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

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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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POC: Mr. F.L. Hepburn
BACKGROUND
Background

μ-Waves

mm-Waves

300 MHz  →  30 GHz  →  300 GHz

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**

<table>
<thead>
<tr>
<th>Band</th>
<th>Dimensions (mm x mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-Band</td>
<td>10.7 x 4.3</td>
</tr>
<tr>
<td>Ka-Band</td>
<td>7.11 x 3.56</td>
</tr>
<tr>
<td>V-Band</td>
<td>3.8 x 1.9</td>
</tr>
<tr>
<td>W-Band</td>
<td>2.54 x 1.27</td>
</tr>
</tbody>
</table>

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 - 150 GHz

- Perpendicular
- Parallel

Focused at Substrate
Synthetic Aperture Focusing

Antenna Motion Direction

\[ \mathbf{g}(x_1, y_1; z=0) \quad \mathbf{g}(x_2, y_2; z=0) \quad \mathbf{g}(x_3, y_3; z=0) \quad \mathbf{g}(x_4, y_4; z=0) \]

\[ s(x_1, y_1; z=-h) \]
Synthetic Aperture Focusing

Antenna Motion Direction

\[ \begin{align*}
  g(x_1,y_1;z=0) & \rightarrow R_{11} \\
  g(x_2,y_2;z=0) & \rightarrow R_{21} \\
  g(x_3,y_3;z=0) & \rightarrow R_{31} \\
  g(x_4,y_4;z=0) & \rightarrow R_{41}
\end{align*} \]

\[ s(x_1,y_1;z=-h) \]
Synthetic Aperture Focusing

**Antenna Motion Direction**

\[ g(x_1, y_1; z=0) \quad g(x_2, y_2; z=0) \quad g(x_3, y_3; z=0) \quad g(x_4, y_4; z=0) \]

\[ s(x_1, y_1; z = -h) \quad s(x_2, y_2; z = -h) \]

\[ s(x_n, y_n; z = -h) = \sum_{i=1}^{4} g(x_m, y_m; z = 0) \exp(j2kR_{mn}) \]
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.
Scanner Schematic

- Motor
- Linear stage
- Carriage
- Rotary stage
## Rotary Axis Specifications

<table>
<thead>
<tr>
<th></th>
<th>rpm</th>
<th>up to 50</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidirectional</td>
<td>arc.sec</td>
<td>&lt; 35</td>
<td></td>
</tr>
<tr>
<td>Repeatability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>arc.sec</td>
<td>&lt; 150</td>
<td></td>
</tr>
<tr>
<td>wobble</td>
<td>arc.sec</td>
<td>&lt; 60</td>
<td></td>
</tr>
<tr>
<td>Vertical runout</td>
<td>mm</td>
<td>&lt; 0.2</td>
<td></td>
</tr>
<tr>
<td>Radial runout</td>
<td>mm</td>
<td>&lt; 0.2</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>lb (Kg)</td>
<td>&lt; 66 (30)</td>
<td>Total weight including the motor</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>in</td>
<td>&gt; 1.5&quot;</td>
<td>For cable routing from the front (linear stage) to the back (slip-ring)</td>
</tr>
<tr>
<td>Payload</td>
<td></td>
<td></td>
<td>The linear stage + The payload of the linear stage</td>
</tr>
</tbody>
</table>
# Linear Axis Specifications

## Linear axis

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual carriage system</td>
<td></td>
<td></td>
<td></td>
<td>moving in opposite directions from the center</td>
</tr>
<tr>
<td>Ball screw</td>
<td></td>
<td></td>
<td></td>
<td>half right-hand/half left-hand thread</td>
</tr>
<tr>
<td>Travel distance</td>
<td>in (mm)</td>
<td>24 (600)</td>
<td></td>
<td>on each side/carriage.</td>
</tr>
<tr>
<td>Speed</td>
<td>in/sec</td>
<td>&lt; 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Payload</td>
<td>lb (Kg)</td>
<td>22 (10)</td>
<td></td>
<td>for each carriage</td>
</tr>
<tr>
<td>Bidirectional Accuracy</td>
<td>mils (mm)</td>
<td>&lt; 4 (0.1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deflection (any direction)</td>
<td>mm</td>
<td>&lt; 0.2 mm</td>
<td></td>
<td>Due to load, table weight etc.</td>
</tr>
<tr>
<td>Weight</td>
<td>lb (Kg)</td>
<td>&lt; 45 (20)</td>
<td></td>
<td>Weight of the linear stage (not critical)</td>
</tr>
<tr>
<td>Driver</td>
<td></td>
<td>Servo motor + Driver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Home and EOT switches</td>
<td></td>
<td></td>
<td></td>
<td>with Repeatability &lt; 0.05 mm</td>
</tr>
</tbody>
</table>
Final Rotary Scanner
Transceiver Schematic
I/Q Detector Test Setup

Diagram:

- Signal 1040 MHz
- Reference 1040 MHz
- BPF Helical filter
- RF amp. NLB-310
- Resistive Divider
- AD8347 (Sig., Ref., I₁, Q₁)
- AD8347 (Sig., Ref., I₂, Q₂)
## Transceiver Test Results

<table>
<thead>
<tr>
<th>Load</th>
<th>AD8354 IQ MIXER Referenced to VNA</th>
<th>VNA Referenced to Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_{\text{phase}}$ (deg.)</td>
<td>$\sigma_{\text{mag}}$ (dB)</td>
</tr>
<tr>
<td>50 MIL OFFSET-SHORT</td>
<td>0.71</td>
<td>0.1358</td>
</tr>
<tr>
<td>100 MIL OFFSET-SHORT</td>
<td>0.86</td>
<td>0.1345</td>
</tr>
<tr>
<td>Q- OPEN ENDED WG.</td>
<td>0.62</td>
<td>0.1318</td>
</tr>
</tbody>
</table>
SAFT Algorithm Flow Chart

Main Form
- EMSAF Form
  - OpenFile(…)

MicrowaveUtil.dll
(Dynamic Link Library)
- MicrowaveDataHolder
  - ImportMatlabData(…)
  - ImportRotScanData(…)
  - WideBandHolography(…)
  - FDSAFT(…)
  - FDSAFT_Nonuniform(…)

Fourier.lib
(Static Library)
- FFT2D_f(…)
- FFT2D_d(…)
- FFT3D_f(…)
- FFT3D_d(…)
- brute_force(…)

Gfx Subsystem
- GfxPlot
  - InitializeDevice(…)
  - SetupCamera(…)
  - UpdatePlot(…)
  - PlotFlatBitmap(…)
  - PlotFlatTriangleMesh(…)

GfxTarget
- ARGBColor
  - ToUARGB(…)
  - ToARGB(…)
  - Blend(…)
- ARGBColorMap
  - Set(…)
  - GetColor(…)
- GfxValueTexture
  - AssignCoords(…)
  - AssignValues(…)
  - AssignColorMap(…)
  - AssignScale(…)
  - UpdateTexture(…)
  - Paint(…)
- GfxValueTriangleMesh
  - AssignVertices(…)
  - AssignVerticesRectangle(…)
  - AssignValues(…)
  - AssignValuesRectangle(…)
  - AssignColorMap(…)
  - AssignScale(…)
  - UpdateTriangleMesh(…)
  - Paint(…)

Value Scale
- ProcessColorValue(…)
- ProcessAlphaValue(…)
Polarization Transformation

Radial & Azimuthal
to
Vertical & Horizontal
Two Thin Wires
Images of Thin Wires - 45 GHz

Radial

Azimuthal

Standoff Distance = 70 mm
Images of Thin Wires – 45 GHz

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

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.