Millimeter Wave Synthetic Aperture Imaging System with a Unique Rotary Scanning System

M.T. Ghasr[1], D. Pommerenke[2], J.T. Case[1], A.D. McClanahan[1], A. Aflaki-Beni[2], M. Abou-Khousa[1], K. Guinn[1], F. De Paulis[2], S. Kharkovsky[1] and R. Zoughi[1]

Electrical and Computer Engineering Department
[1]Applied Microwave Nondestructive Testing Laboratory (*amntl*)
[2]Electromagnetic Compatibility Laboratory (EMC)
Missouri University of Science and Technology (S&T)
Rolla, MO 65409

ABSTRACT

In recent years, millimeter wave imaging techniques, using synthetic aperture focusing and holographical approaches, have shown tremendous potential for nondestructive testing applications, involving materials and structures used in space vehicles, including the space shuttle external fuel tank spray on foam insulation and its acreage heat tiles. The ability of signals at millimeter wave frequencies (30 – 300 GHz) to easily penetrate inside of low loss dielectric materials, their relatively small wavelengths, and the possibility of detecting coherent (magnitude and phase) reflections make them suitable for high resolution synthetic aperture focused imaging the interior of such materials and structures. To accommodate imaging requirements, commonly a scanning system is employed that provides for a raster scan of the desired structure. However, most such scanners, although simple in design and construction, are inherently slow primarily due to the need to stop and start at the beginning and end of each scan line. To this end, a millimeter wave synthetic aperture focusing system including a custom-designed transceiver operating at 35 – 45 GHz (Q-band) and unique and complex rotary scanner was designed and developed. The rotary scanner is capable of scanning an area with approximately 80 cm in diameter in less than 10 minutes at step sizes of 3 mm and smaller. The transceiver is capable of producing accurate magnitude and phase of reflected signal from the structure under test. Finally, a synthetic aperture focusing algorithm was developed that translates this rotary-obtained magnitude and phase into a synthetic aperture focusing image of inspected structures. This paper presents the design of the transceiver and the rotary scanning system along with showing several images obtained with this system from various complicated structures.

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Applied Microwave Nondestructive Testing Lab. (*amntl*)
Electrical and Computer Engineering Department
Missouri University of Science and Technology (S&T)
Rolla, MO 65409
zoughi@mst.edu
(573) 341-4656

A. Aflaki-Beni, F. De Paulis
and D. Pommerenke

Electromagnetic Compatibility (EMC) Laboratory
Electrical and Computer Engineering Department
Missouri University of Science and Technology (S&T)
Rolla, MO 65409

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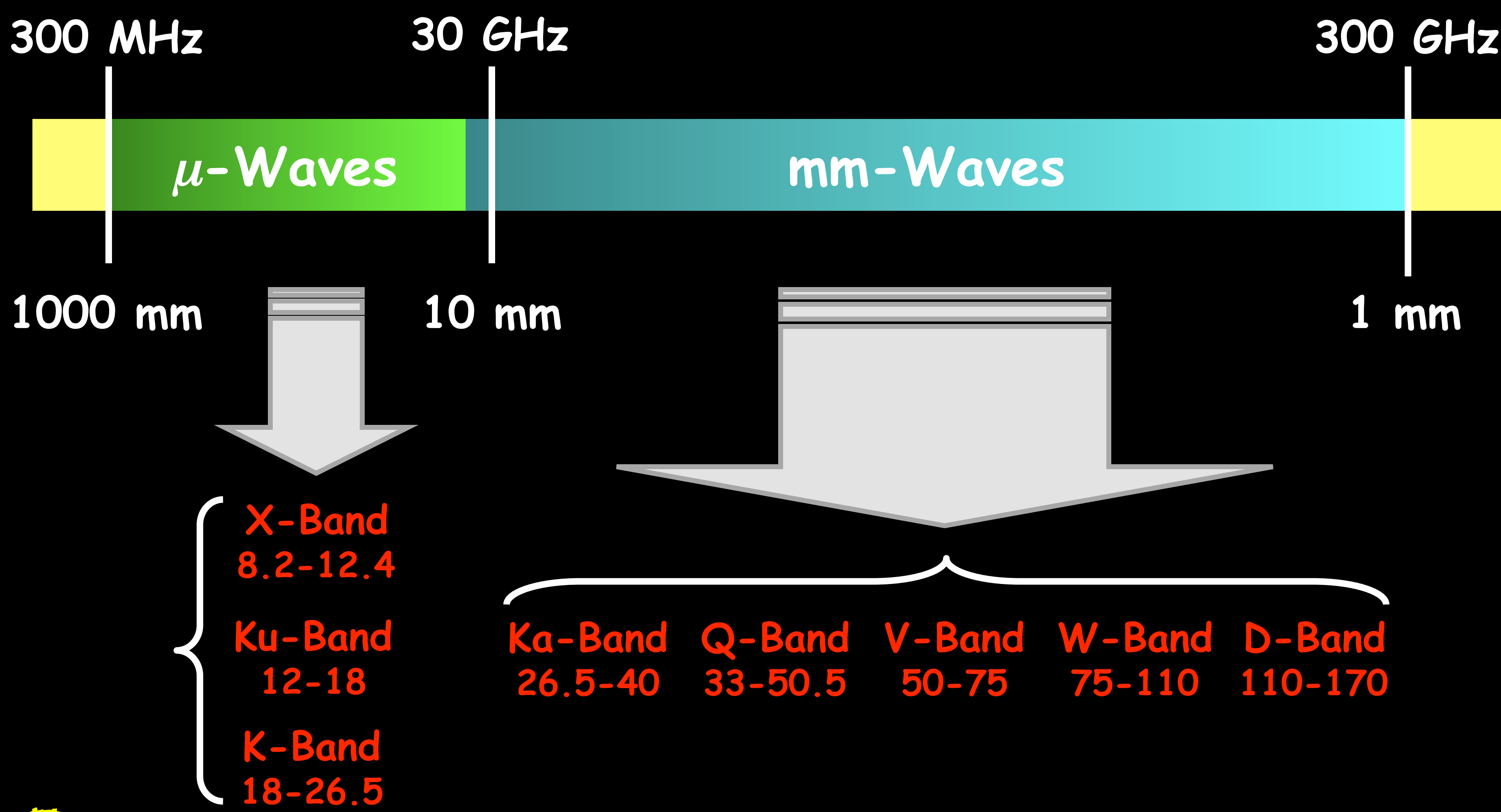
POC: Mr. F.L. Hepburn

BACKGROUND

Background


300 MHz
30 GHz
300 GHz
μ-Waves
mm-Waves
1000 mm
10 mm
1 mm
X-Band
8.2-12.4
Ku-Band
12-18
K-Band
18-26.5
Ka-Band
26.5-40
Q-Band
33-50.5
V-Band
50-75
W-Band
75-110
D-Band
110-170

Background

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

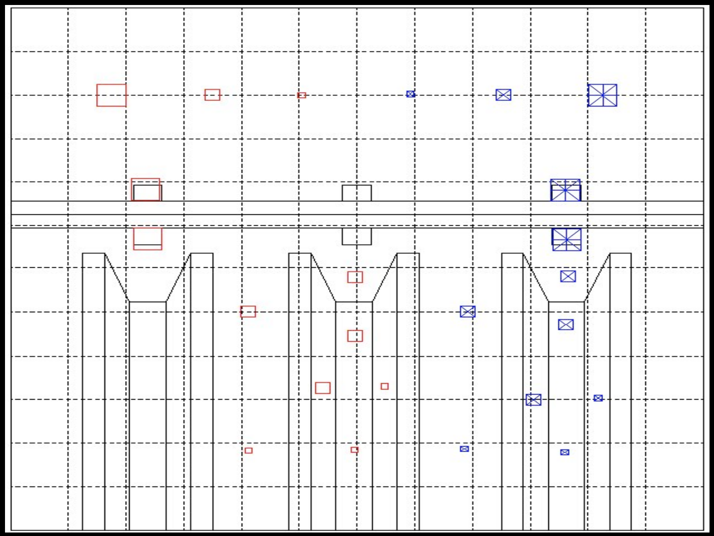
10 mm

IMAGING
and
COMPOSITE INSPECTION

Foundation

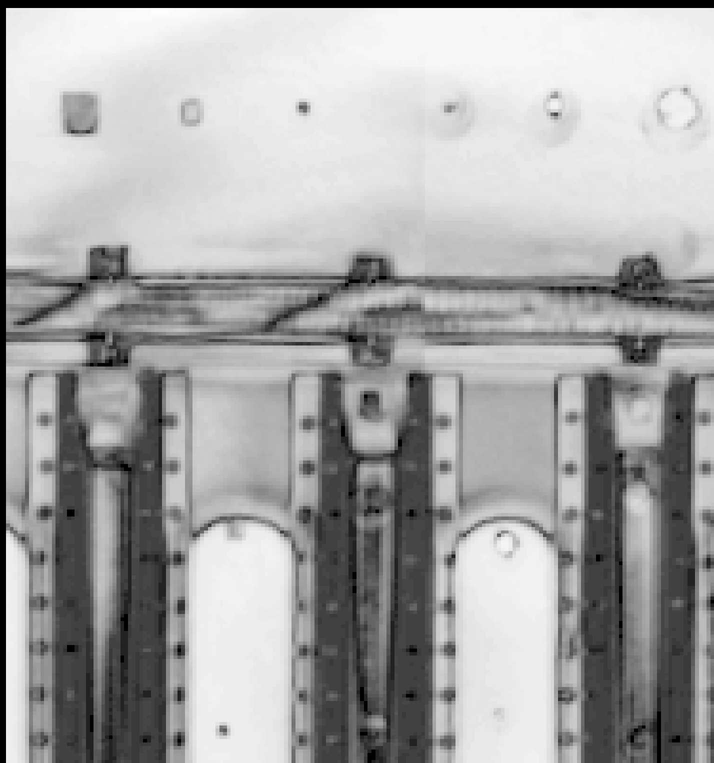
- Robust imaging capabilities since:
  - ✓ Wavelength in mm range
  - ✓ Probes are small
  - ✓ Different "focusing techniques"
  - ✓ Different "image reconstruction" techniques
- No need for a separate transmitter and receiver (i.e., mono-static systems).
- No need for pulsed systems.

POD Panel

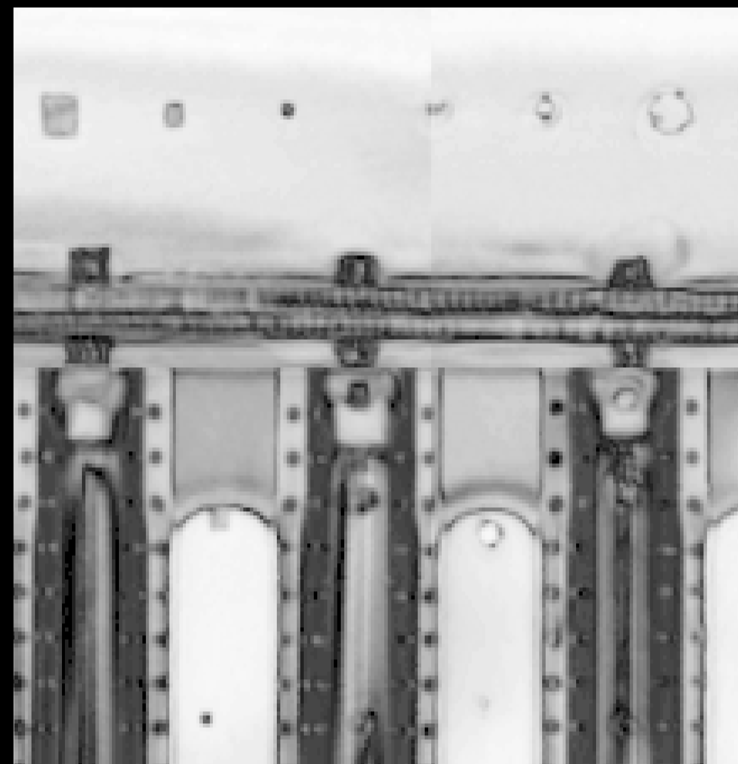


POD Panel – 150 GHz

Perpendicular

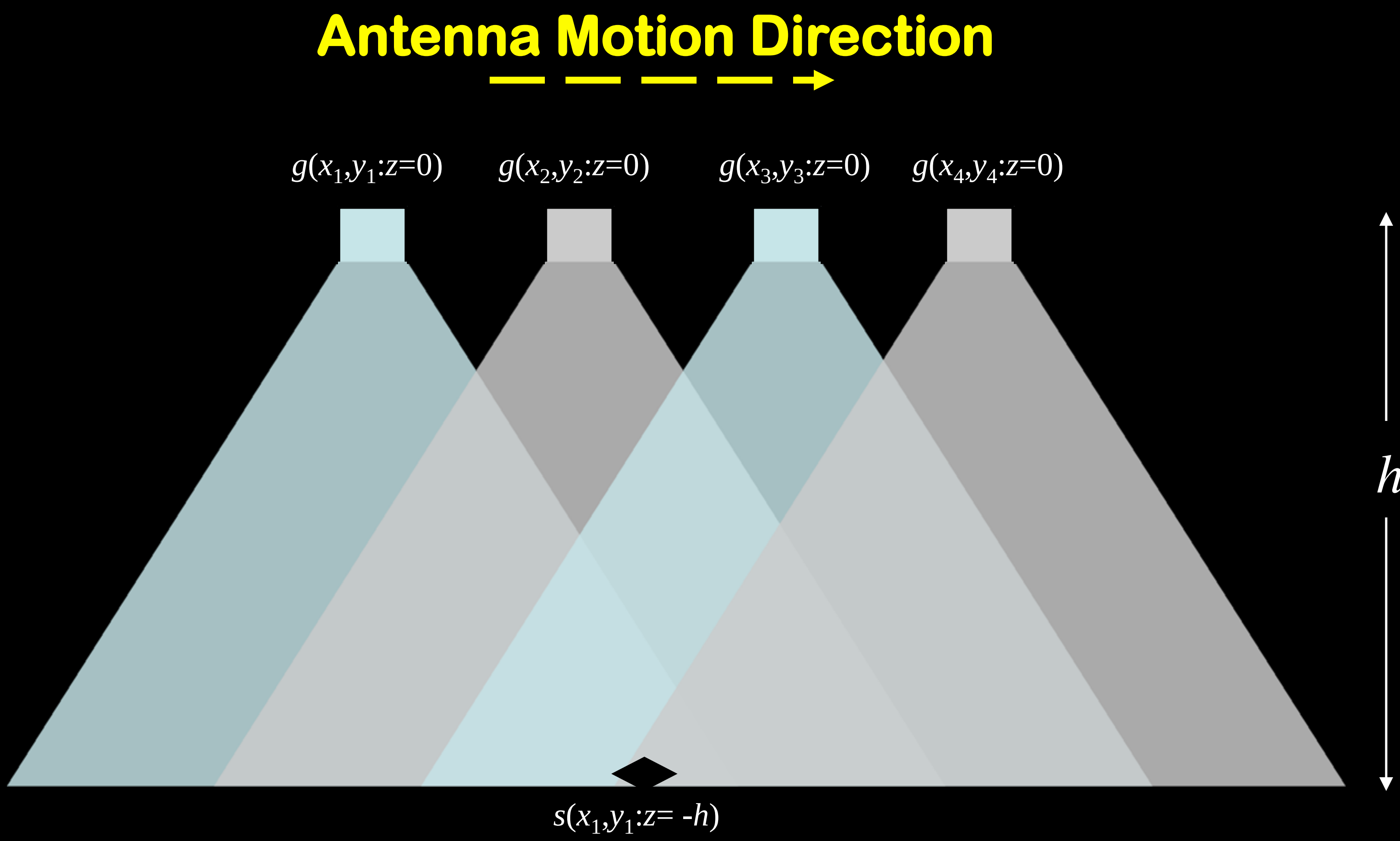


Parallel

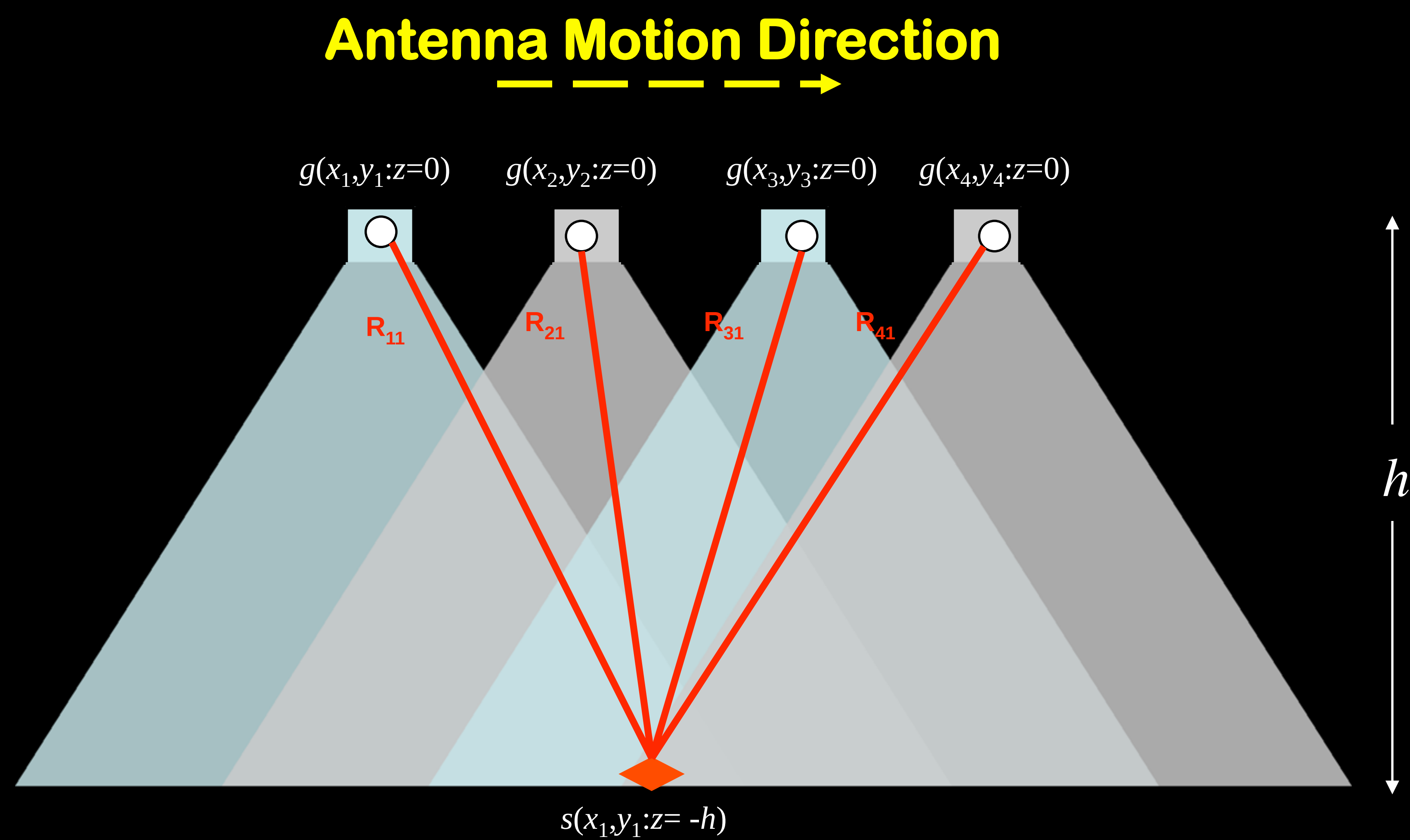


Focused at Substrate

Synthetic Aperture Focusing

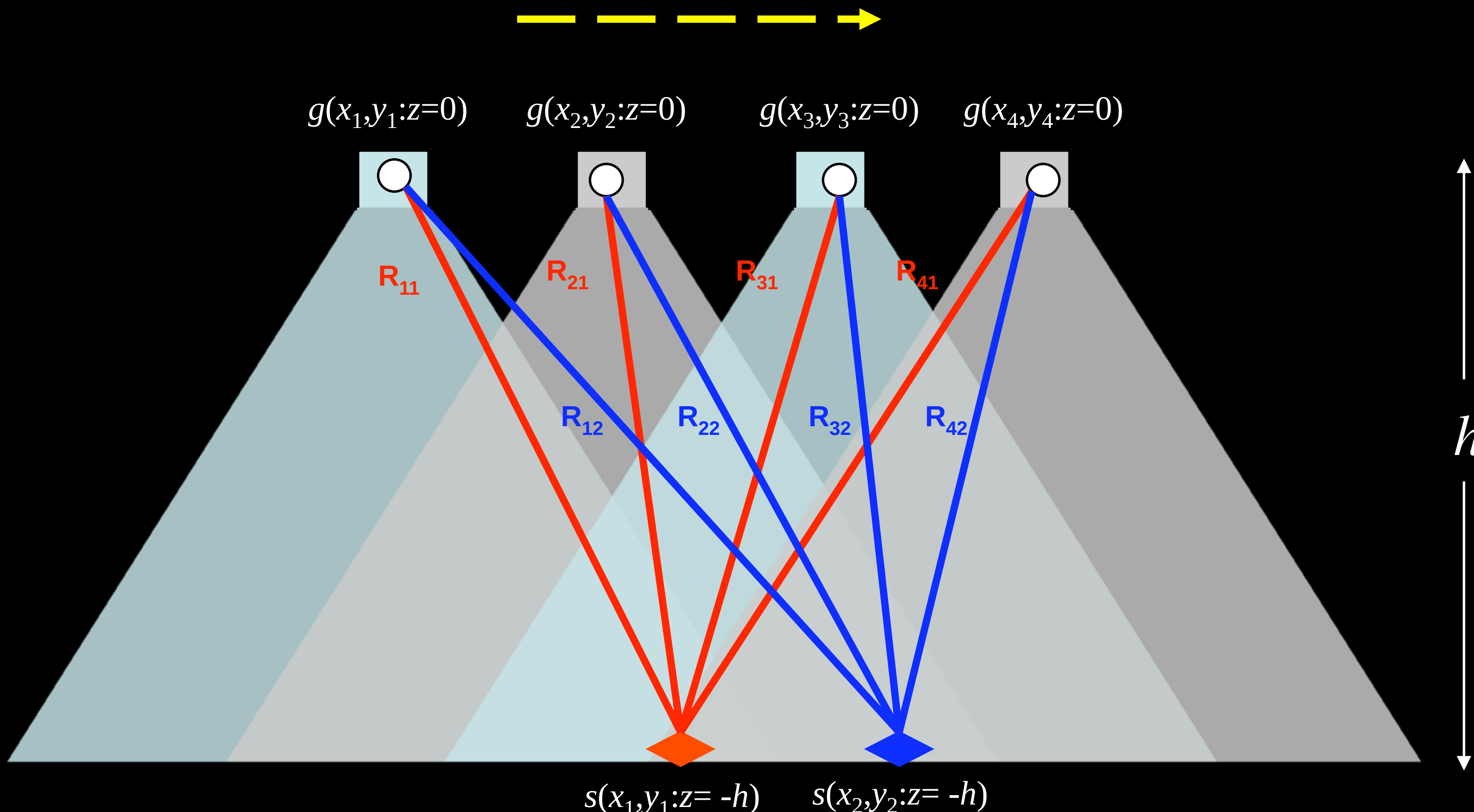


Synthetic Aperture Focusing



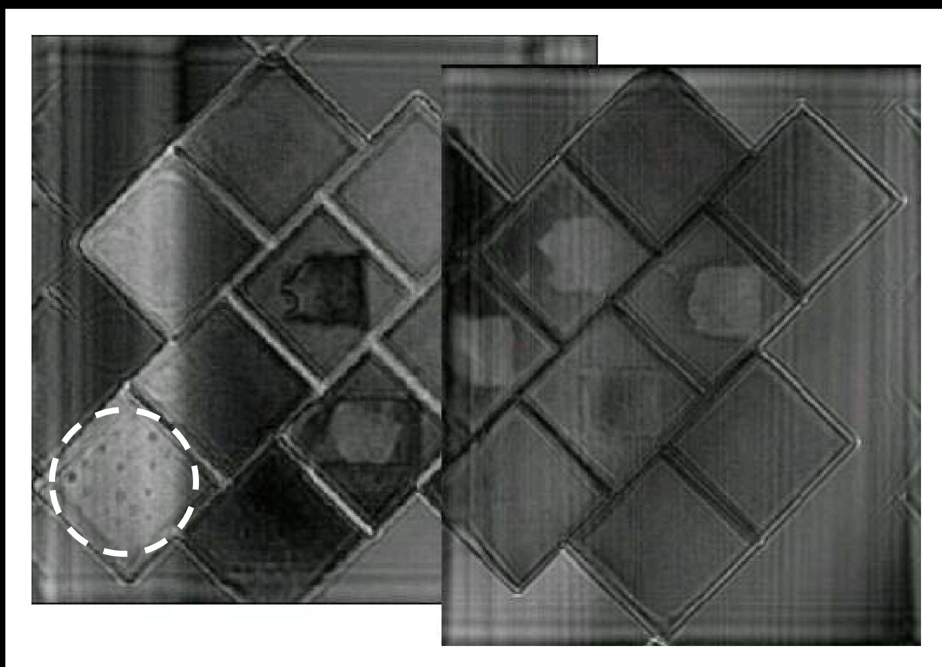
Synthetic Aperture Focusing

Antenna Motion Direction



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

Heat Tiles - Q-Band



Justification – Rotary Scanner

- Conventional raster scanning a 2' by 2' area may take upwards 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

Justification –Transceiver (Q-Band)

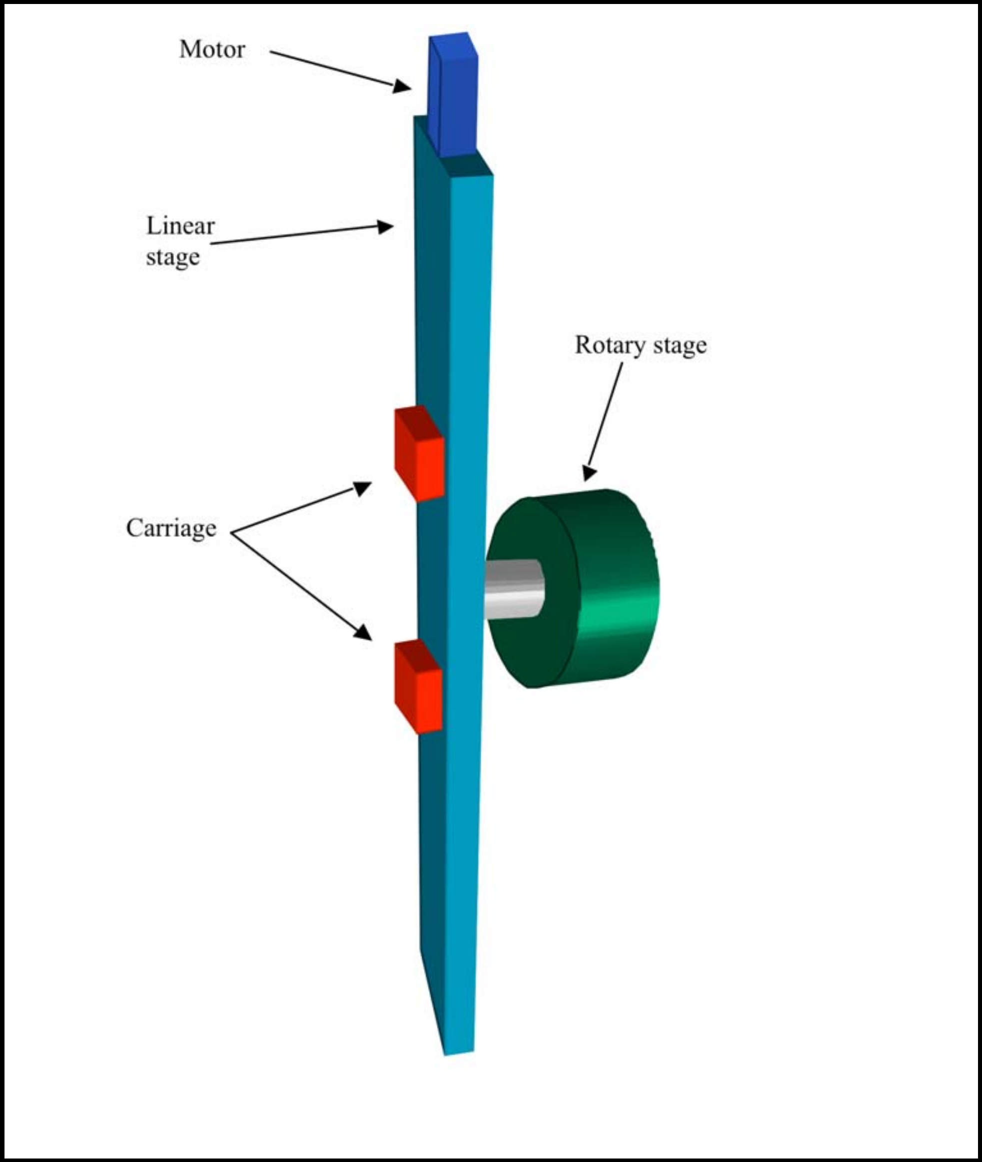
- **Wideband system requirements:**
  - ✓ Q-band (33-50 GHz): 35-45 GHz transceiver
  - ✓ High-resolution images
  - ✓ Coherent reflection measurement – SAFT
  - ✓ Previous results obtained at NASA MSFC at Q-band
- **SAFT image production.**

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.

Missouri S&T

Scanner Schematic



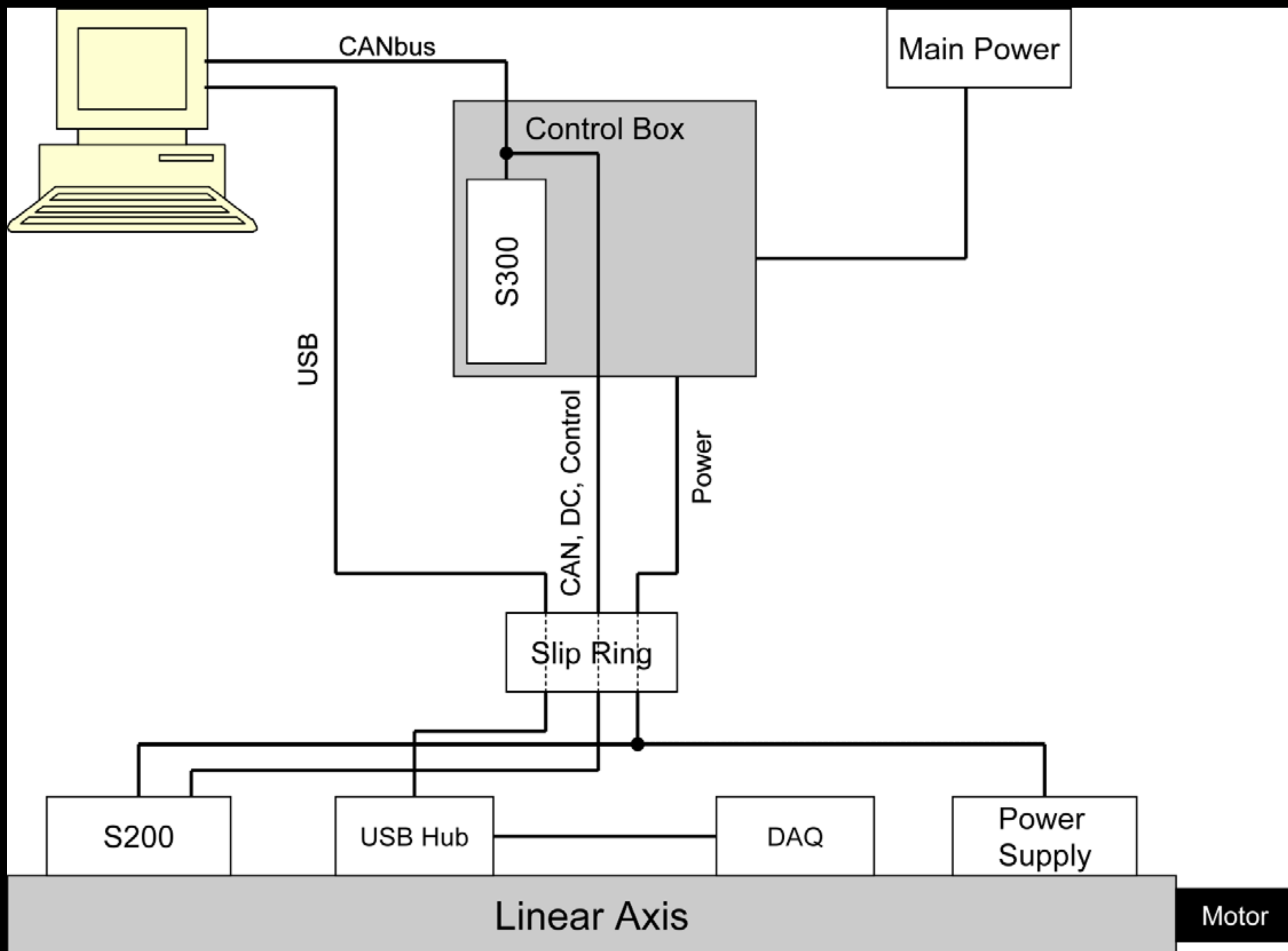
Rotary Axis Specifications

Rotary axis specs			
Speed	rpm	up to 50	Comments
Bidirectional Repeatability	arc.sec	< 35	
Accuracy	arc.sec	< 150	
wobble	arc.sec	< 60	
Vertical runout	mm	< 0.2	
Radial runout	mm	< 0.2	
Weight	lb (Kg)	< 66 (30)	Total weight including the motor
Bore diameter	in	> 1.5"	For cable routing from the front (linear stage) to the back (slip-ring)
Payload	The linear stage + The payload of the linear stage		

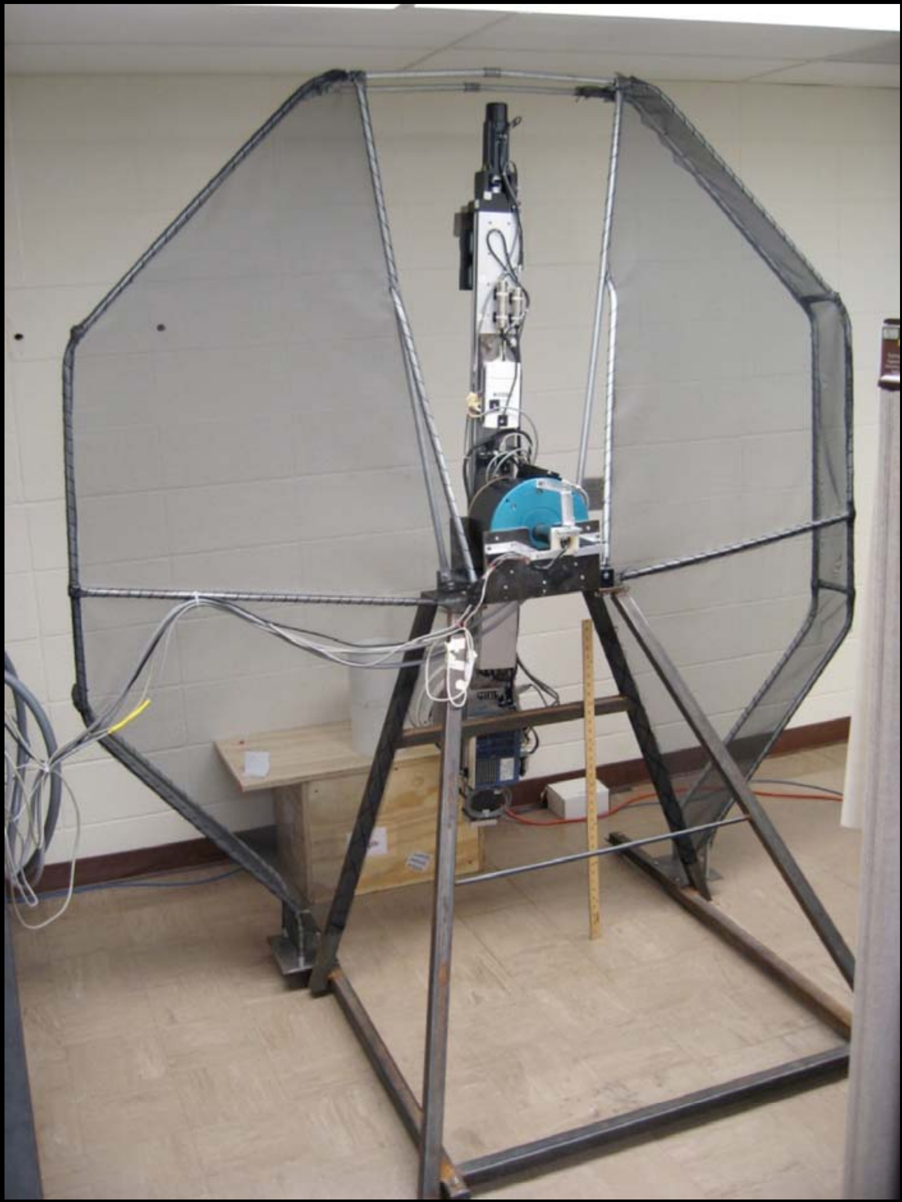
Linear Axis Specifications

Linear axis			
Dual carriage system moving in opposite directions from the center			
Ball screw half right-hand/half left-hand thread			
Travel distance	in (mm)	24 (600)	on each side/carriage.
Speed	in/sec	< 1	
Payload	lb (Kg)	22 (10)	for each carriage
Bidirectional Accuracy	mils (mm)	< 4 (0.1)	
Deflection (any direction)	mm	< 0.2 mm	Due to load, table weight etc.
Weight	lb (Kg)	< 45 (20)	Weight of the linear stage (not critical)
Driver	Servo motor + Driver		
Home and EOT switches with Repeatability < 0.05 mm			

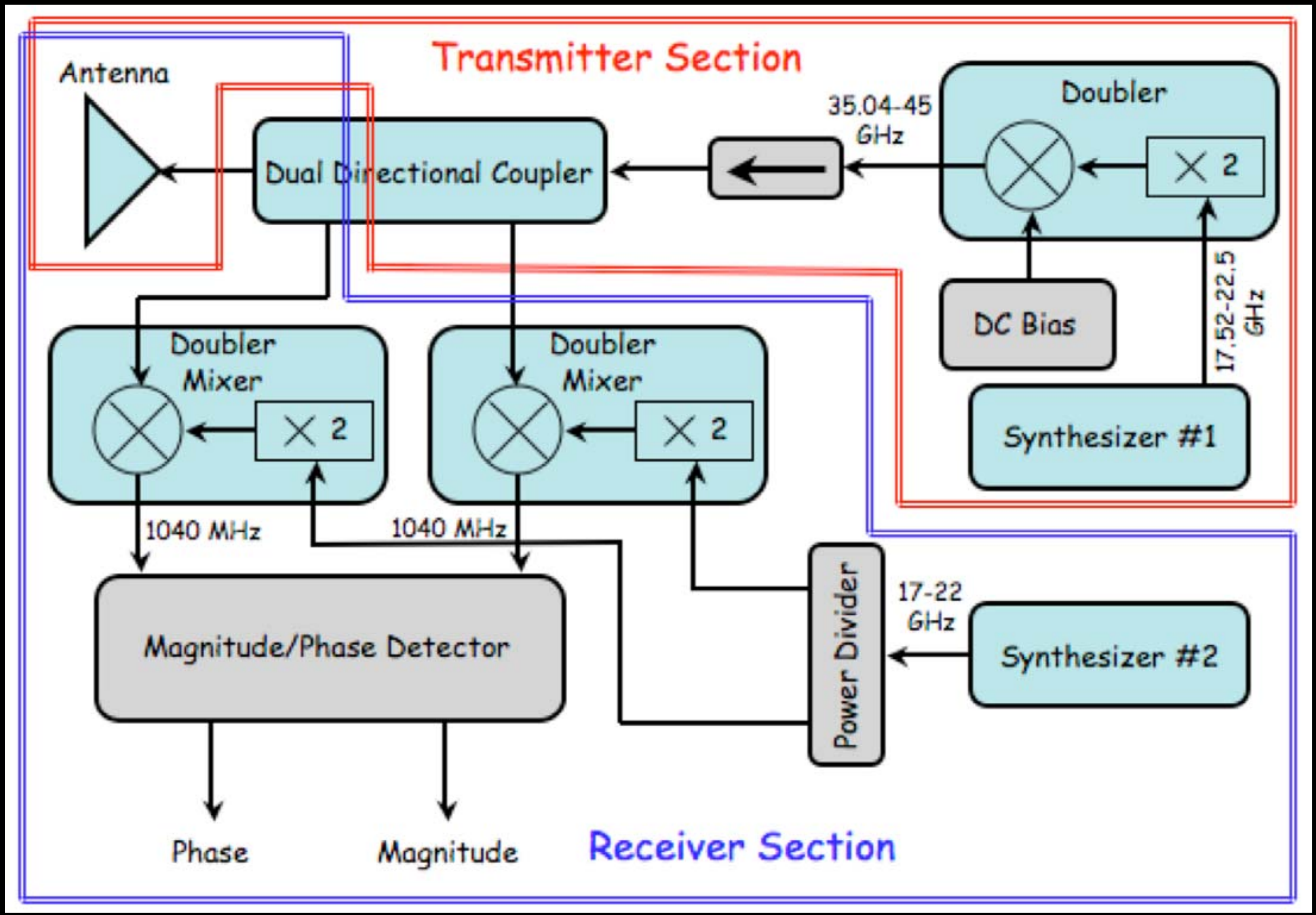
Electrical Power & Comm. Diagram



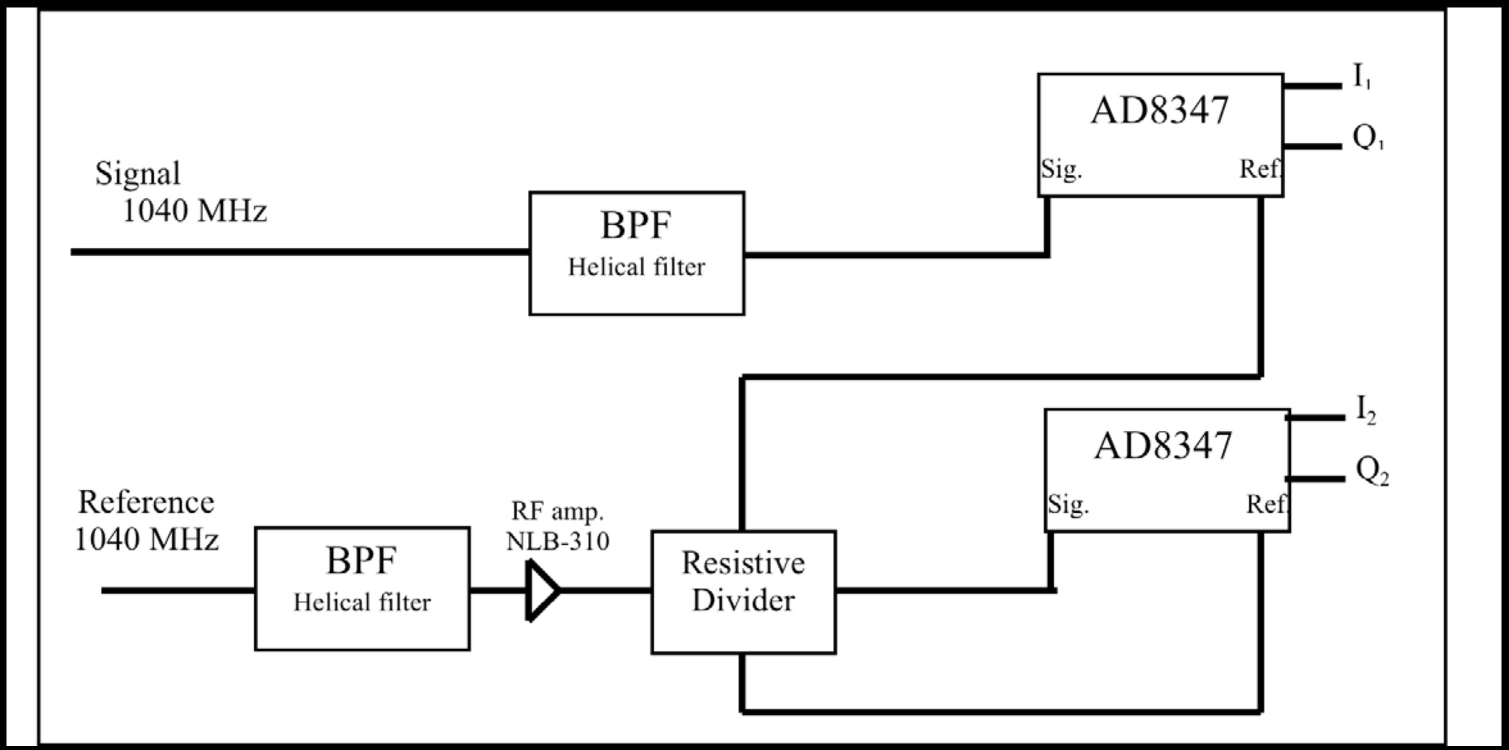
Final Rotary Scanner



Transceiver Schematic



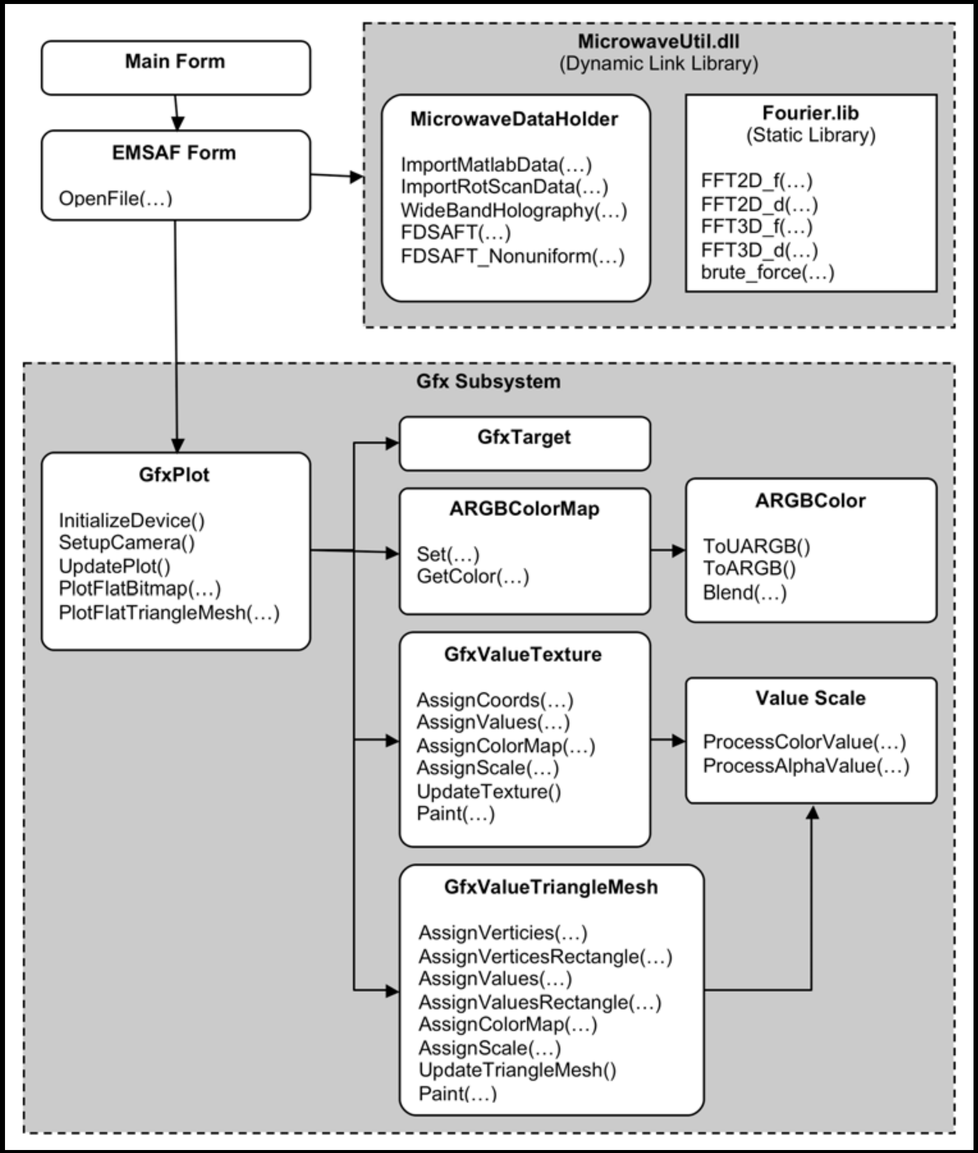
I/Q Detector Test Setup



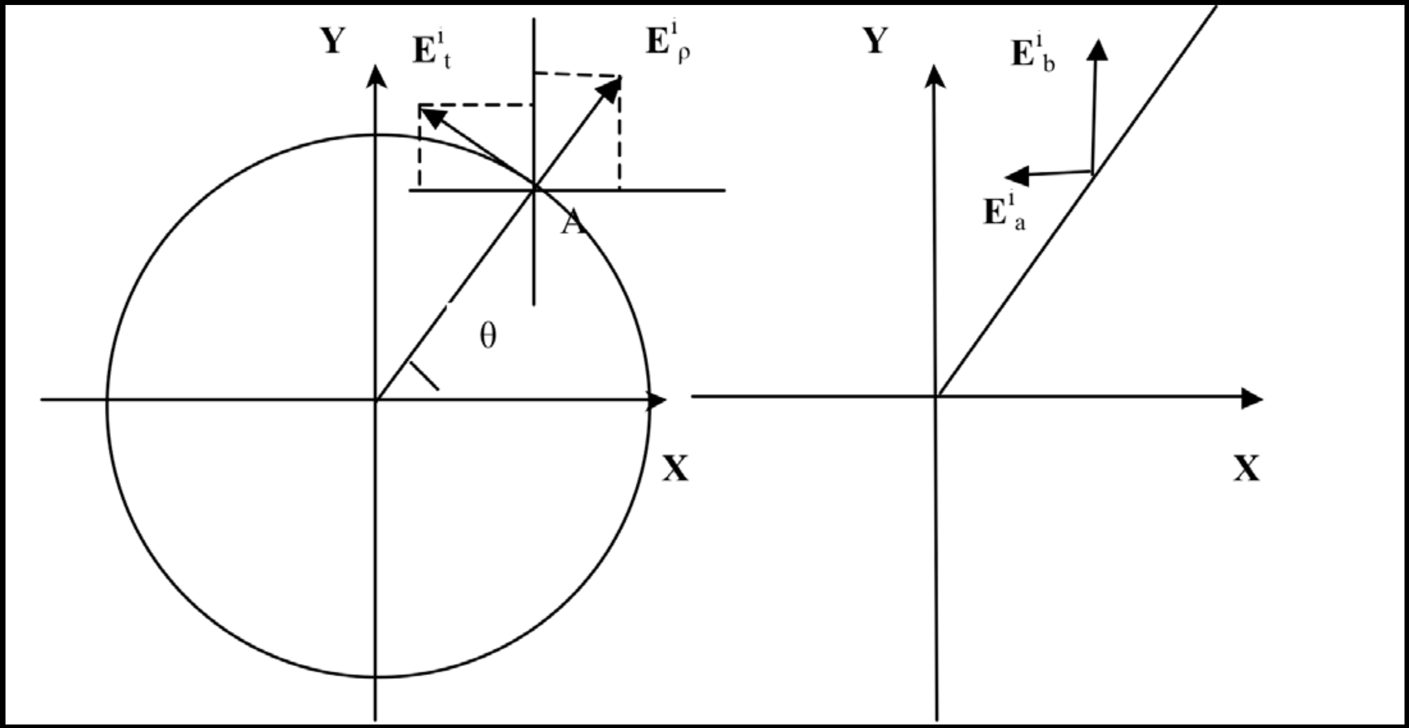
Transceiver Test Results

Load	AD8354 IQ MIXER Referenced to VNA		VNA Referenced to Theory	
	σ_{phase} (deg.)	σ_{mag} (dB)	σ_{phase} (deg)	σ_{mag} (dB)
50 MIL OFFSET-SHORT	0.71	0.1358	0.43	0.0656
100 MIL OFFSET-SHORT	0.86	0.1345	0.5119	0.0886
Q- OPEN ENDED WG.	0.62	0.1318		

SAFT Algorithm Flow Chart



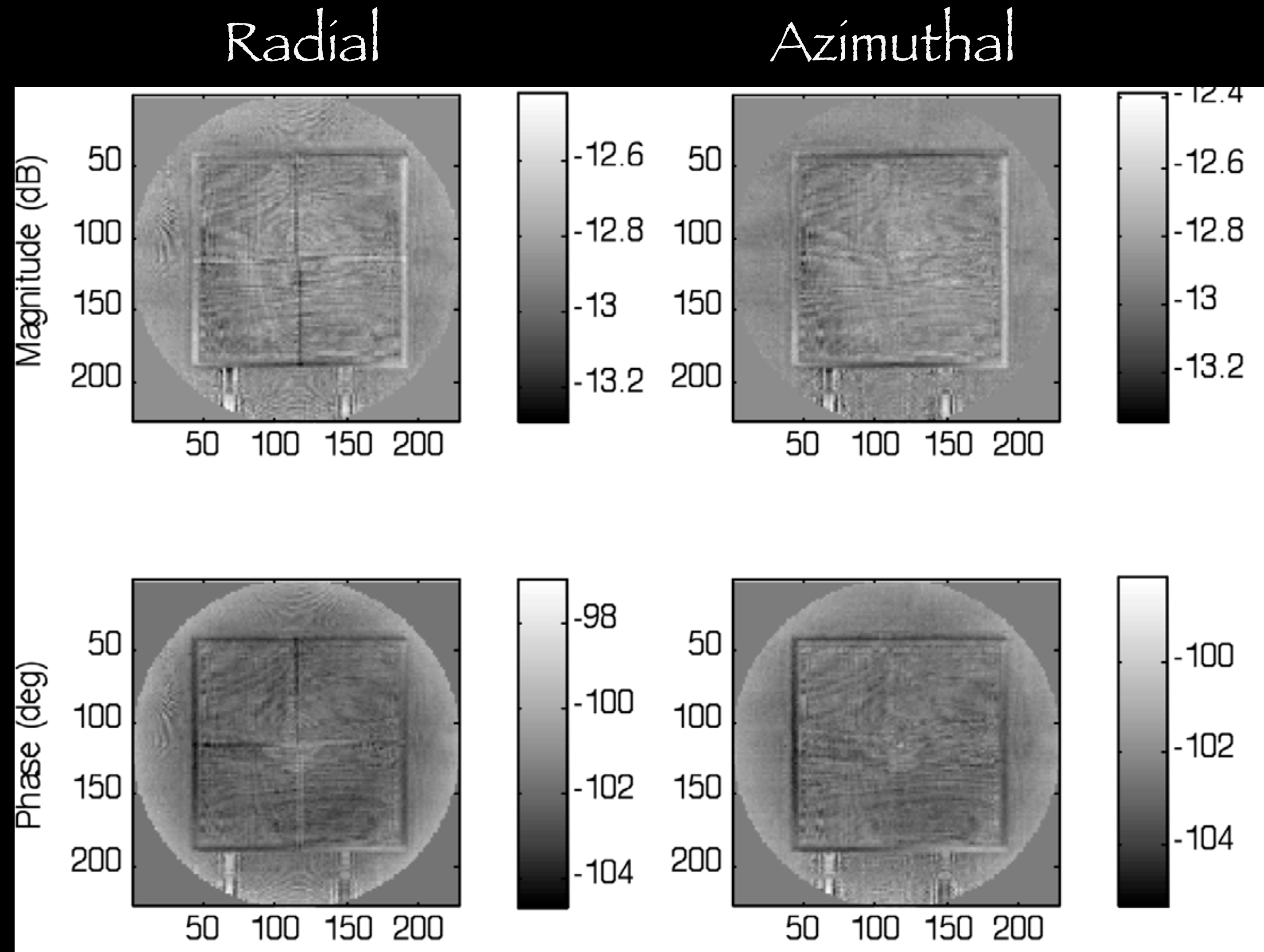
Polarization Transformation



Radial & Azimuthal
to
Vertical & Horizontal

Two Thin Wires

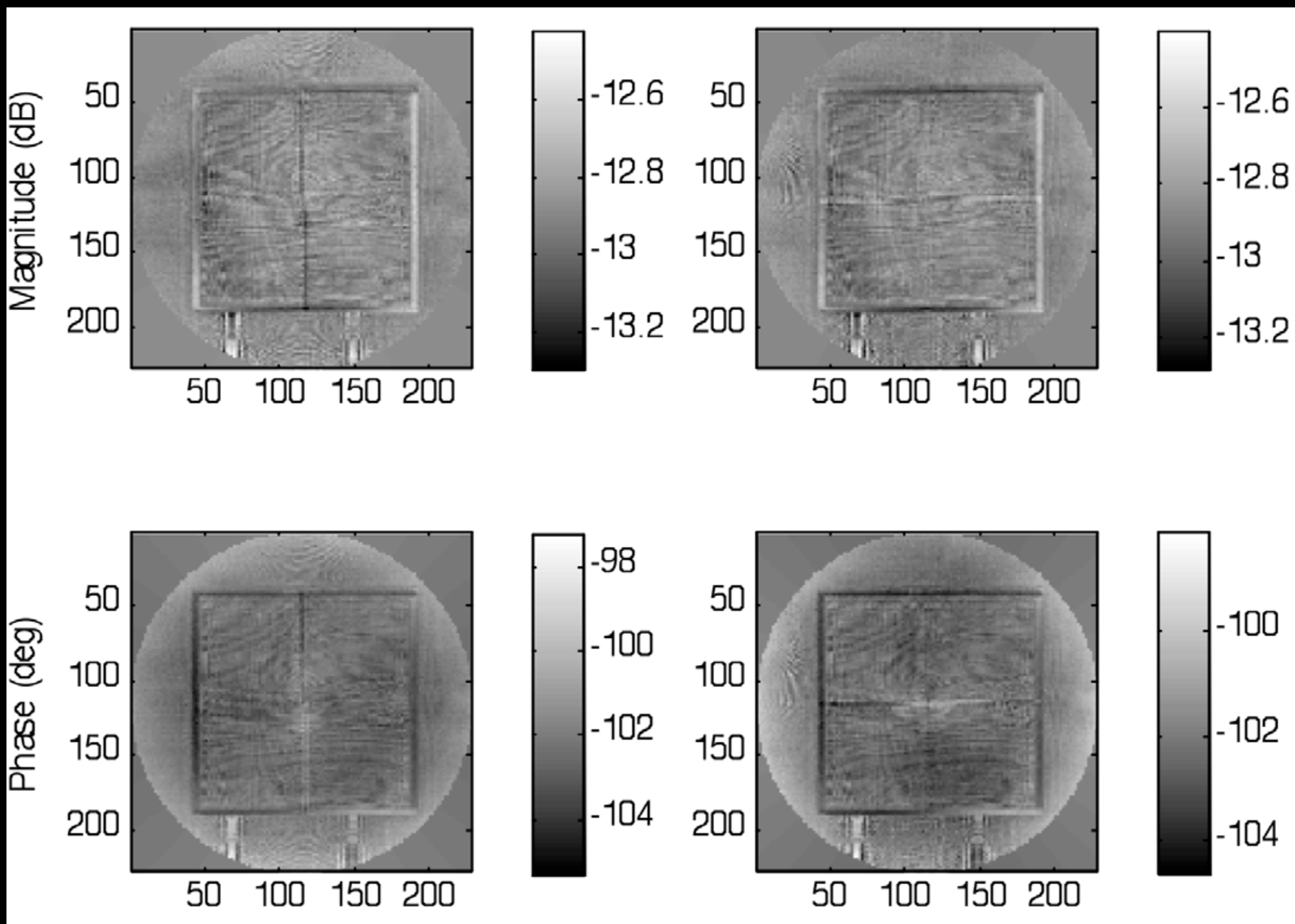
Images of Thin Wires – 45 GHz



Standoff Distance = 70 mm

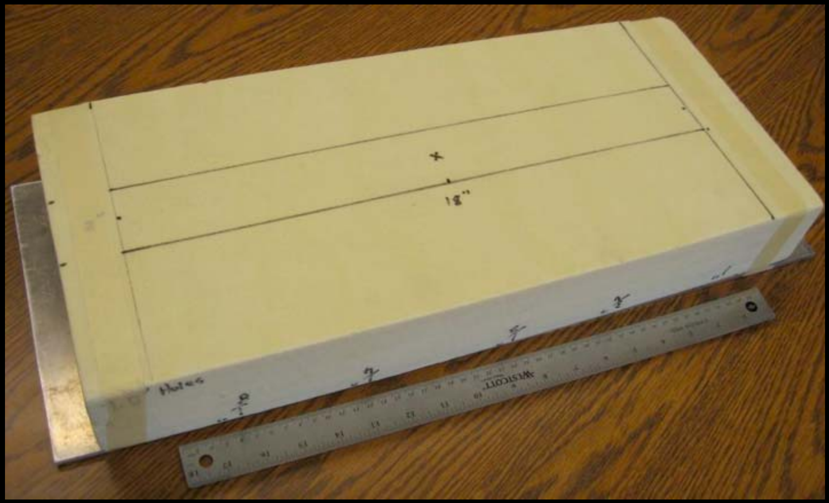
Images of Thin Wires – 45 GHz

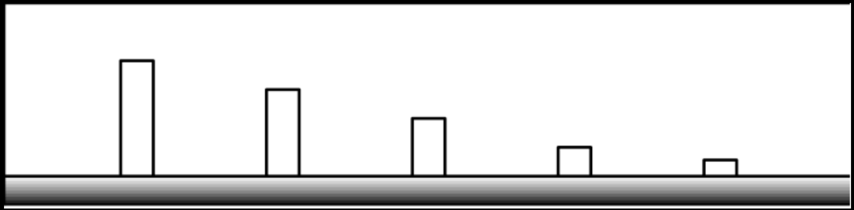
Vertical Horizontal

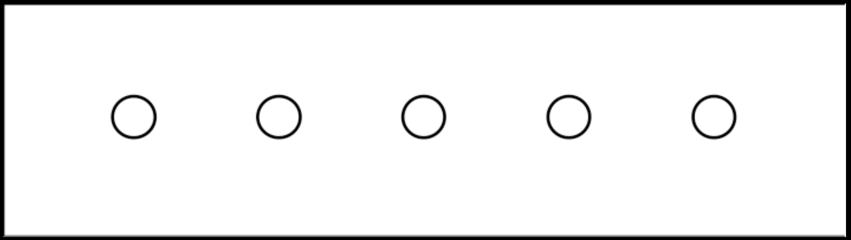


Standoff Distance ≈ 70 mm

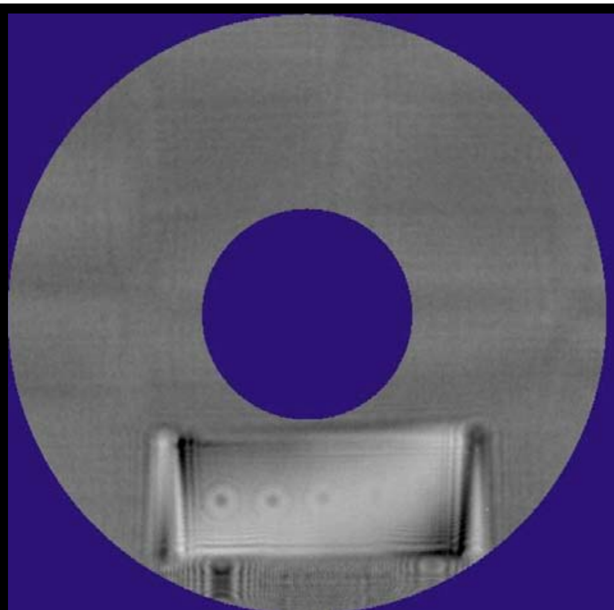
Flat Bottom Holes

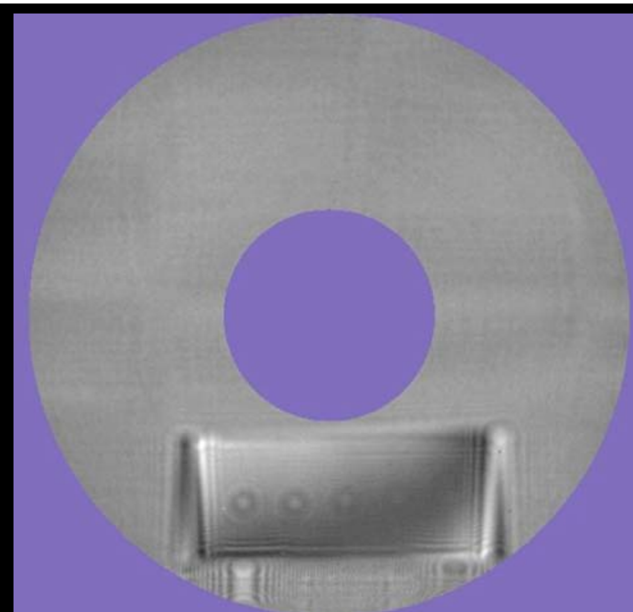




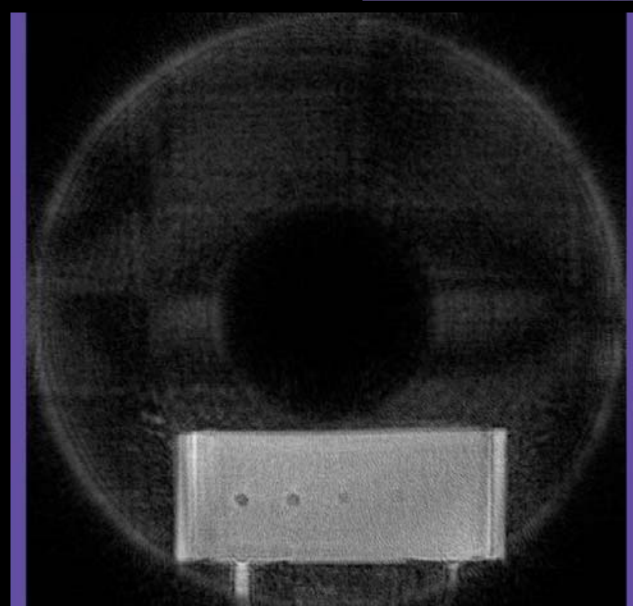


Flat Bottom Holes – 40 GHz

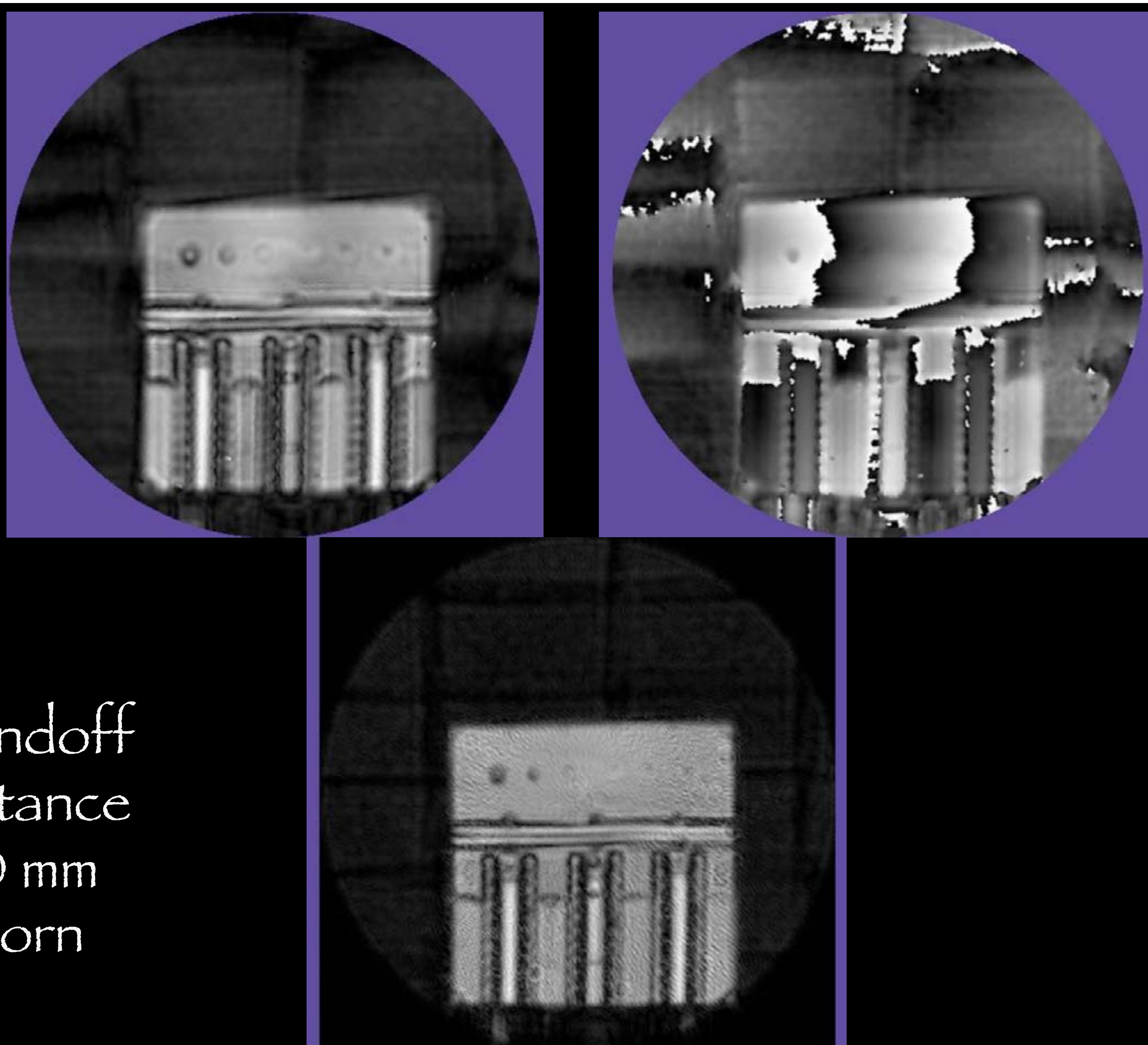




Standoff
Distance
70 mm
OEW

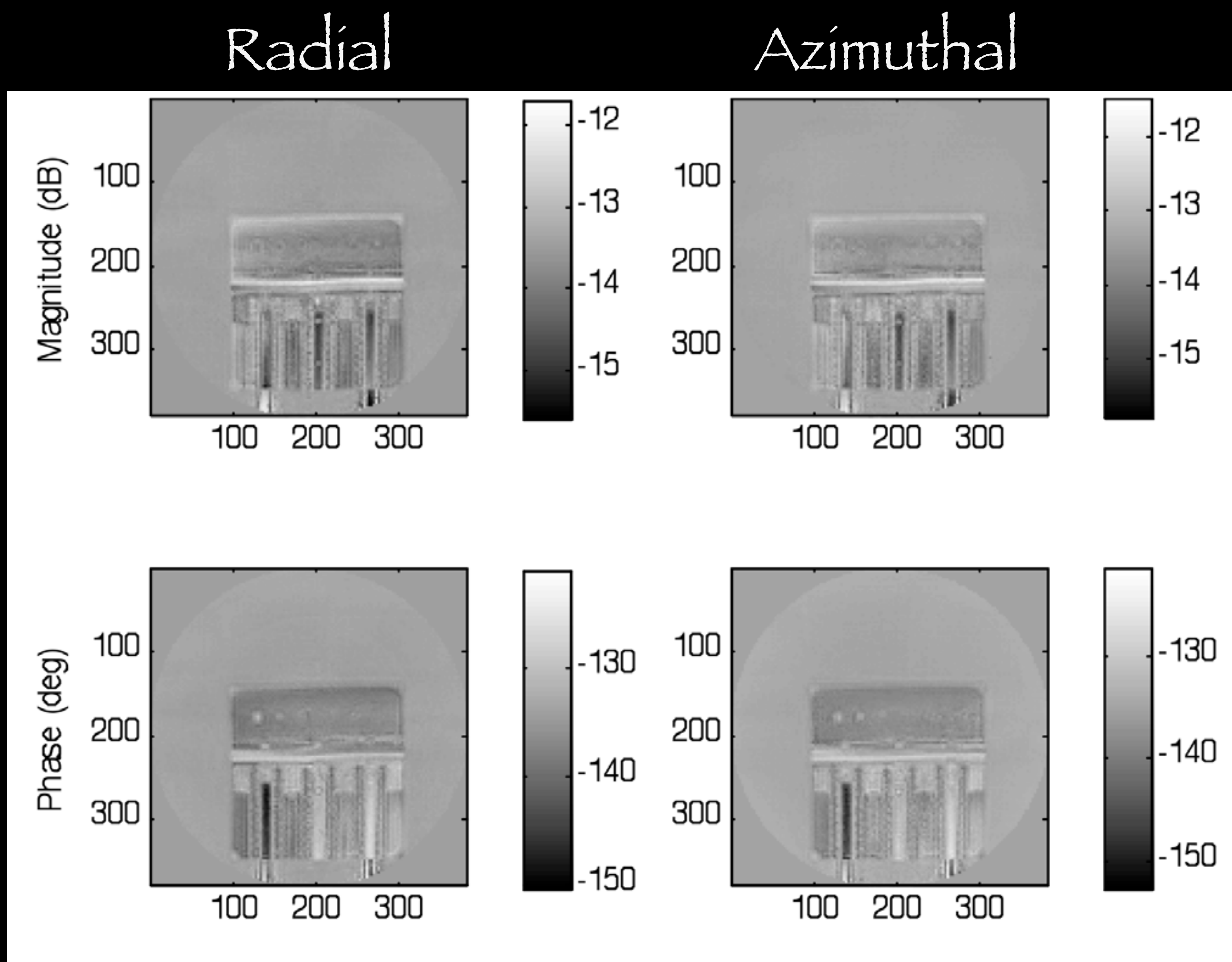


POD Panel – 45 GHz



Standoff Distance 20 mm Horn

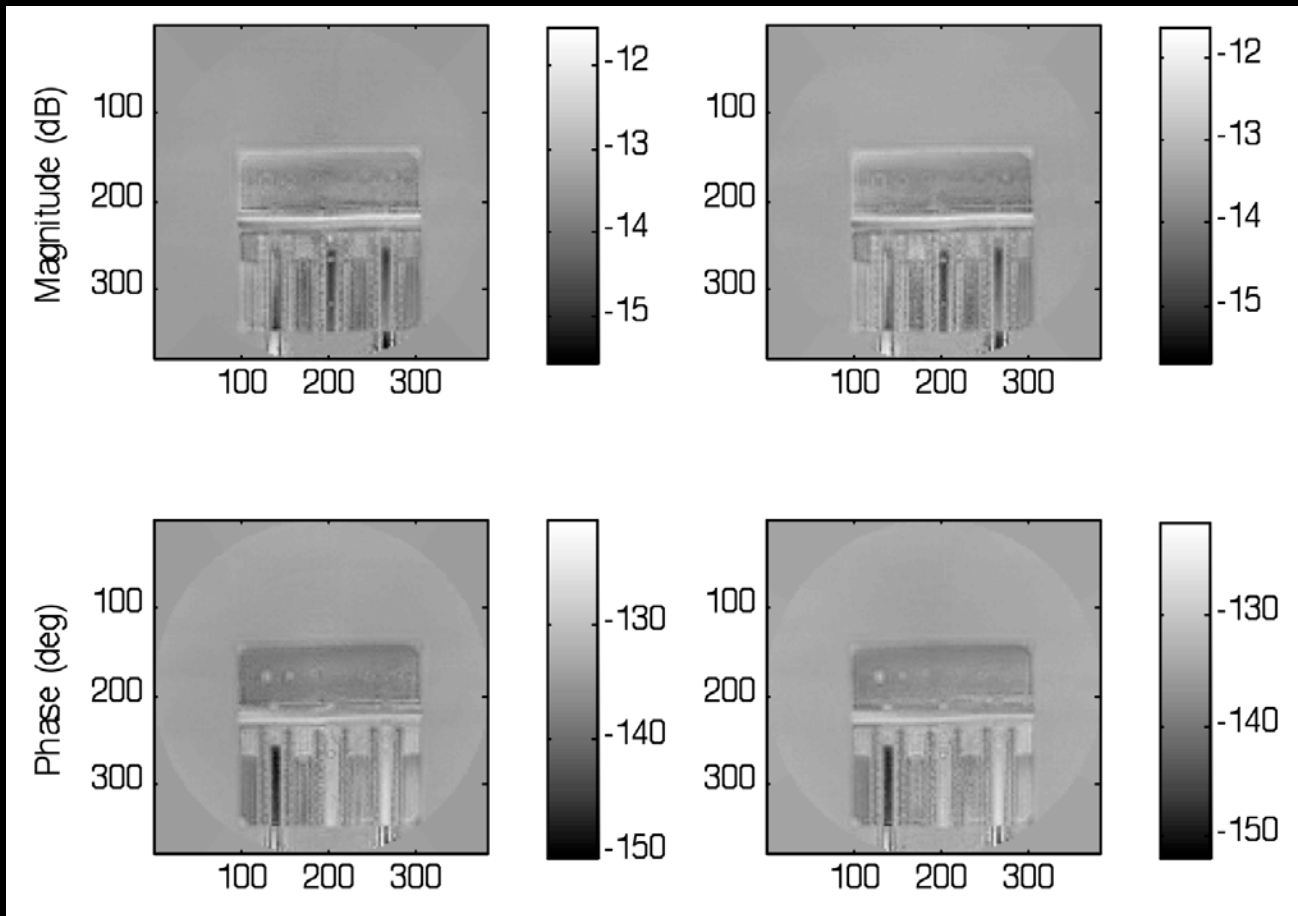
POD Panel – 45 GHz



Standoff Distance ≈ 5 mm
OEW

POD Panel – 45 GHz

Vertical Horizontal



Standoff Distance ≈ 5 mm
OEW

Summary

- Designed and developed a novel and rapid rotary scanner.
- Designed and developed a coherent Q-band transceiver with 10 GHz of BW.
- Capable of producing SAFT images or areas as large as 120 cm in diameter in as short as 15 minutes.
- Dual polarization capable.
- Suitable for large area scans.

Thank you.