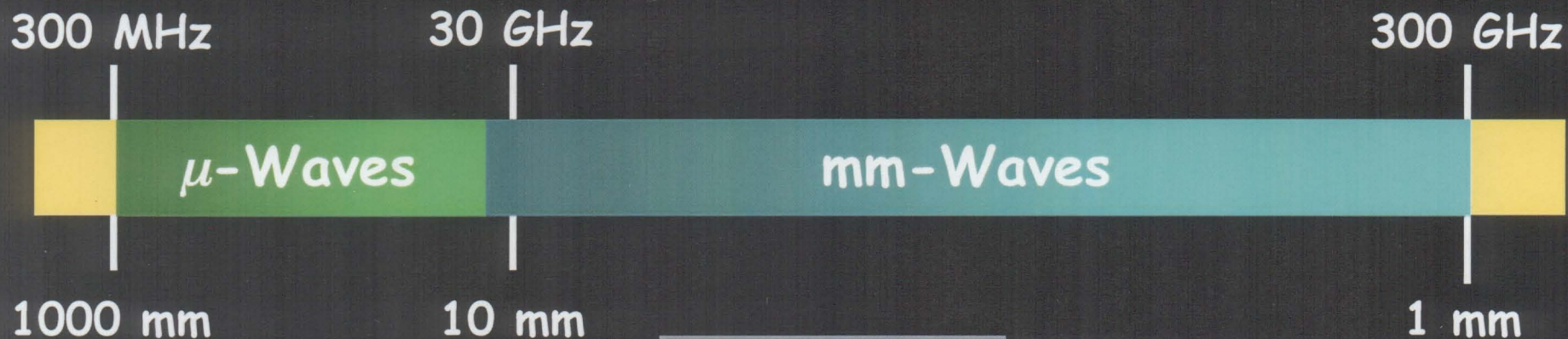
# Outline

---

- ◆  $\mu$ -wave and mm-wave and band designations.
- ◆ Attributes of  $\mu$ -wave and mm-wave NDT&E.
- ◆ Results of initial SOFI imaging.
- ◆ Results of focused mm-wave SOFI and heat tile imaging.
- ◆ Synthetic aperture focusing techniques □ SAF and holography results.
- ◆ Results of heat tile imaging.
- ◆ Discussion.



# $\mu$ -Wave & mm-Wave Spectrum



**K-Band** **Ka-Band** **V-Band** **W-Band** **D-Band** ---  
18-26.5 26.5-40 50-75 75-110 110-170



# Attributes

---

- ◆ Acreage heat tiles are in the family of low permittivity and low loss dielectric materials.
- ◆  $\mu$ -wave and mm-wave signals easily penetrate into these materials and are sensitive to dielectric property variations.
- ◆ Polarization diversity for image enhancement.
- ◆ No need for a separate transmitter and receiver (i.e., mono-static systems).
- ◆ Obtain images with high spatial resolution □  
**real-** and **synthetic**-aperture methods.



# Attributes

---

- ◆ 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.



# Attributes

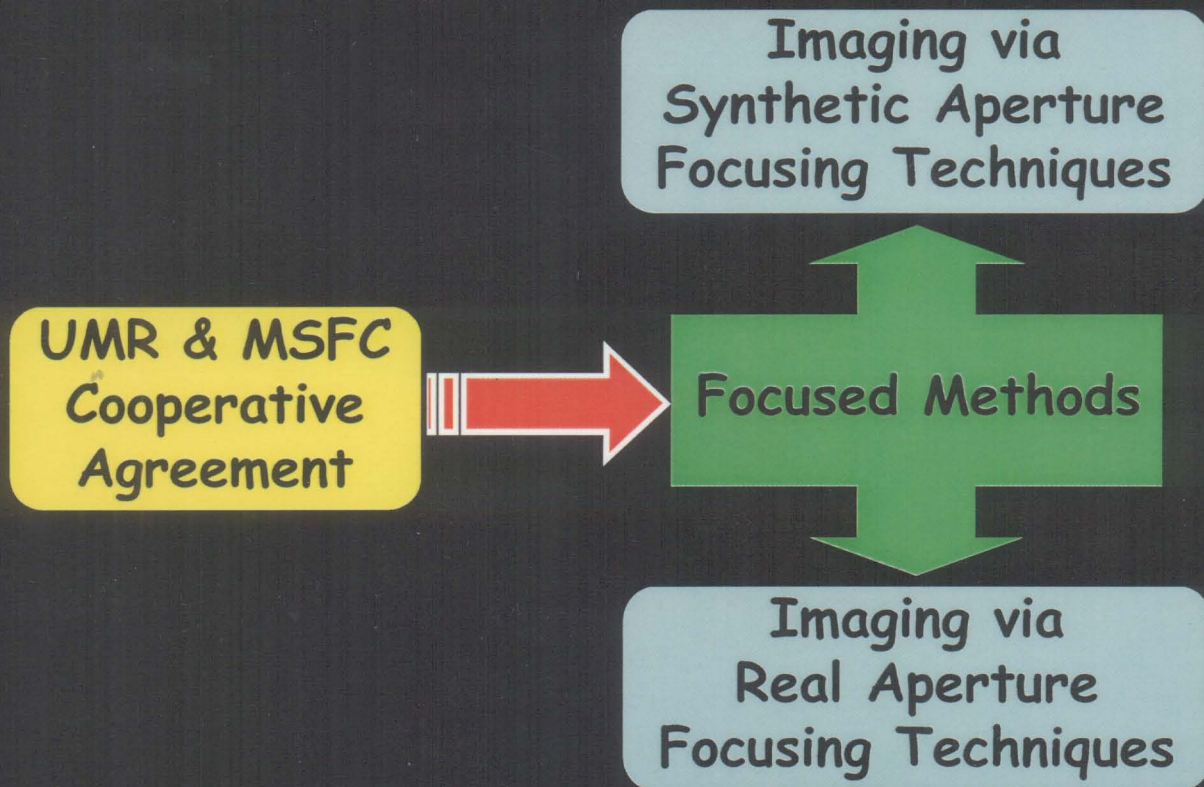
---

- ◆ 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
- ◆ Relatively inexpensive.



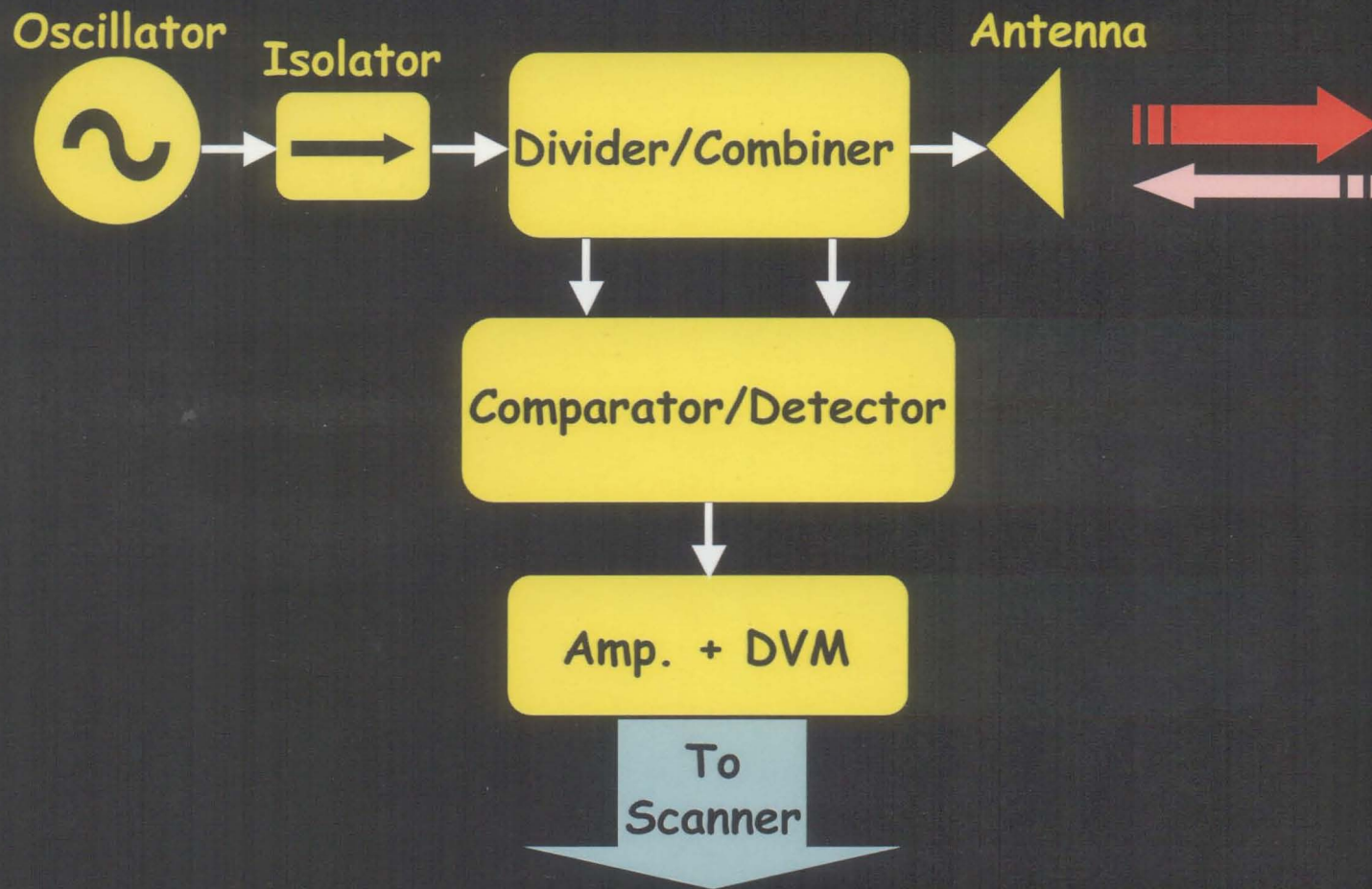
# Collaboration

---





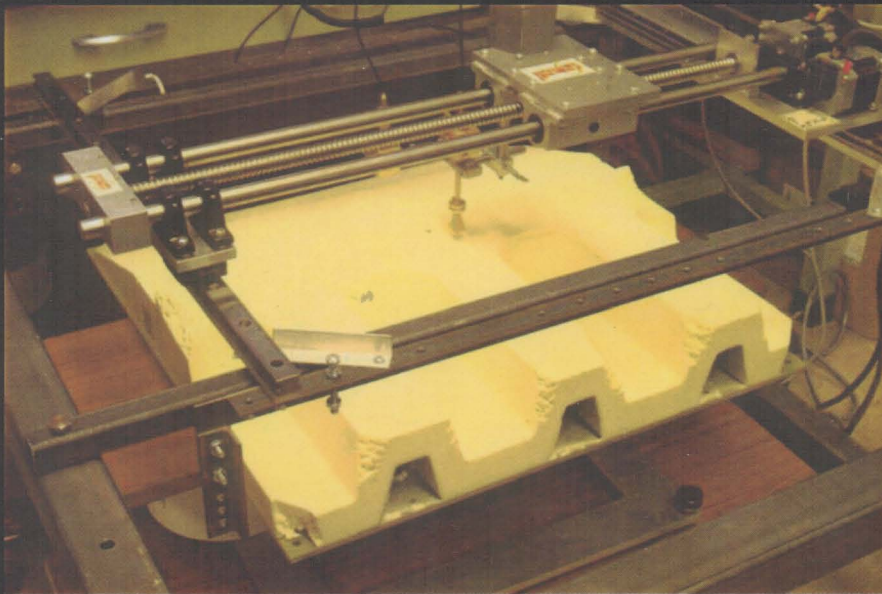
# Real Aperture Focused System



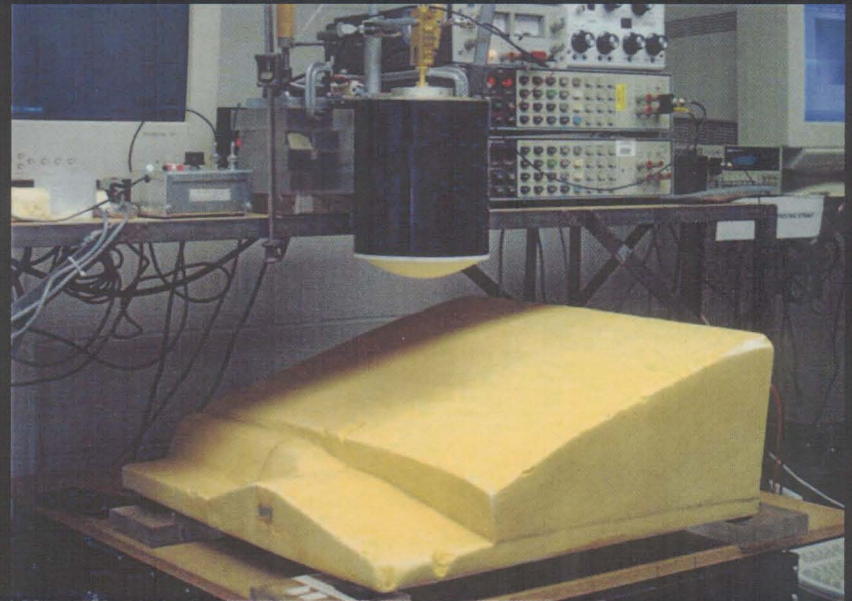


# Real-Aperture Focused Systems

100 GHz

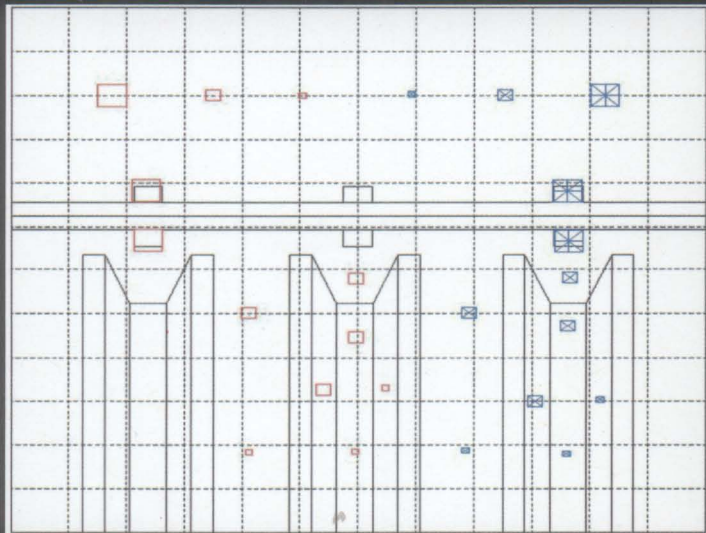


150 GHz





# POD Panel Schematic

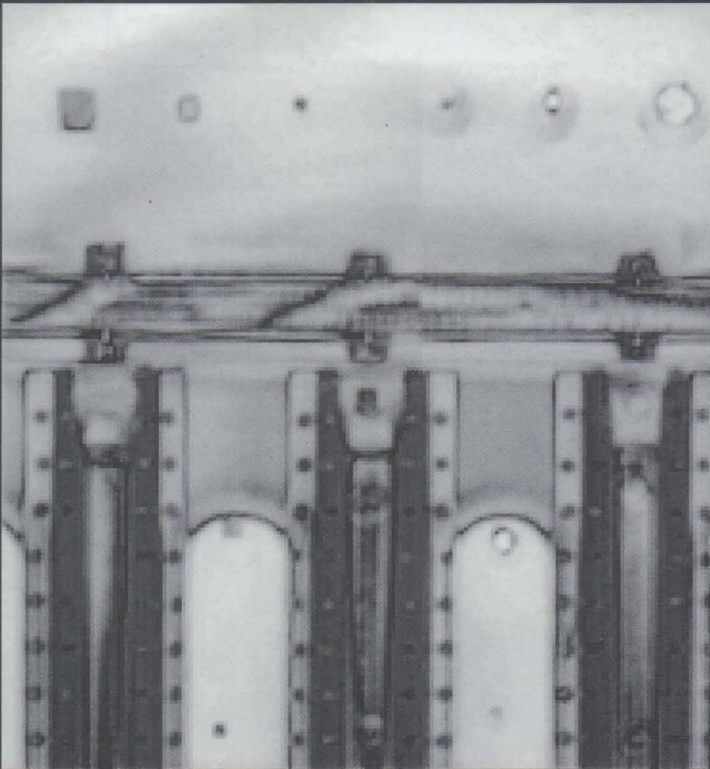




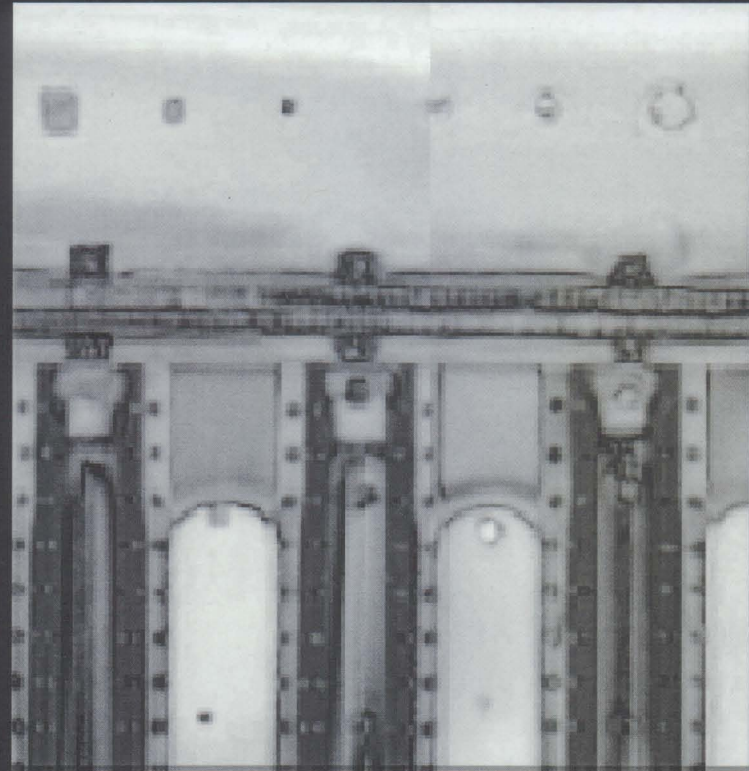
# POD Panel - 150 GHz

---

Perpendicular



Parallel

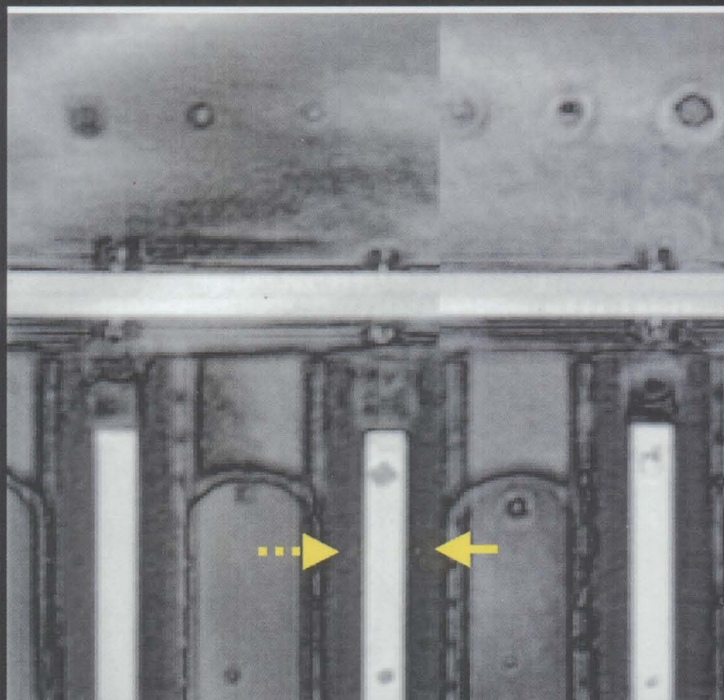


Focused at Substrate

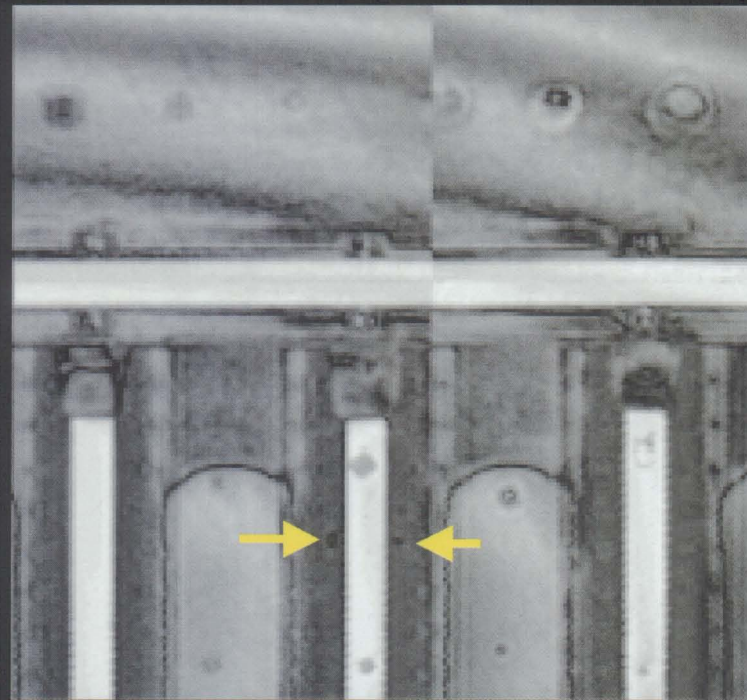


# POD Panel - 150 GHz

Perpendicular



Parallel



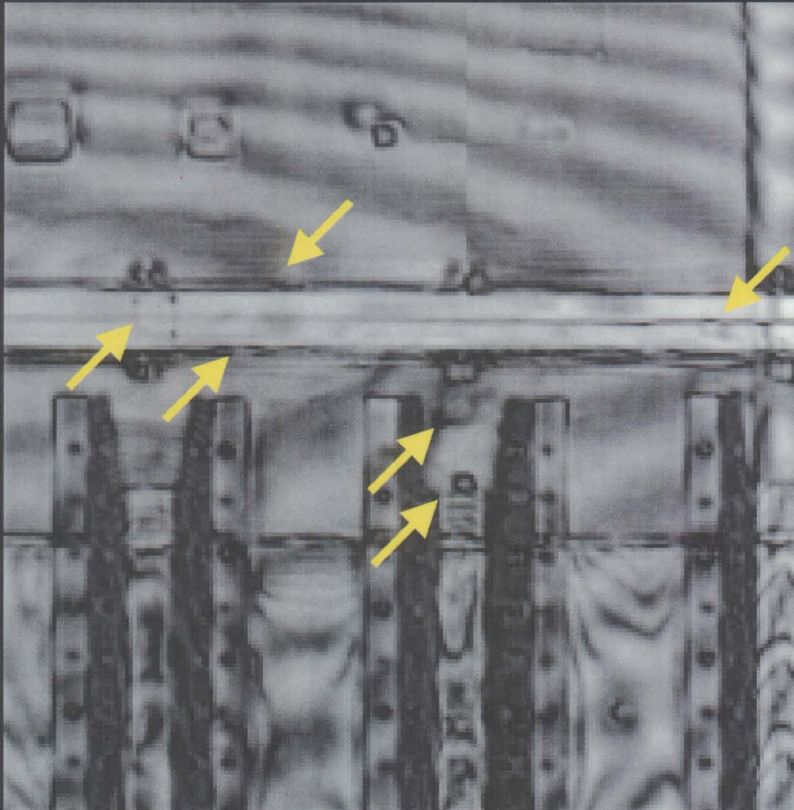
Focused at  $\sim 2.12$  above Substrate



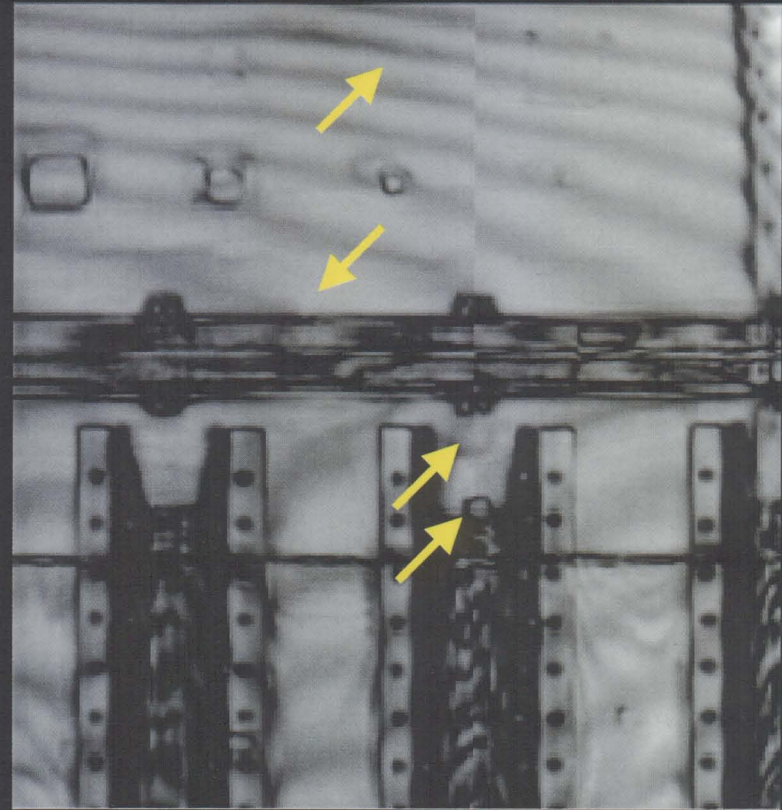
# PAL Ramp – 150 GHz

---

Focused at Conethane



Focused at Substrate





# Acreage Heat Tile Sample

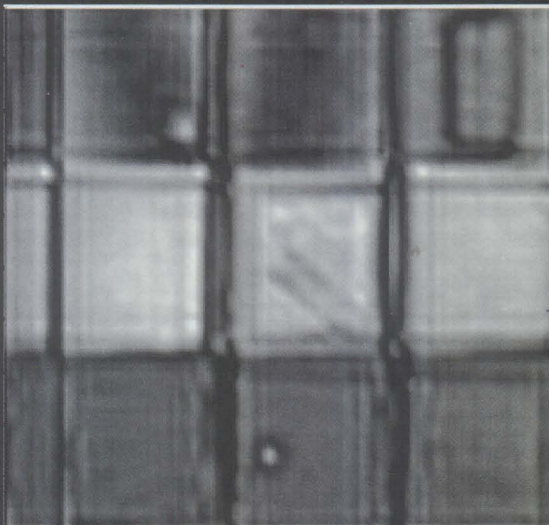




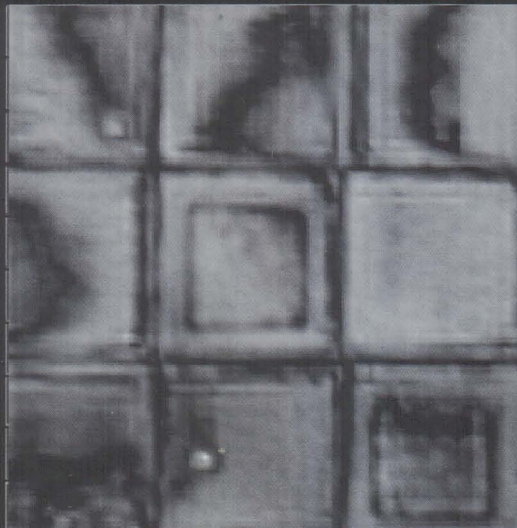
# Heat Tiles

---

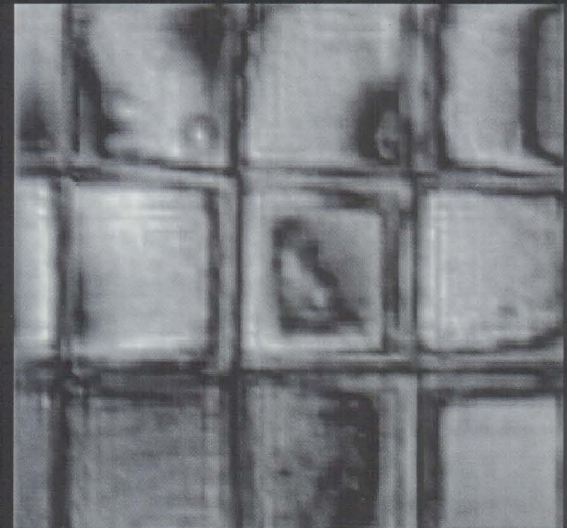
Ka-Band  
33.5 GHz



V-Band  
67 GHz



V-band  
70 GHz



All with small horn antennas.

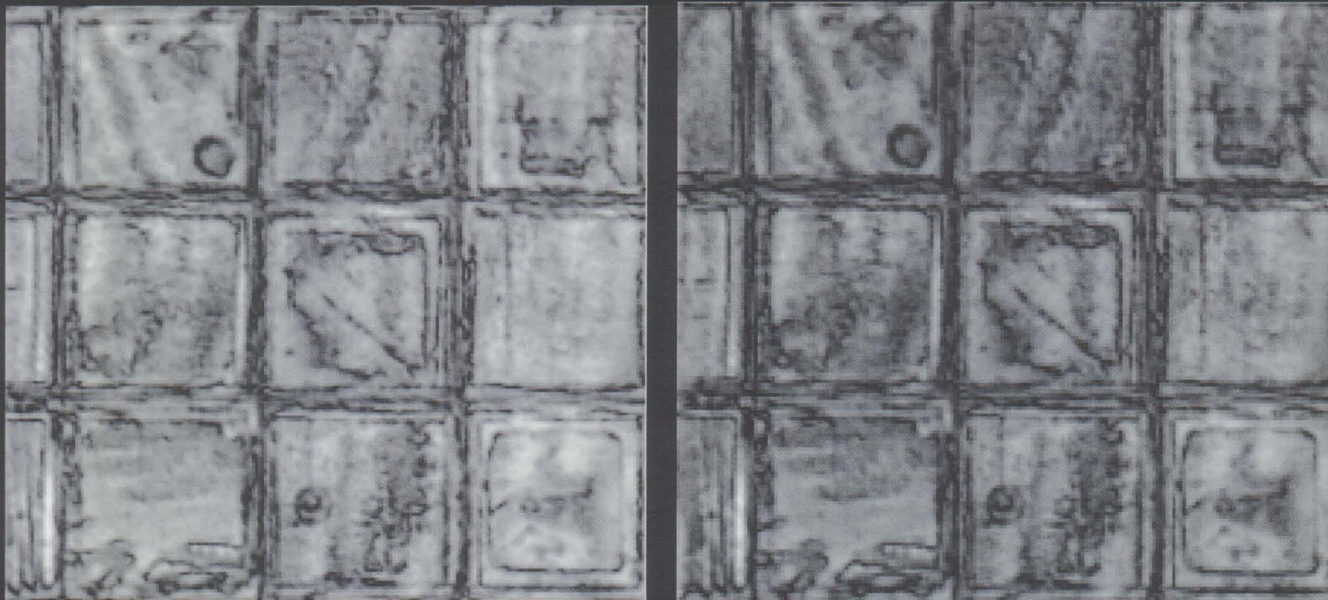




# Heat Tiles

---

D-band  
150 GHz



Using a focusing lens antenna.



# Synthetic-Aperture Focusing

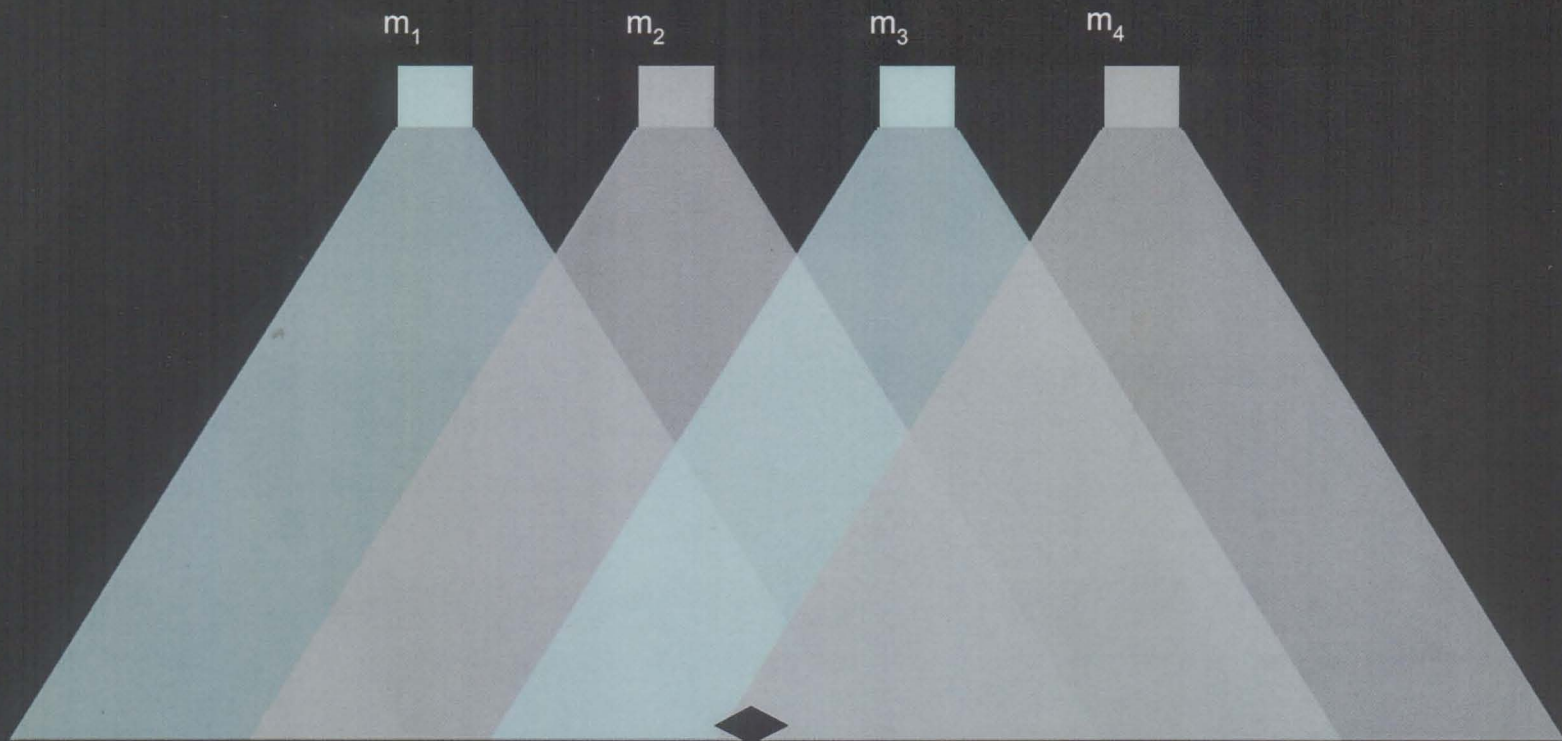
---

- ◆ 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.
- ◆ For SOFI inspection, for example 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

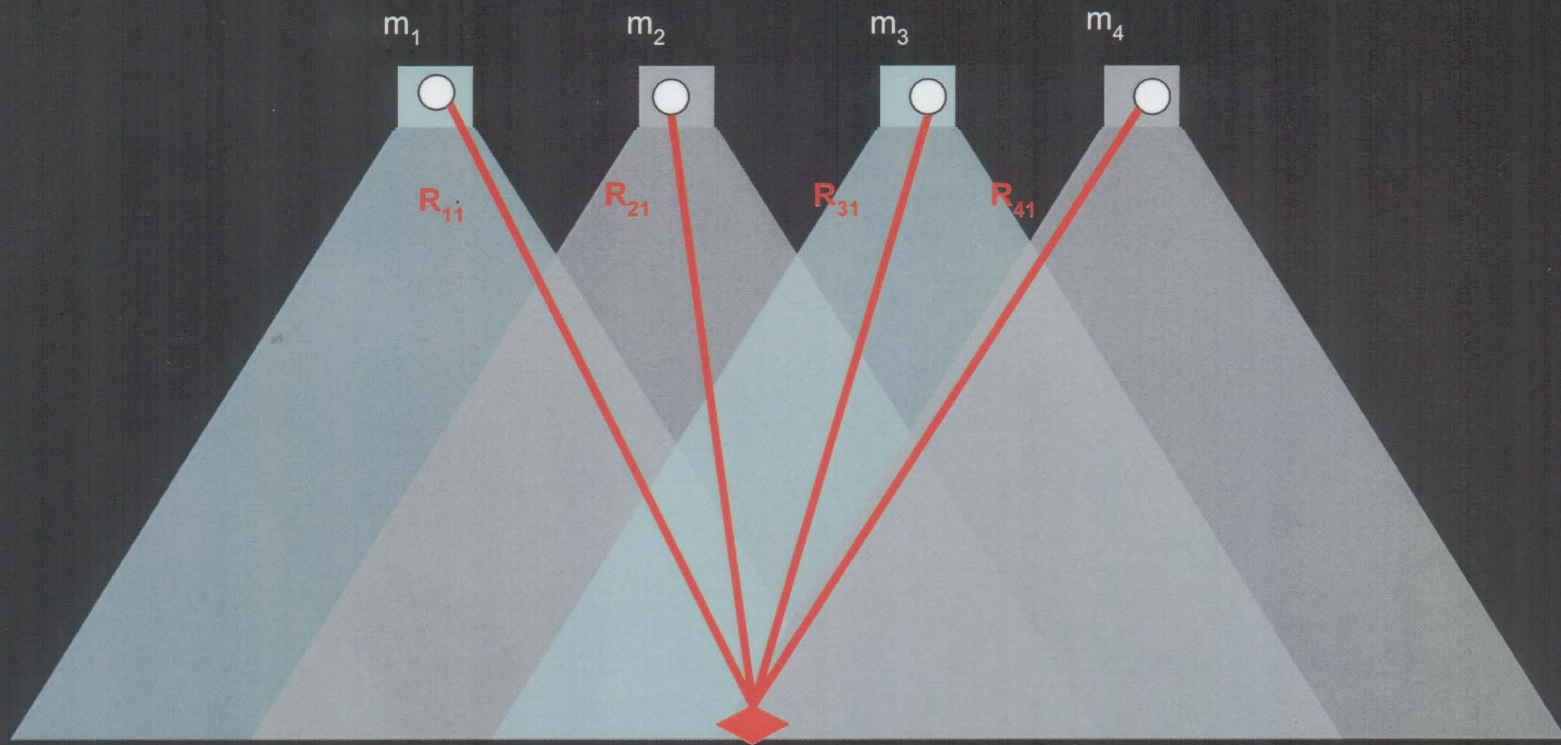
Antenna Motion Direction





# Synthetic Aperture Focusing

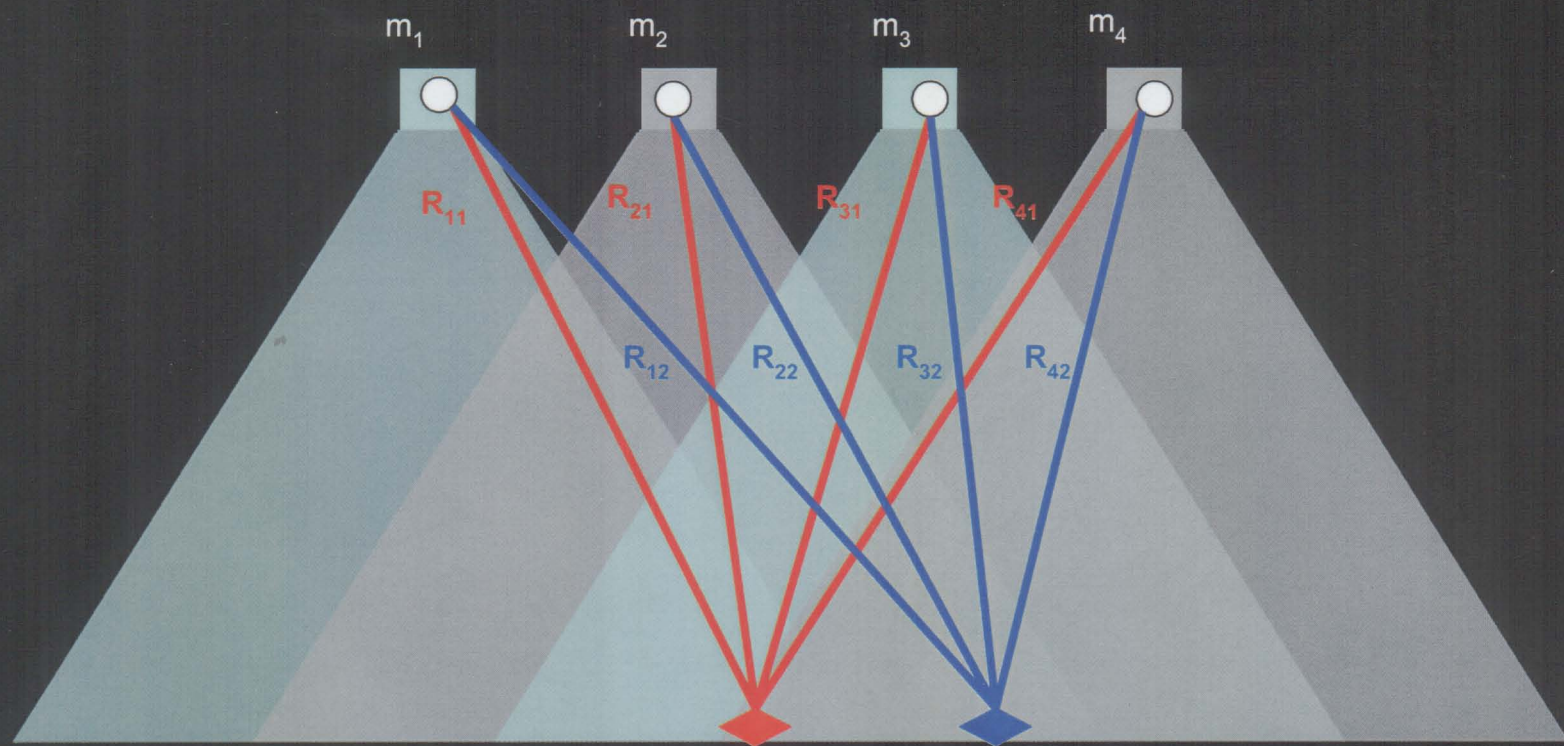
Antenna Motion Direction





# Synthetic Aperture Focusing

Antenna Motion Direction



$$s_k = \sum_{i=1}^4 m_i \exp(j2\beta R_{ik})$$



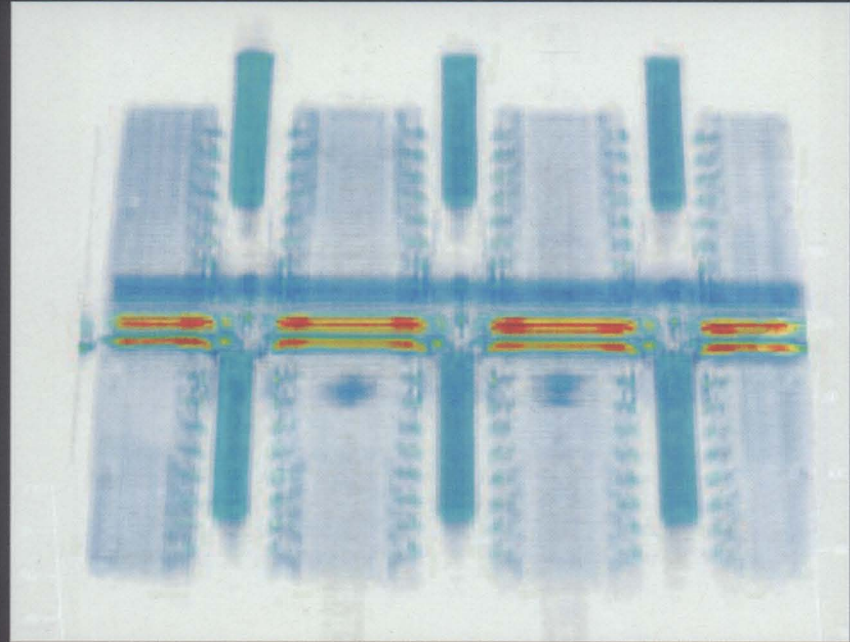
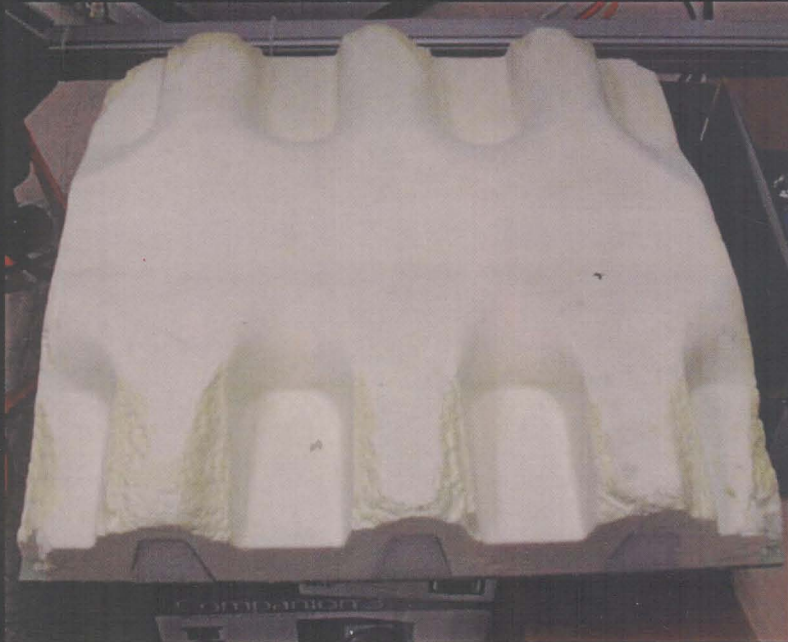
# $\mu$ -Wave Holography

---

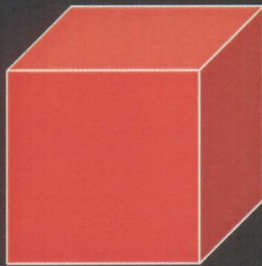
- ◆ Swept frequency measurements, at mm-waves where large bandwidths are available, can be used to produce images with high range (i.e., depth) resolution.
- ◆ This way one may obtain high resolution 3D images of SOFI or acreage heat tiles.



# SOFI Results K-Band



K-Band



V-Band

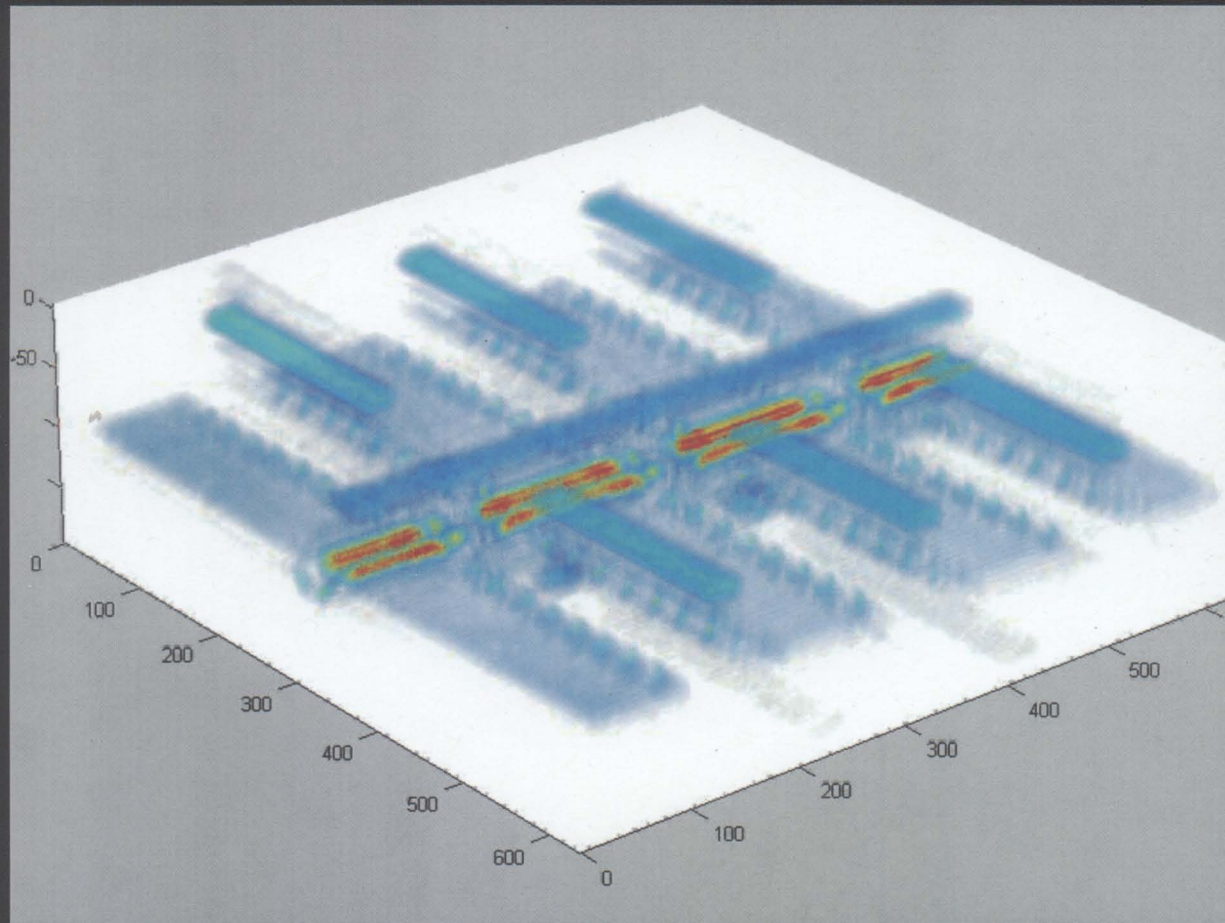


W-Band





# SOFI Results K-Band

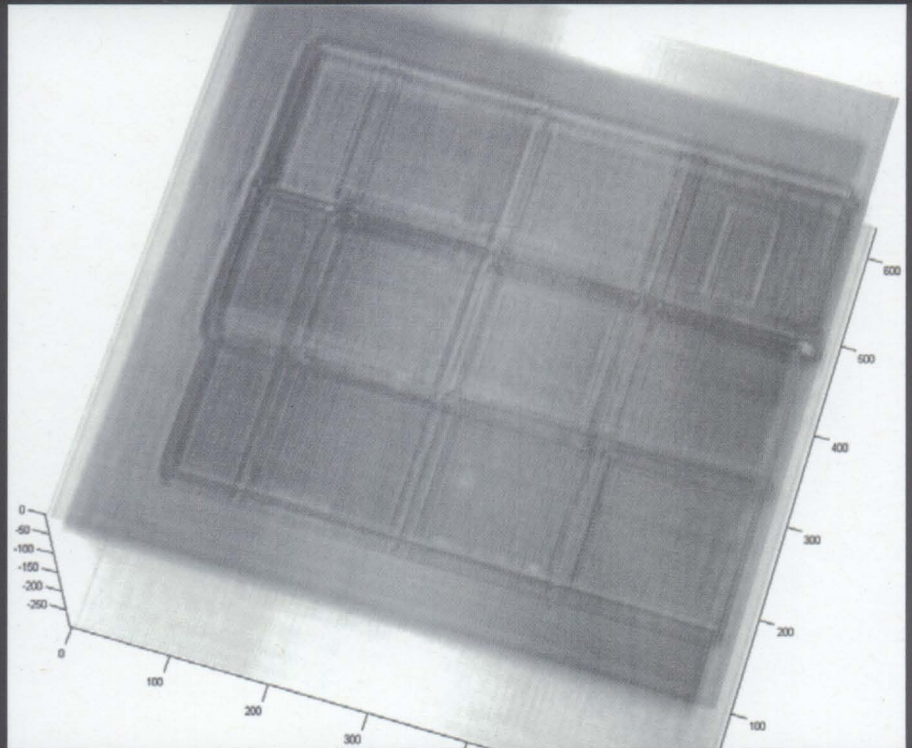
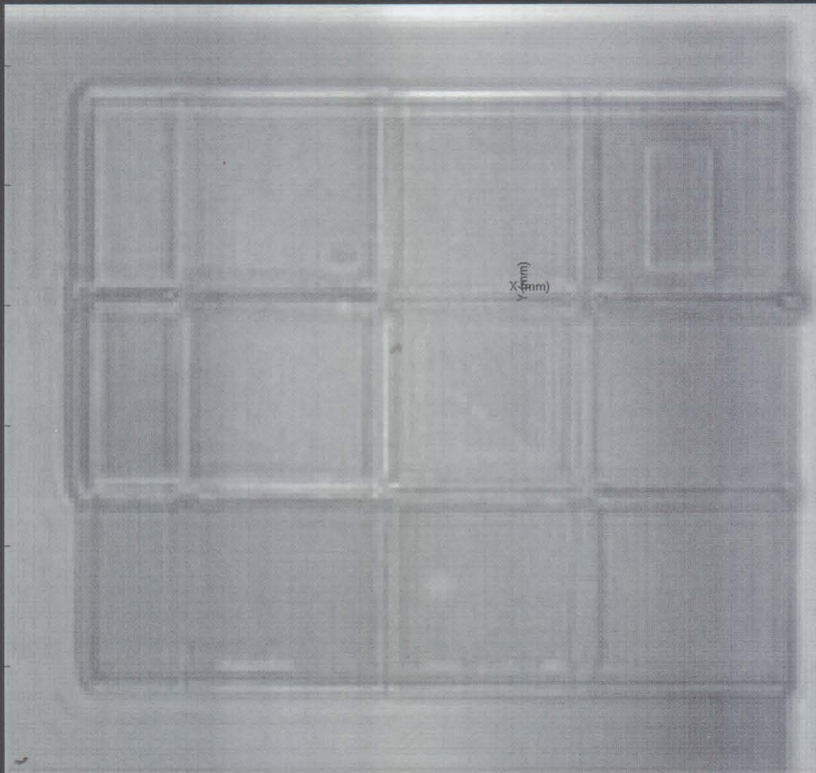


IEEE IMTC 2007

UMR



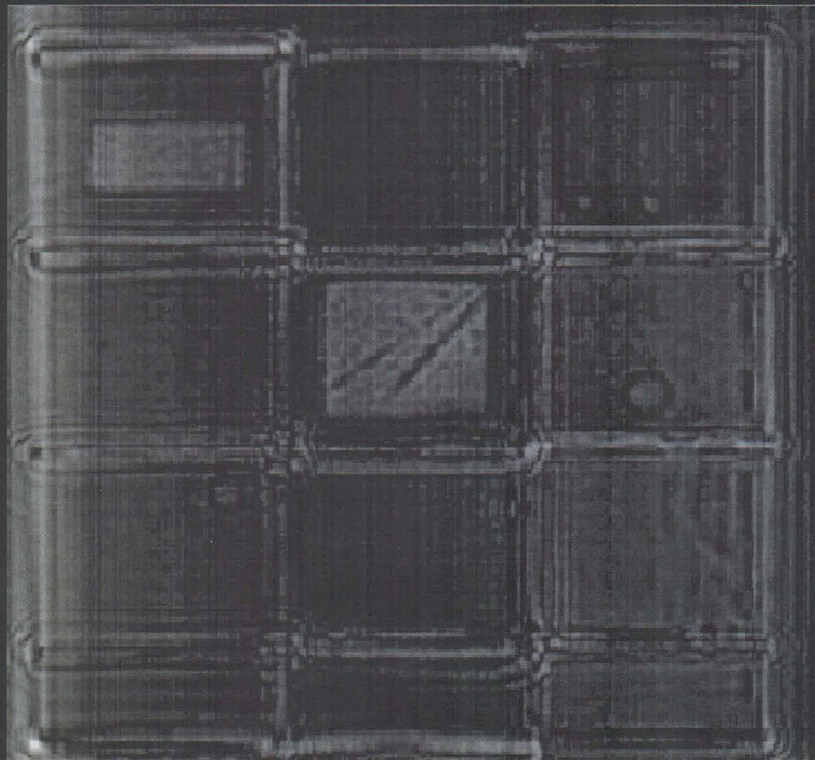
# Heat Tile Results @ K-Band





# Heat Tile Results @ Q-Band

---

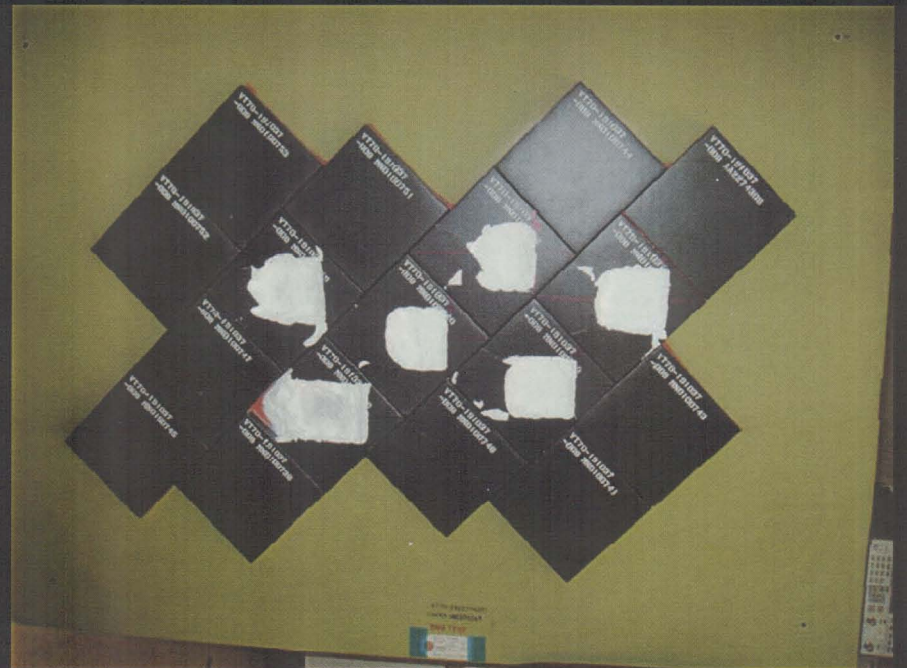
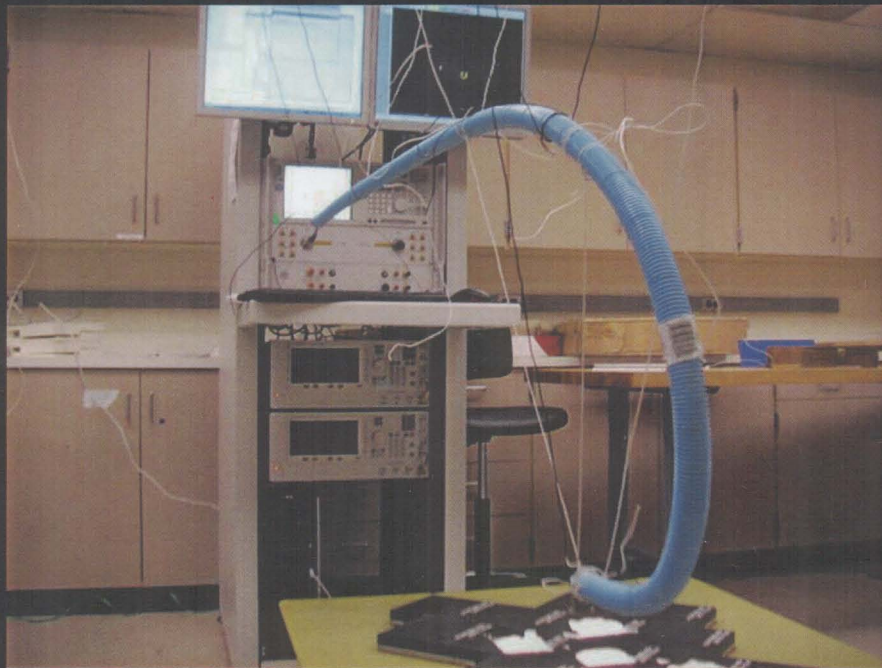


IEEE IMTC 2007

UMR



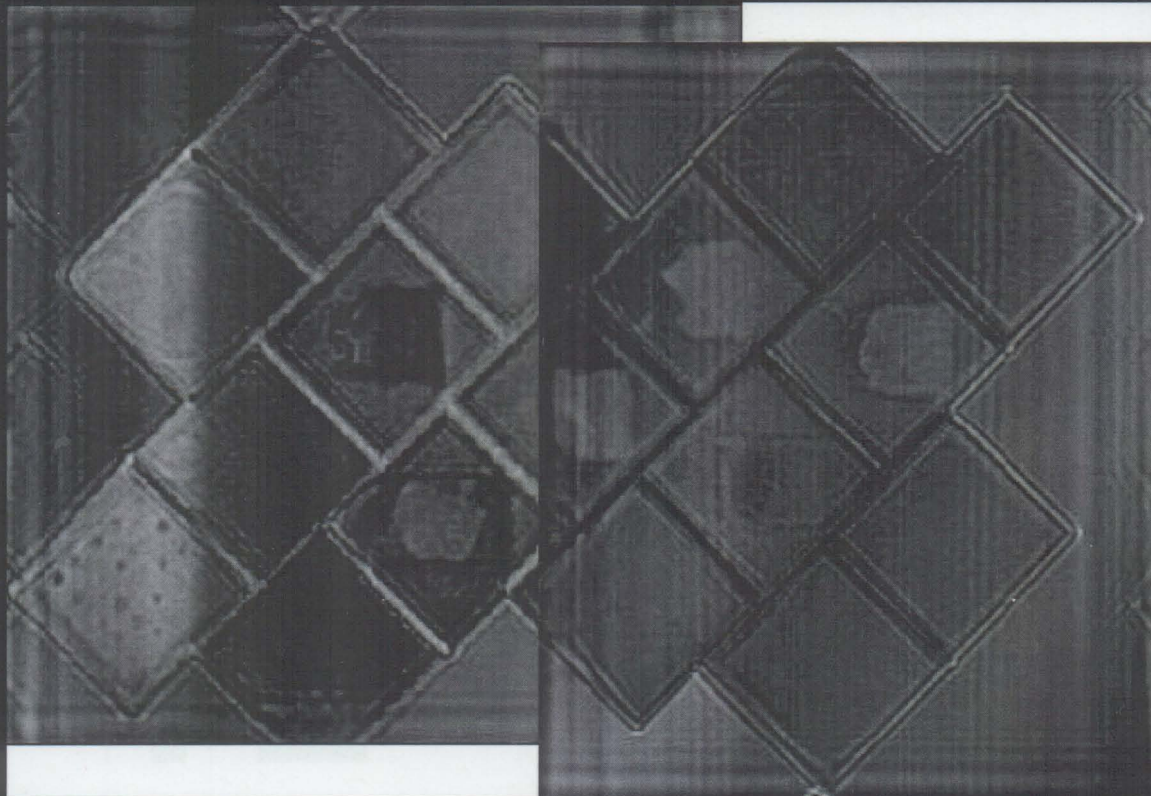
# Heat Tile Panel with Corrosion





# Holography Results @ Q-Band

---





# Discussion

---

- ◆ Detection of disbond, corrosion, and other anomalies is an important and critical issue with respect to the Space Shuttle health monitoring and other similar space vehicles.
- ◆ Real-aperture methods offer high spatial-resolution.
- ◆ Synthetic-aperture methods, in particular a swept-frequency version produces 3D high resolution images with the ability to produce image slices at various depths.
- ◆ Custom-made systems eliminate need for PNA.
- ◆ Scan time may be a practical concern (in some cases).



---

Thank You.

Questions?

