Millimeter-wave Imaging for Concealed Weapon Detection

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Sponsored by ALERT / DHS

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Conclusion

▶ Active mm-wave imaging is effective for security screening

  ■ Cylindrical portal imaging technology is becoming widely deployed

    ● Excellent illumination properties due to the 360 degree (or wide angle) illumination

    ● Allows inspection from multiple viewing angles

    ● High-resolution

    ● Excellent clothing penetration at in the lower mm-wave band

    ● Scanning is rapid (several seconds), with throughput of over 400 people/hour possible

    ● Cost effective

  ■ 3-D imaging provides additional information

    ● Preserves focus (depth of field)

    ● Allows exploitation of depth information or layered reflections for additional target detection techniques

▶ Standoff imaging is being explored using sub-mm imaging

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Terrorist Threats

- ▶ Explosives
- ▶ Suicide vests
- ▶ Weapons
  - ■ Guns
  - ■ Knives
  - ■ Etc.
- ▶ Nuclear, biological, or chemical materials carried in sealed containers

C4

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Introduction

- ► Weapon and explosive detection are critical for airports and other high-security facilities

- ► Metal detectors are unable to detect non-metallic weapons and explosives, and are not useful for identification of detected material

- ► Millimeter-wave imaging is an effective method of detection and identification of items concealed on personnel

- ► Electromagnetic waves
- ► Frequency range: 30 – 300 GHz
  - ▪ UHF 0.3 – 1 GHz
  - ▪ Microwave: 1 – 30 GHz
  - ▪ Millimeter-wave: 30 – 300 GHz
  - ▪ Terahertz: 300 GHz – 10 THz
- ► Wavelength range: 1 - 10 mm
- ► Microwaves/Millimeter-waves
  - ▪ Communication
  - ▪ Radar tracking, imaging (SAR), Police radar
  - ▪ Readily penetrates many optical obscurants
  - ▪ Reflected by objects and human body

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Weapon Detection Imaging Technologies

▶ Active millimeter-wave
- Battelle, PNNL (wideband holographic)
- L3-Communications / SafeView (commercial partner)
- Smiths (Agilent technology)

▶ Passive millimeter-wave imaging systems using FPA's and high-speed scanning
- Qinetic
- Trex
- ThruVision
- Millivision
- others

▶ Low-power X-ray backscatter imaging
- AS&E Inc. (*BodySearch*)
- Rapiscan (*Secure 1000*)

Brijot Passive Millimeter-wave Imaging System
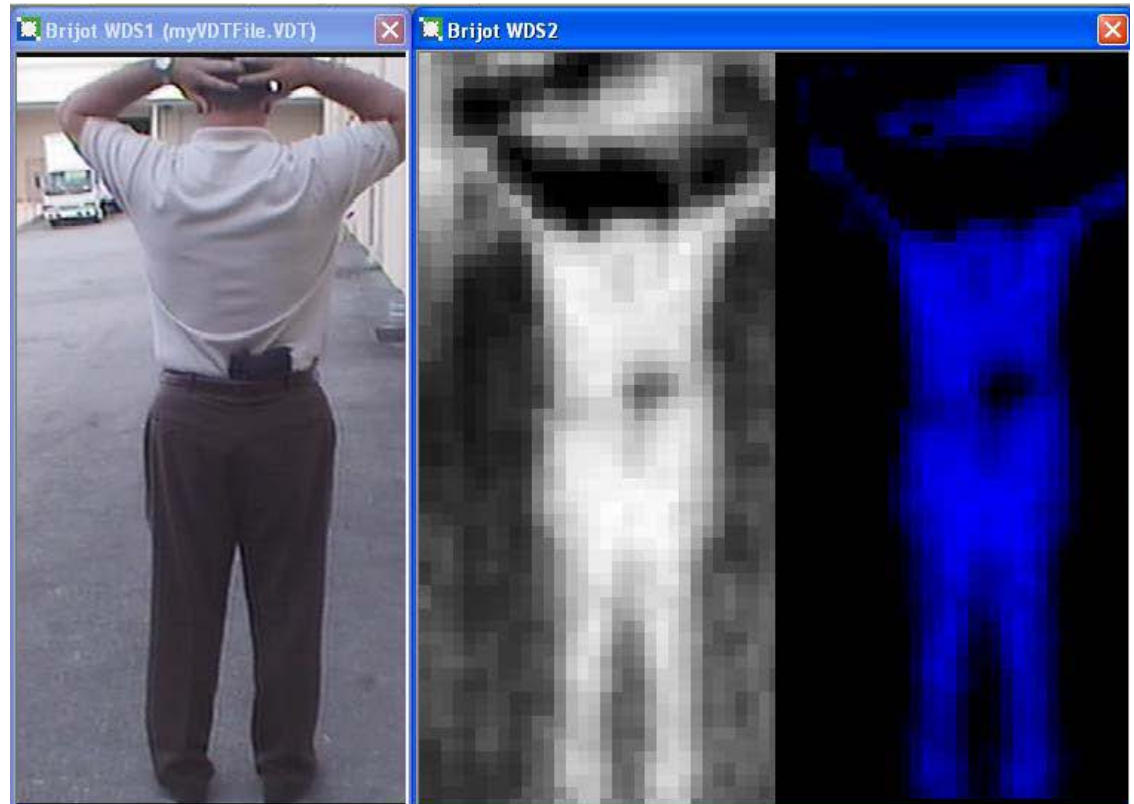
Image from the Brijot BIS-WDS™ Prime that shows a concealed handgun at the rear belt line (Images courtesy of Brijot Imaging Systems)

Trex / Sago Passive Millimeter-wave Imaging System
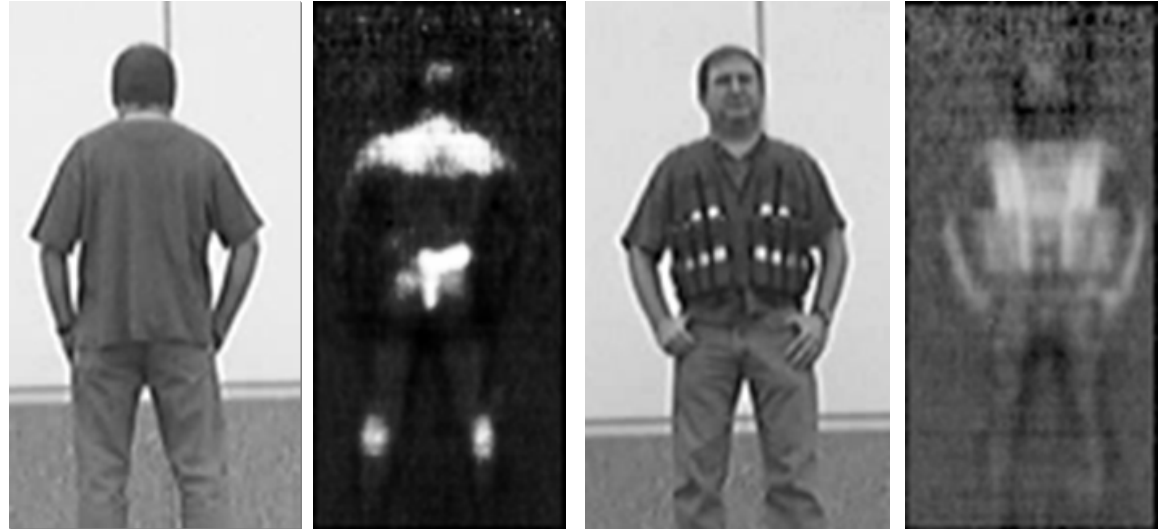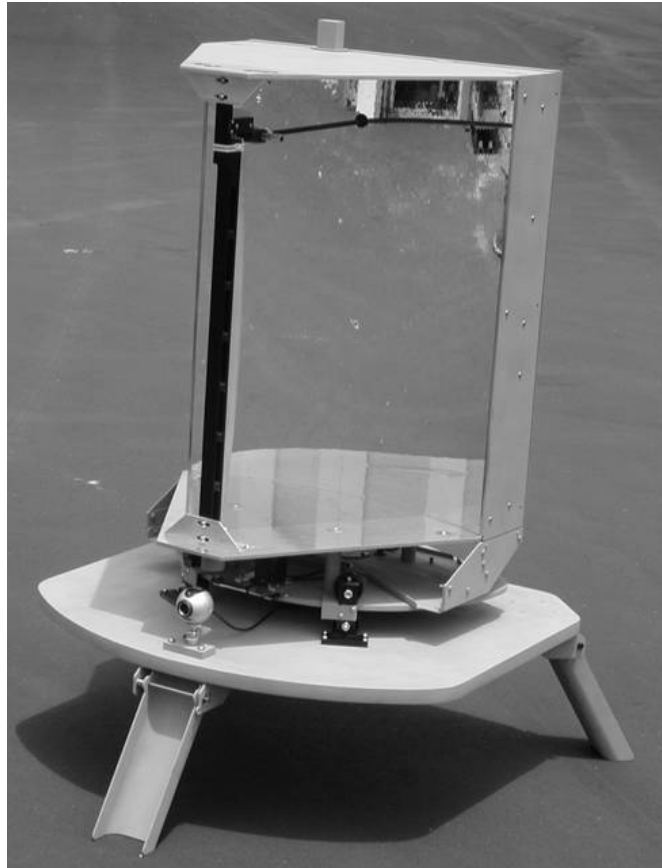
Sago ST150 passive millimeter-wave imaging concealed weapon detection system (Images courtesy of Trex Enterprises / Sago)

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Agilent Active MM-wave Imaging Technology
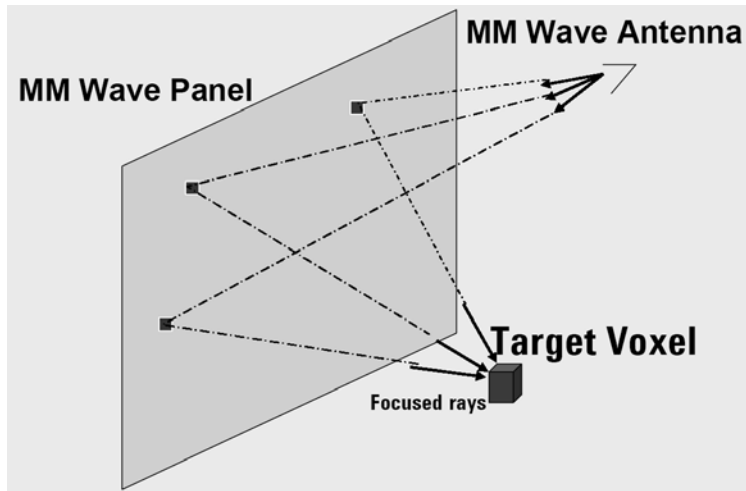
Agilent reflector array operation. Millimeter-wave reflector array panel alters the phase of the transmitted wavefront to allow high-speed digitally controlled focusing over a range of target voxel locations. (Images courtesy of Agilent).

PNNL Active Wideband Holographic Imaging

Wideband Image of Mannequin and Concealed Glock 17 (100 - 112 GHz)

Optical
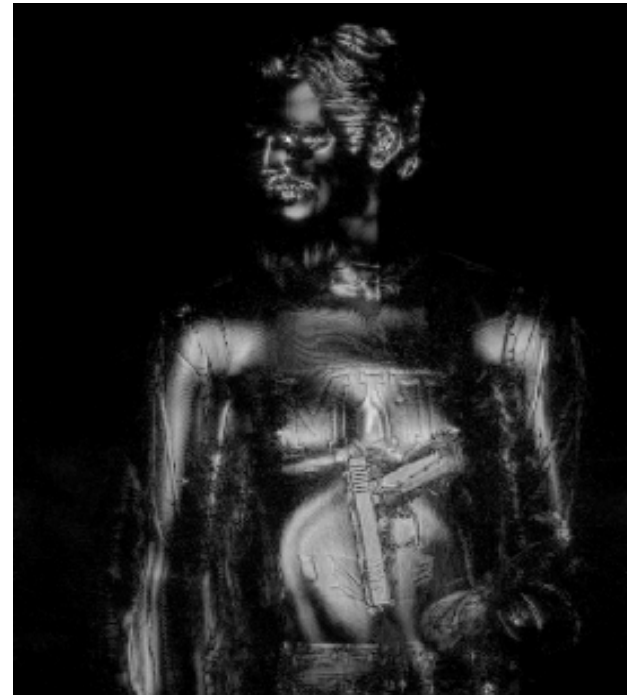
100 - 112 GHz

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Advantages of Millimeter-wave Holographic Imaging Technique

- Active scanned source imaging results in 2X improvement in image resolution

- Near-field, large aperture, for simultaneous high resolution, wide illumination imagery

- Focusing done using computer reconstruction, no lens or reflector required

- Wideband techniques enable 3-D volumetric imaging

- Millimeter-waves are low power and non-ionizing and pose no health threat

- Wide angular illumination suppresses undesirable specular reflection of many targets

- Lateral Resolution

$$\delta_x = \frac{\lambda}{2} F\#$$
$$= 0.5 \text{ cm at } 30 \text{ GHz}$$

- Range Resolution

$$\delta_r = \frac{c}{2B}$$
$$= 2.5 \text{ cm at } 27-33 \text{ GHz}$$

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Licensed Commercial Cylindrical Holographic Imaging Systems

PNNL cylindrical prototype system

Intellifit body measurement system

Editor's Choice - 2004
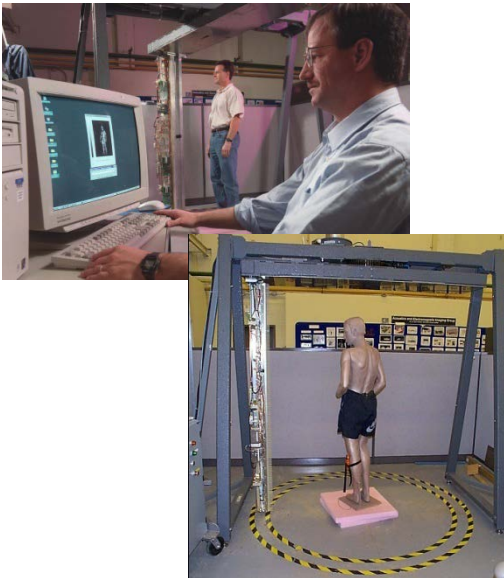
L-3 ProVision system deployed in London

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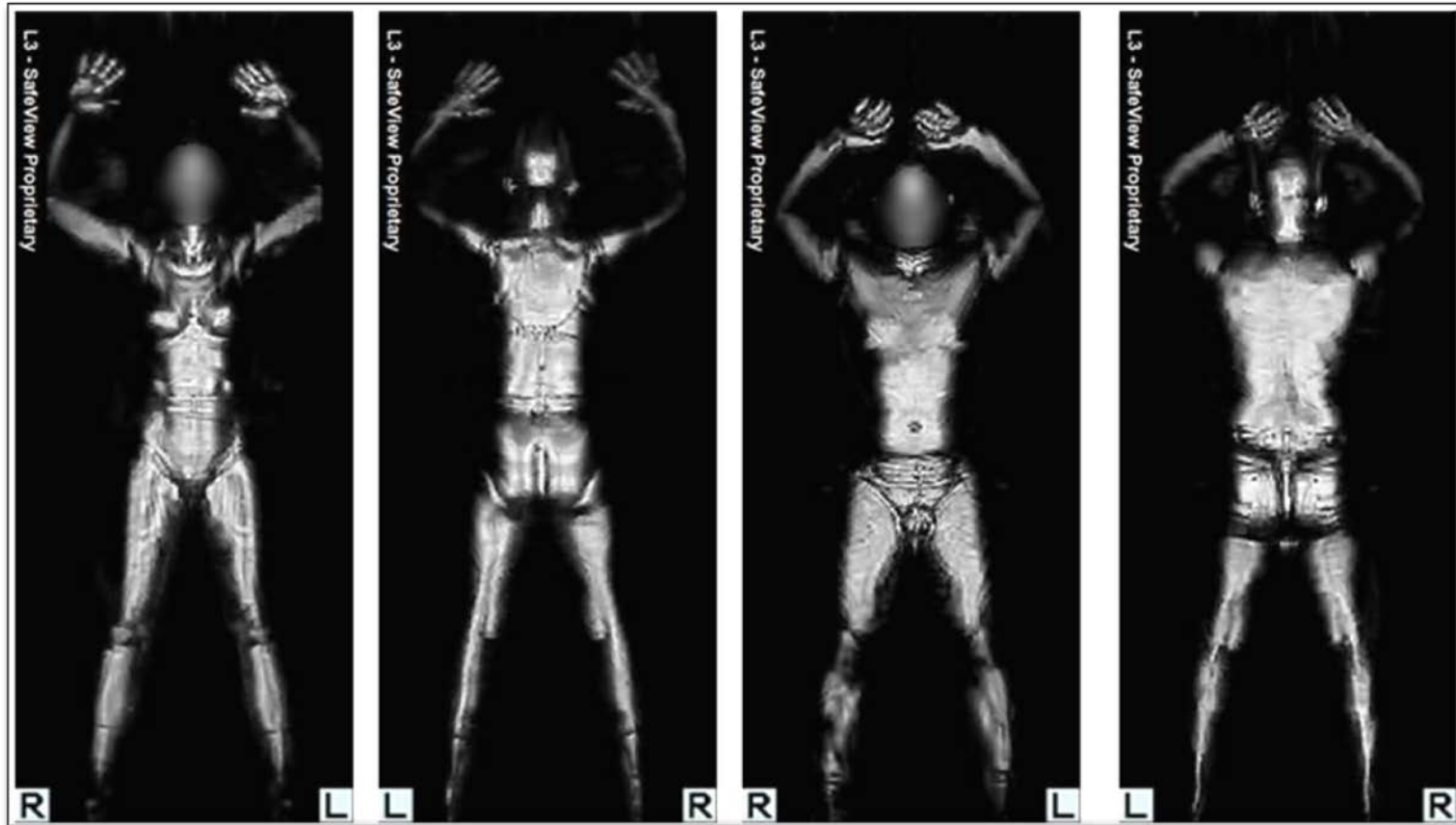
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L-3 ProVision

▶ Active Millimeter Wave Portal

- 24.5-30 GHz
- 2 384 element arrays
- Detects metals, and non-metals (ceramics, wood, plastic, etc.)
- Liquids and gels
- Paper and coin currency
- Safe radio waves, low power, non-ionizing (not x-ray)
- Walk-through – stop 2 seconds
- Fast: 300 – 600 people per hour

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Millimeter-wave Images from the L-3 ProVision™ system

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Holographic Millimeter-wave Imaging Technique

▶ Transmit antenna emits diverging (spherical) wave

▶ Receiver records amplitude and phase of scattered wavefront

▶ Transmitter/receiver, or transceiver, is scanned over a two-dimensional planar aperture and swept over a wide frequency bandwidth

▶ 3-D image formed using mathematical focusing

■ Holographic, wavefront reconstruction

■ Fourier transform based - efficient

transceiver position
(x', y', z_0)

y

x

z

target

scanned aperture

target point
(x, y, z)

Millimeter-wave Transceiver (Heterodyne)
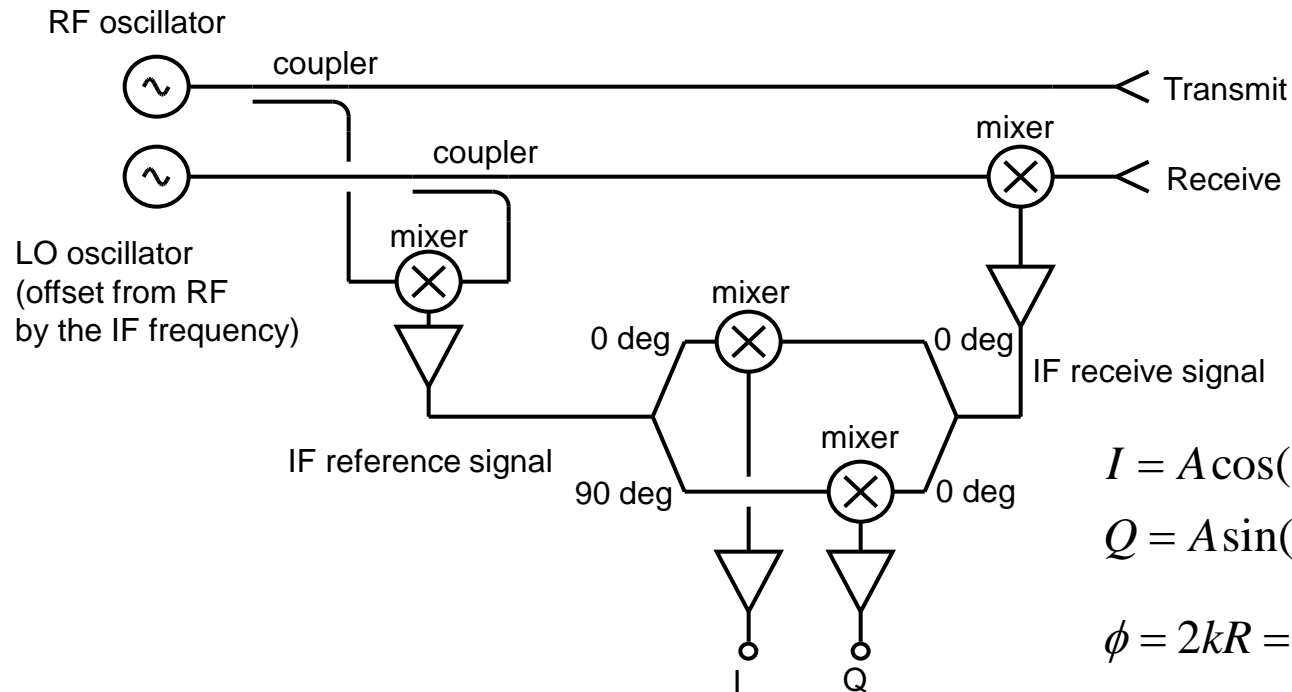
$$I = A\cos(\phi)$$

$$Q = A\sin(\phi)$$

$$\phi = 2kR = 2\frac{2\pi}{\lambda}R = 2\frac{2\pi f}{c}R$$

$\phi = 2\pi$ times the number of λ's to target and back

Measures phase and amplitude of scattered wavefront with high sensitivity
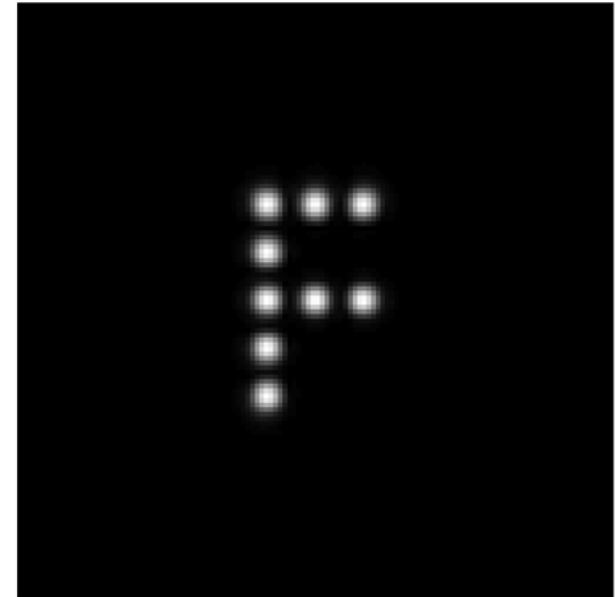
Holographic Image Reconstruction

Hologram
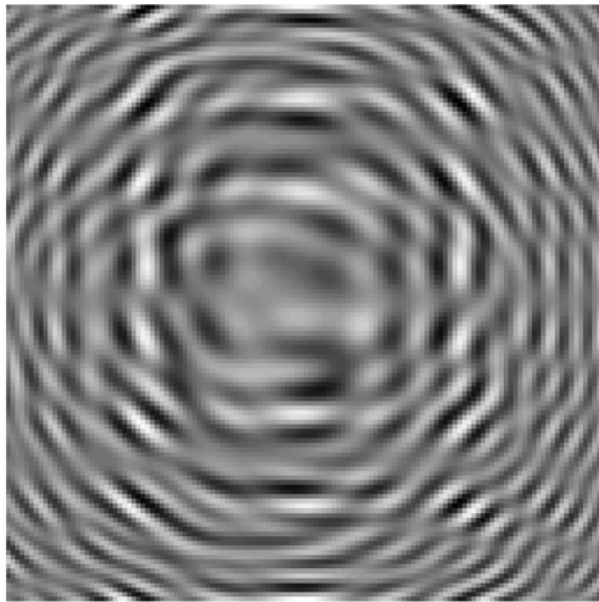
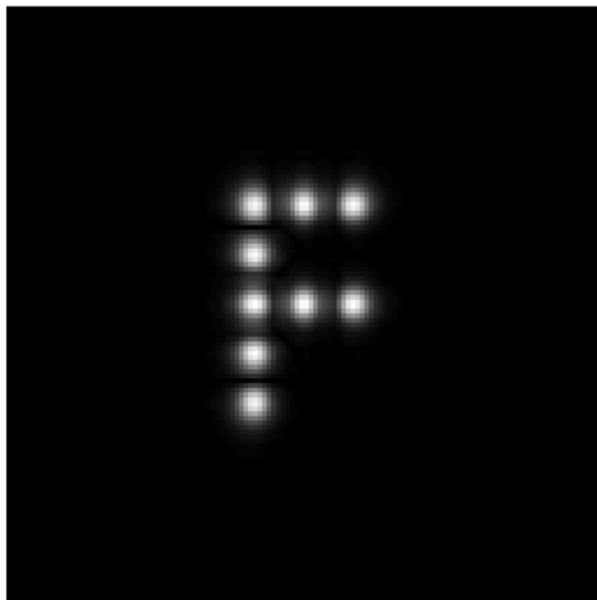Spatial Frequency Domain /
Angular Frequency
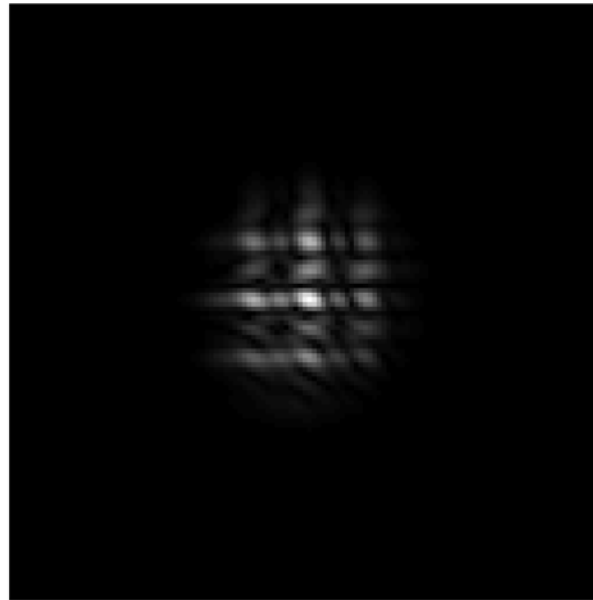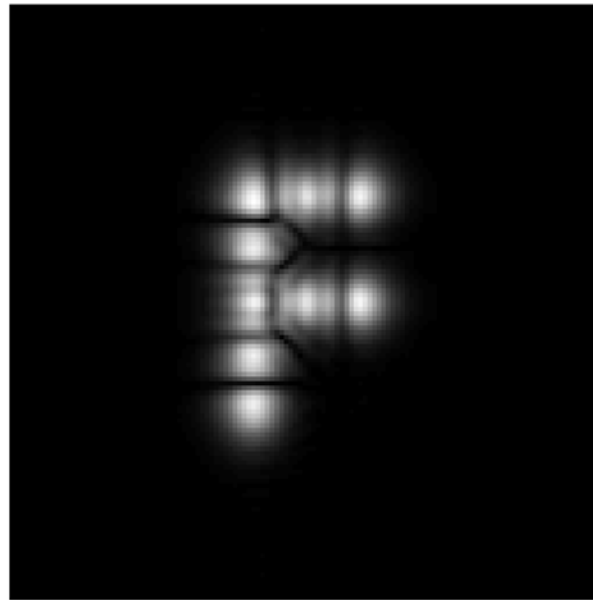
Reconstructed Image

2-D FFT and
Back-propagator

Inverse 2-D FFT and
magnitude

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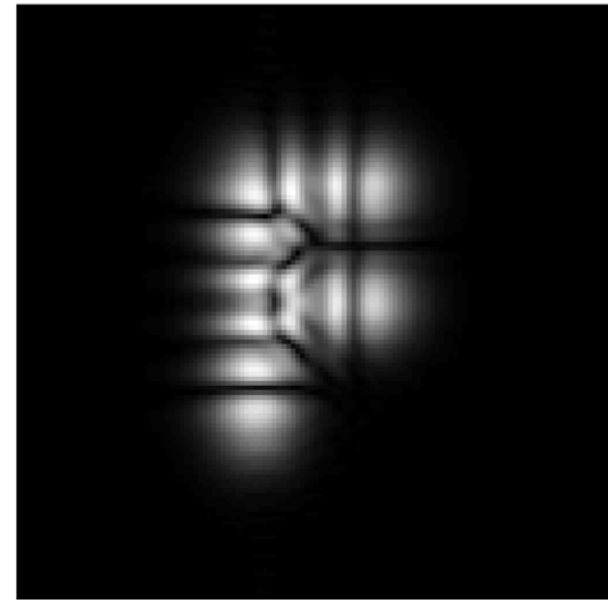
Holographic Reconstruction – Depth of Focus

► A depth must be specified for single frequency holographic image reconstruction

| 50 cm (correct) | 54 cm | 58 cm |

Increasing Reconstruction Depth ⟶

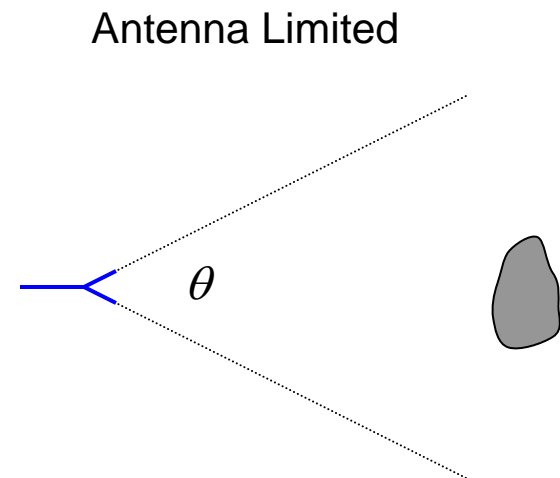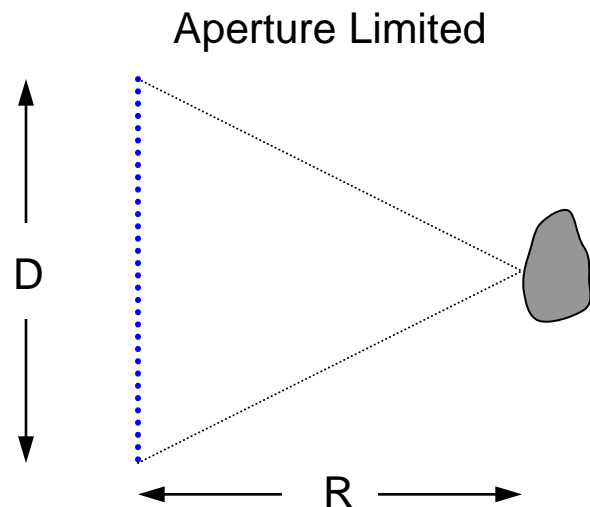Image goes out of focus unless depth to target is known (and constant)

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Wideband 3-D Image Reconstruction

▶ Limitations of single frequency holographic imaging

■ Cannot measure the range to the target and therefore the correct depth of focus is unknown

■ Images of objects that have a range of depths cannot be in complete focus, i.e. only portions of the image will be focus

▶ Recording the amplitude and phase of the wavefront over a range of frequencies can provide fully 3-D imaging

▶ 3-D Algorithm

■ 2-D Spatial Fourier Transforms decompose wavefronts into plane waves at known angles

■ Interpolation onto uniform 3-D spatial frequency domain grid

■ Phase term back-propagates the plane wave to the object's plane

■ 3-D Spatial Inverse Fourier Transform converts back to spatial domain

■ Maximum value projection typically shown – full 3-D information available

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Image Resolution

▶ Image resolution is determined by the wavelength and the angular extent of the illumination

▶ The angular extent can be limited by the size of the aperture (aperture limited), or by the beamwidth of the antenna (antenna limited)

Aperture Limited   Antenna Limited

$$\delta_x = \frac{\lambda}{4\sin(\theta/2)} \approx \frac{\lambda}{2}F^{\#} \qquad \text{where} \quad F^{\#} = \frac{R}{D}$$

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Range Resolution

▶ Range resolution is determined by the bandwidth of the system

▶ The distance between two distinct targets must be sufficiently large so that one additional cycle is generated in the I or Q waveforms during the sweep

$$\delta_r = \frac{c}{2B}$$

▶ For example, a bandwidth of 10 GHz (e.g. 10-20 GHz operation) results in a range resolution of 1.5 cm
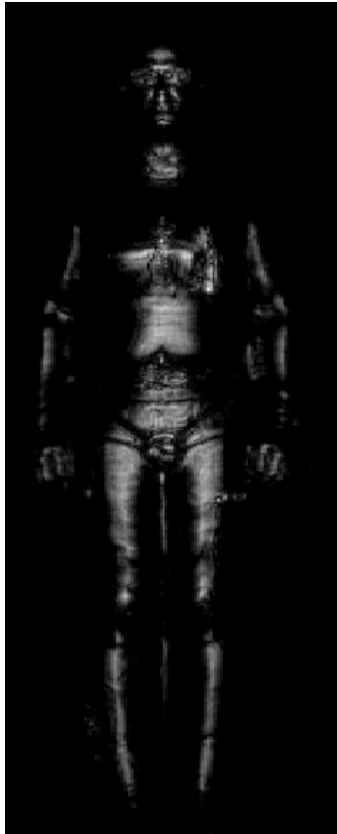
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Prototype Wideband Imaging System
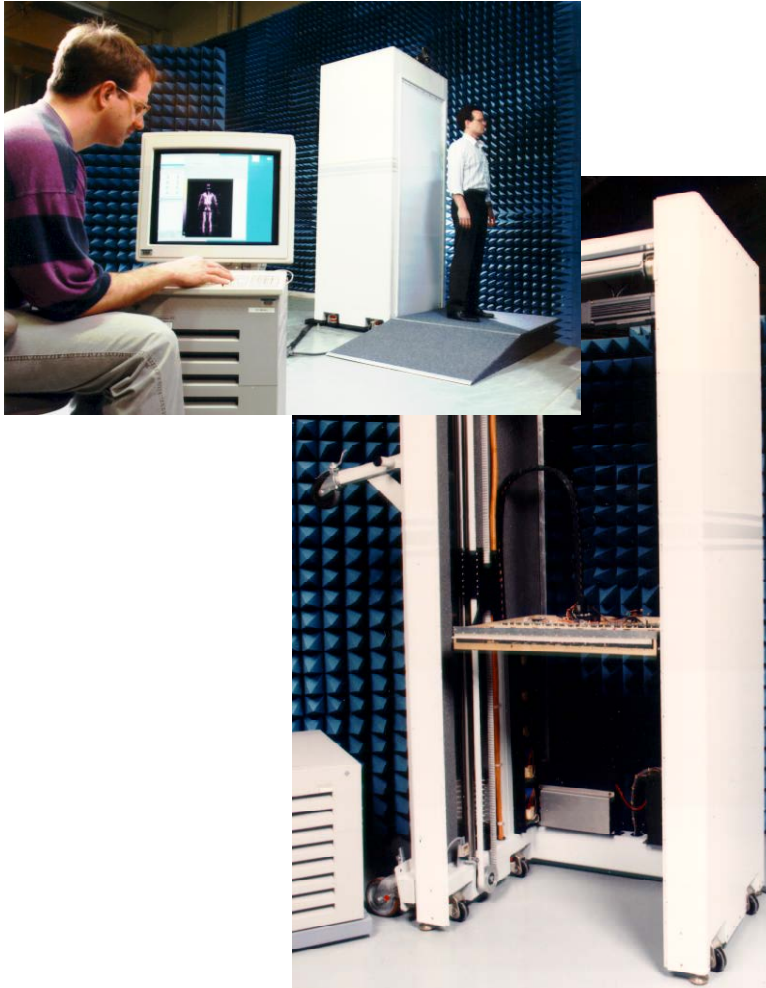
- K-a band switched linear array
- 27 - 33 GHz
- 128 elements
- Pin-diode switching
- 5.7 mm sampling
- 0.73 meter aperture

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Comparison of Wideband and Narrow-band Millimeter-wave Images
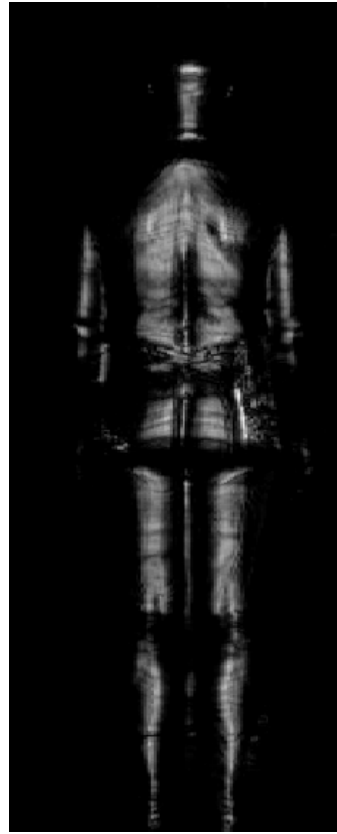
Wideband images of man at 27 - 33 GHz   Narrowband images of man at 35 GHz
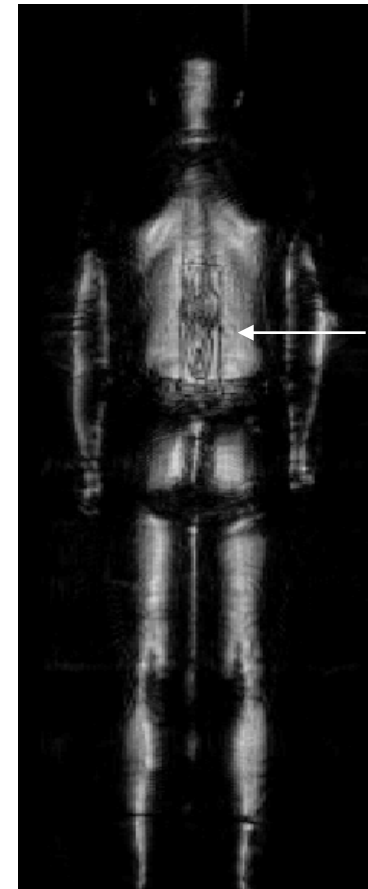
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Wideband Image of a Man with Concealed RDX Plastic Explosive (27 – 33 GHz)

Optical - plastic explosive

No explosive

RDX

Concealed explosive

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Wideband Images of Man with Plastic Explosive Simulant (27 – 33 GHz)

Optical - duct putty explosive simulant

No explosive

Concealed explosive

Wide Angle Illumination

▶ Wide-angle illumination is critical

- Lateral resolution is proportional to $1/\sin(\theta)$

- Many targets are smooth compared to the wavelength in the microwave and millimeter-wave frequency ranges

- Specular reflection will prevent scattered wavefront from returning to the transceiver

▶ Technique does not have inherent blind spots – images reflectivity, which can be low in the backscattered direction
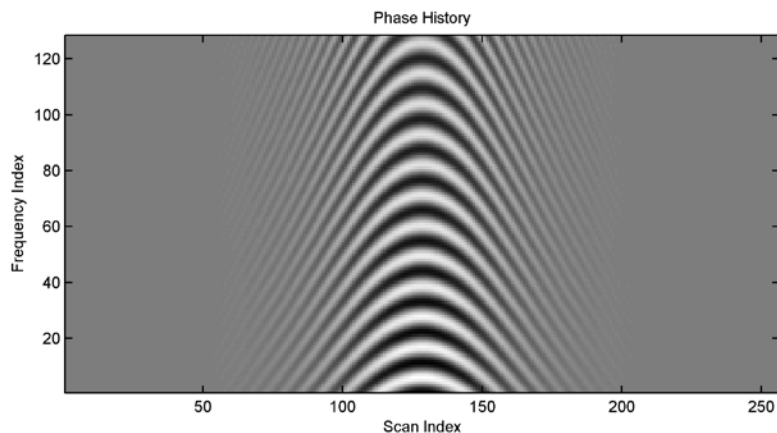

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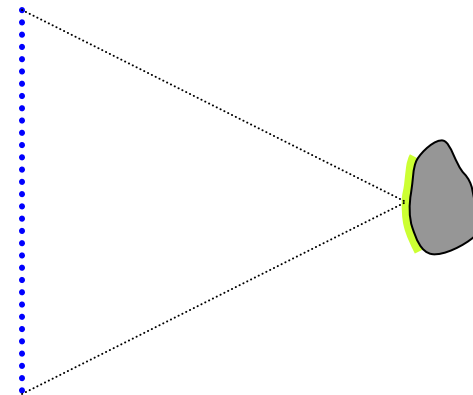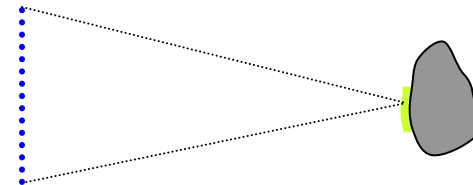
Physical Optics Scattering from a Cylinder

Spherical wave
illumination source

$\hat{n}_s$

$\hat{k}$
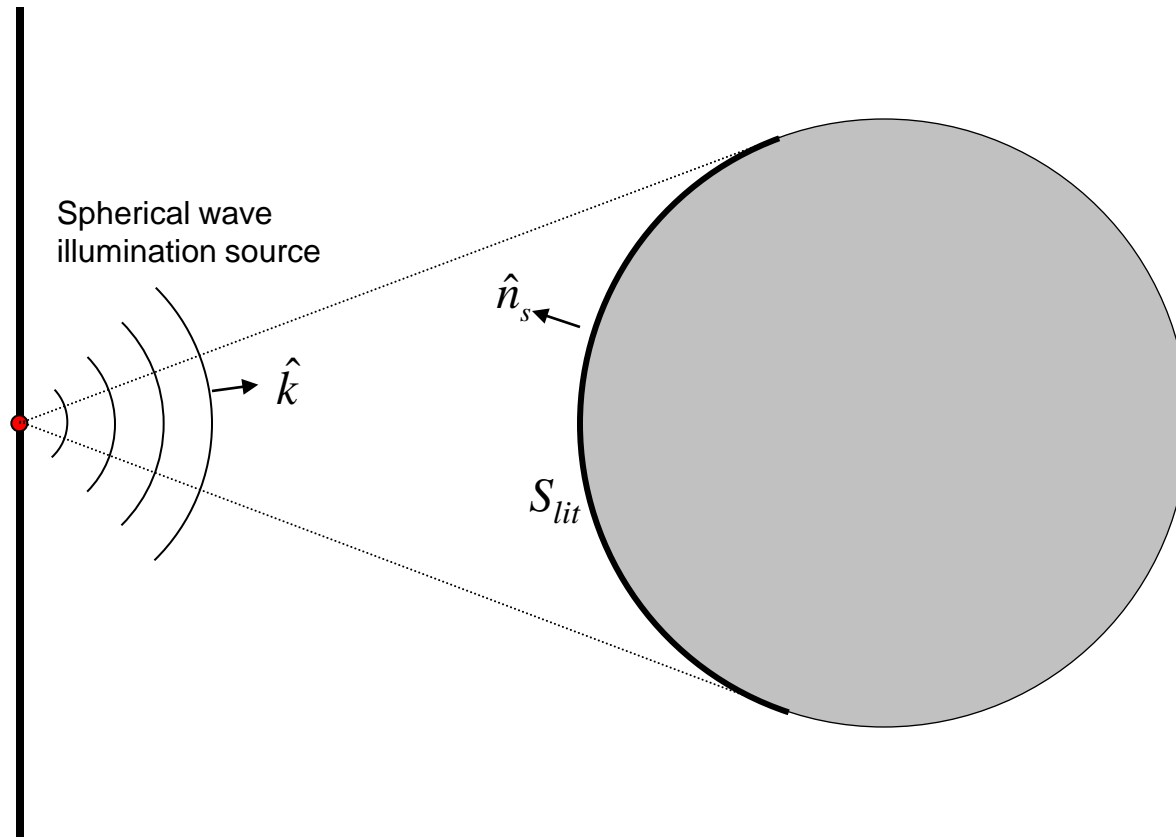
S_{lit}

$$\overline{E}^s(\overline{r}) = \frac{jkZ_0}{4\pi} \iint\limits_{S_{lit}} \hat{k} \times \hat{k} \times (2\hat{n}_s \times \overline{H}^i) \frac{e^{-jk|\overline{r}-\overline{r}'|}}{|\overline{r}-\overline{r}'|} dS$$

Physical Optics Simulation of Cylinder (range = 25 cm)
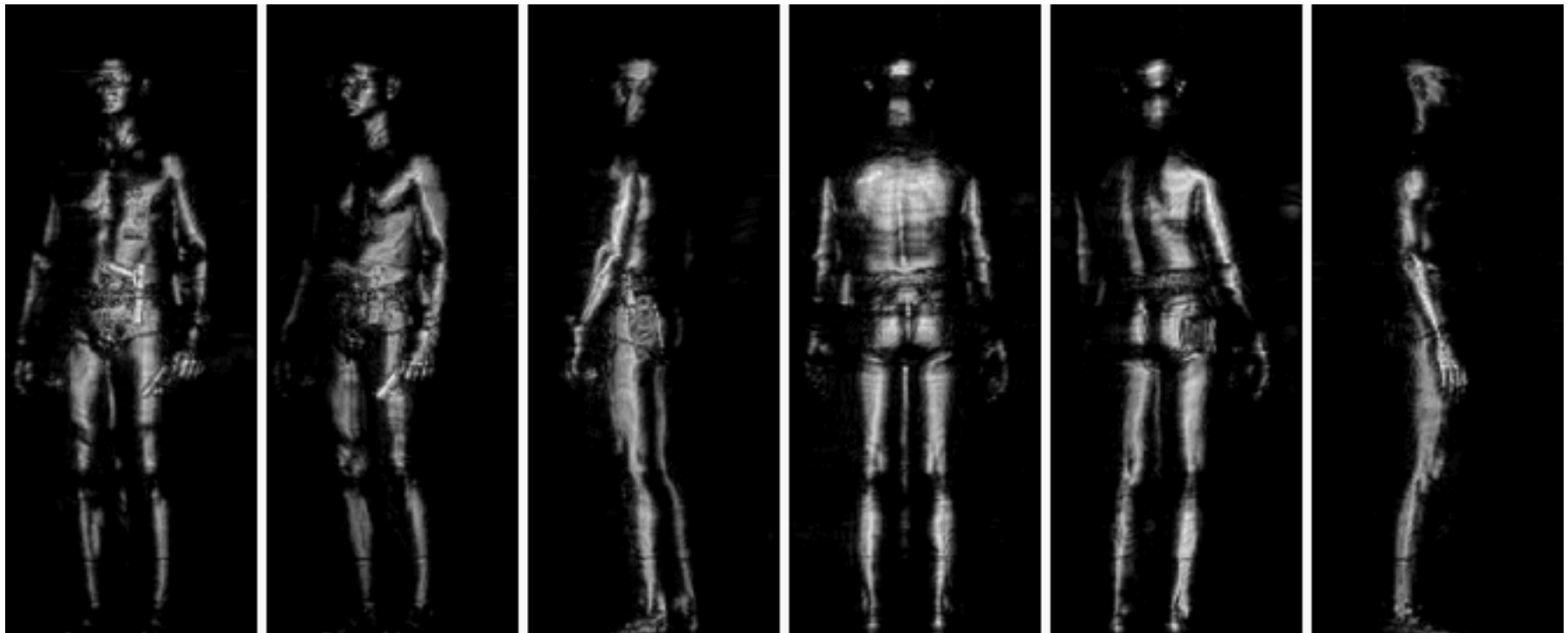
90 degree beamwidth

180 degree beamwidth
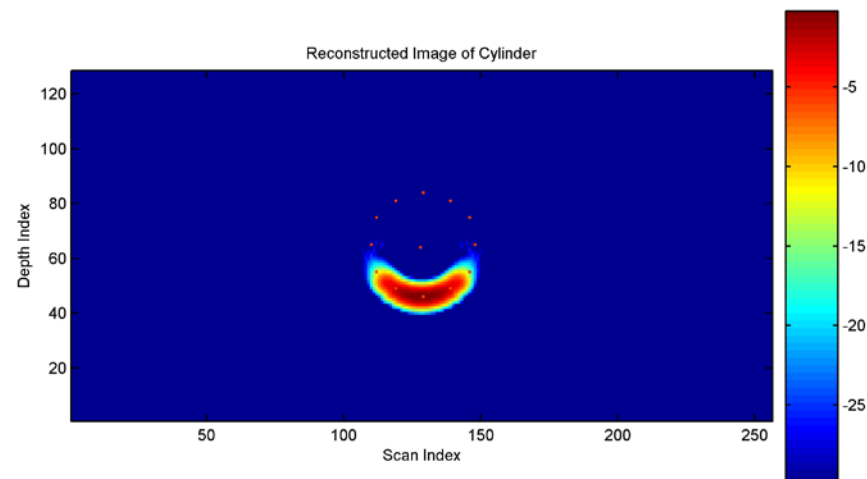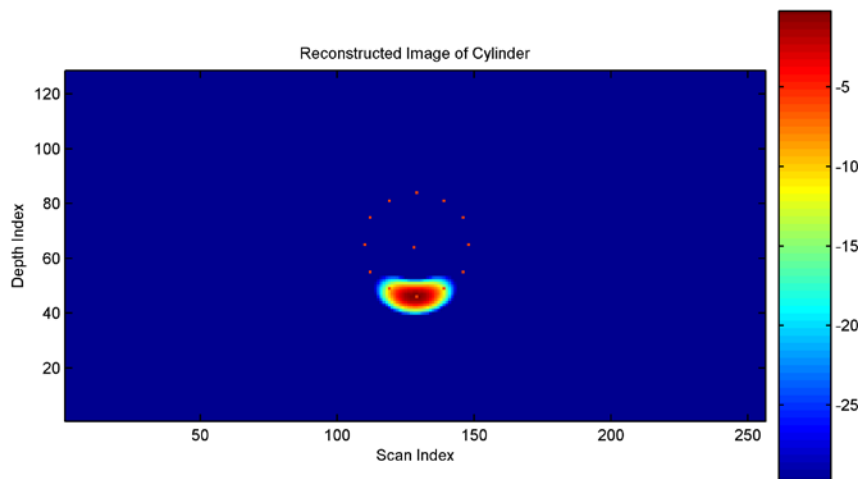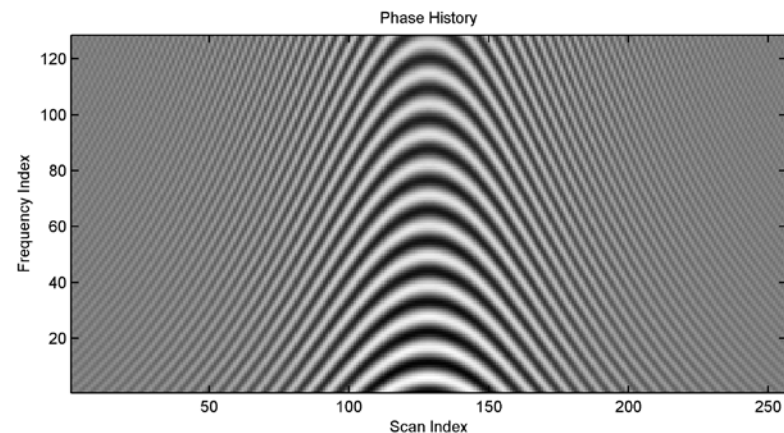
10-20 GHz, 1 m. aperture, cyl. diam. 15 cm, 25 cm range to cyl center, beamwidth 90 & 180 degrees with hamming weighting

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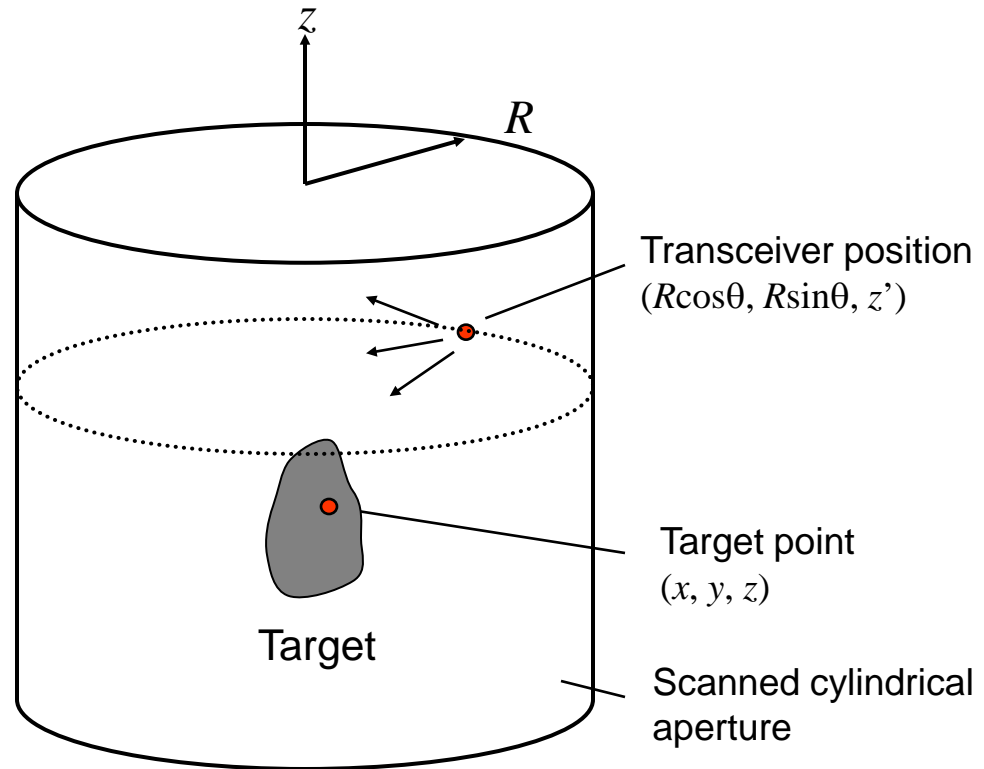# Wideband Millimeter-wave Weapons Detection System

| 20° | 40° | 120° | 180° | 210° | 270° |

27 - 33 GHz images of man carrying concealed weapons

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Cylindrical Imaging Technique

▶ Novel wideband image reconstruction algorithm has been developed which allows for fully focused 3-D imagery from a single cylindrical data set

▶ Reconstruction algorithm based almost entirely on Fourier Transforms which are implemented efficiently using the FFT algorithm

▶ Algorithm is readily separated into parallel instructions for parallel processing computers

▶ Viewing angle may be rotated about the subject to form a 3-D video animation of the resulting image data

z

R

Transceiver position
$(R\cos\theta, R\sin\theta, z')$

Target point
(x, y, z)

Target

Scanned cylindrical aperture

Wideband reflection data gathered over a 2D cylindrical aperture

Rotating Target 3-D Reconstruction

- ▶ Reconstruction (x, y, z) volume rotates with angular arc segment

- ▶ Images are combined to form a video animation of the rotating target

- ▶ Bandwidth of millimeter-wave illumination is important for depth of field (focusing) only
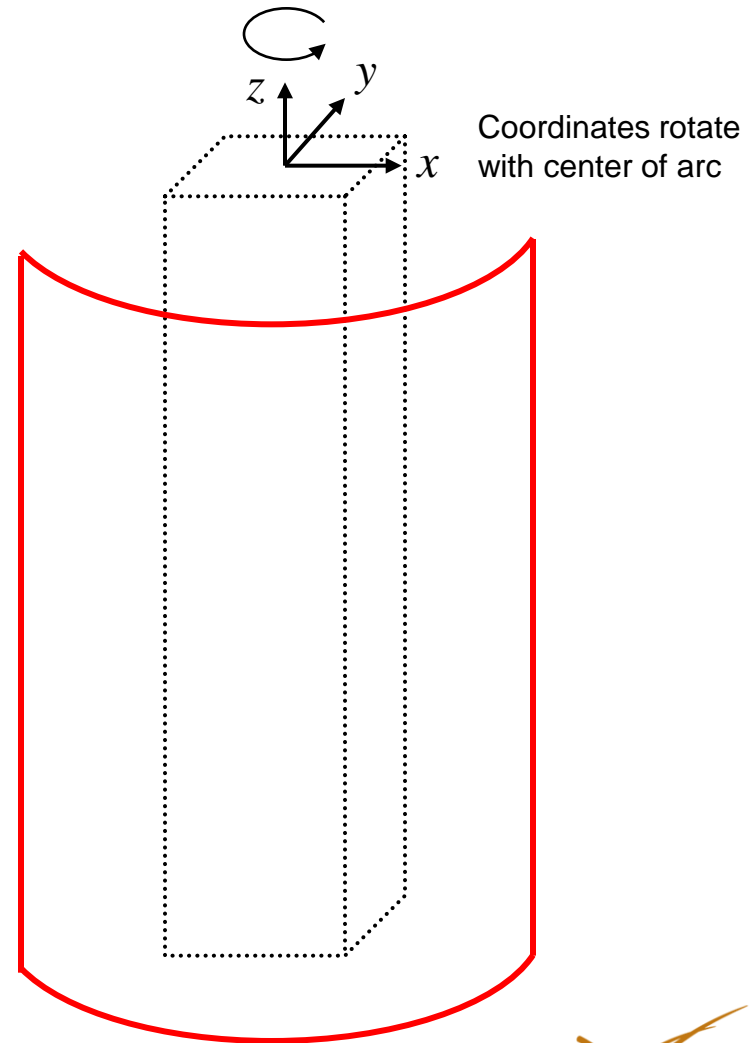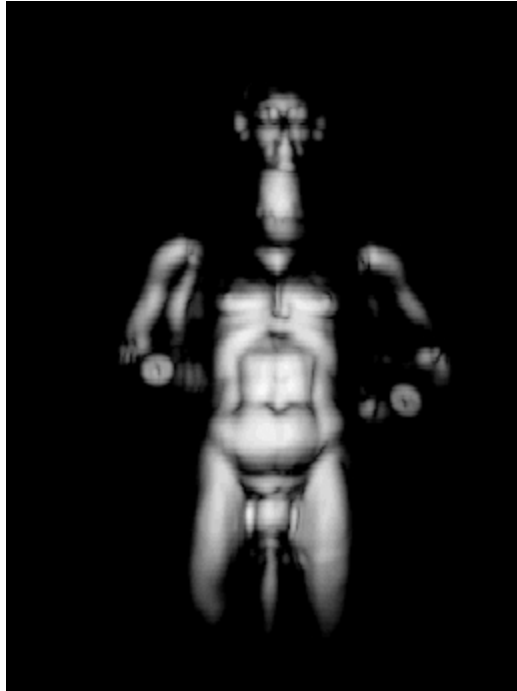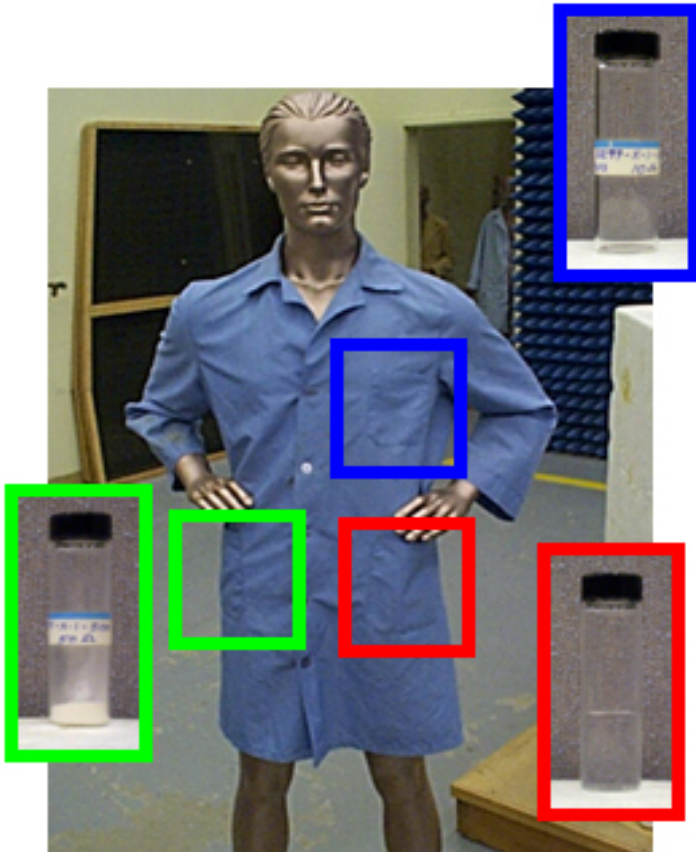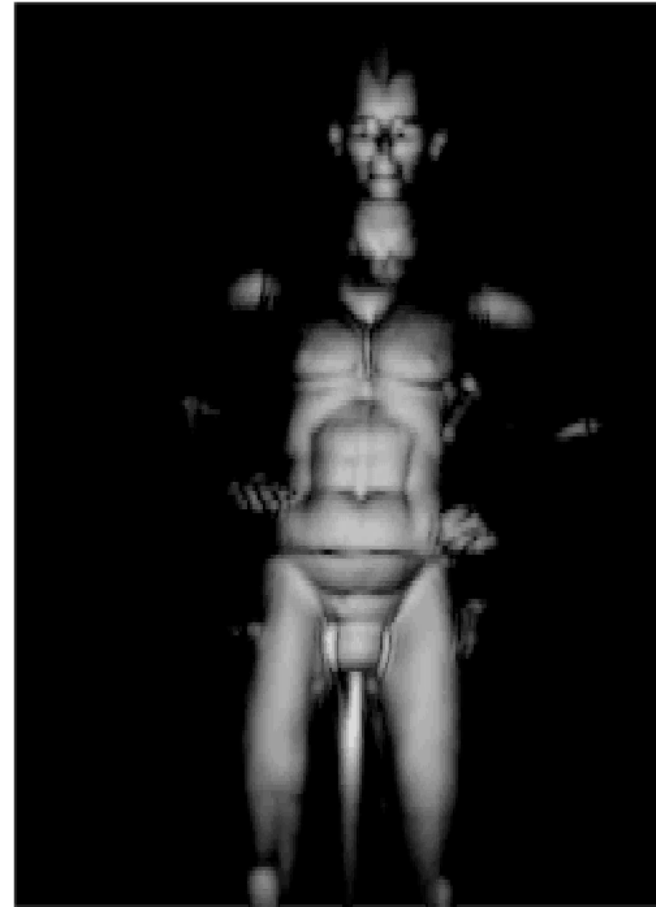
Coordinates rotate with center of arc

10-20 GHz cylindrical image reconstructions

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Cylindrical Imaging Results at 10 – 20 GHz

Optical – 3 glass vials
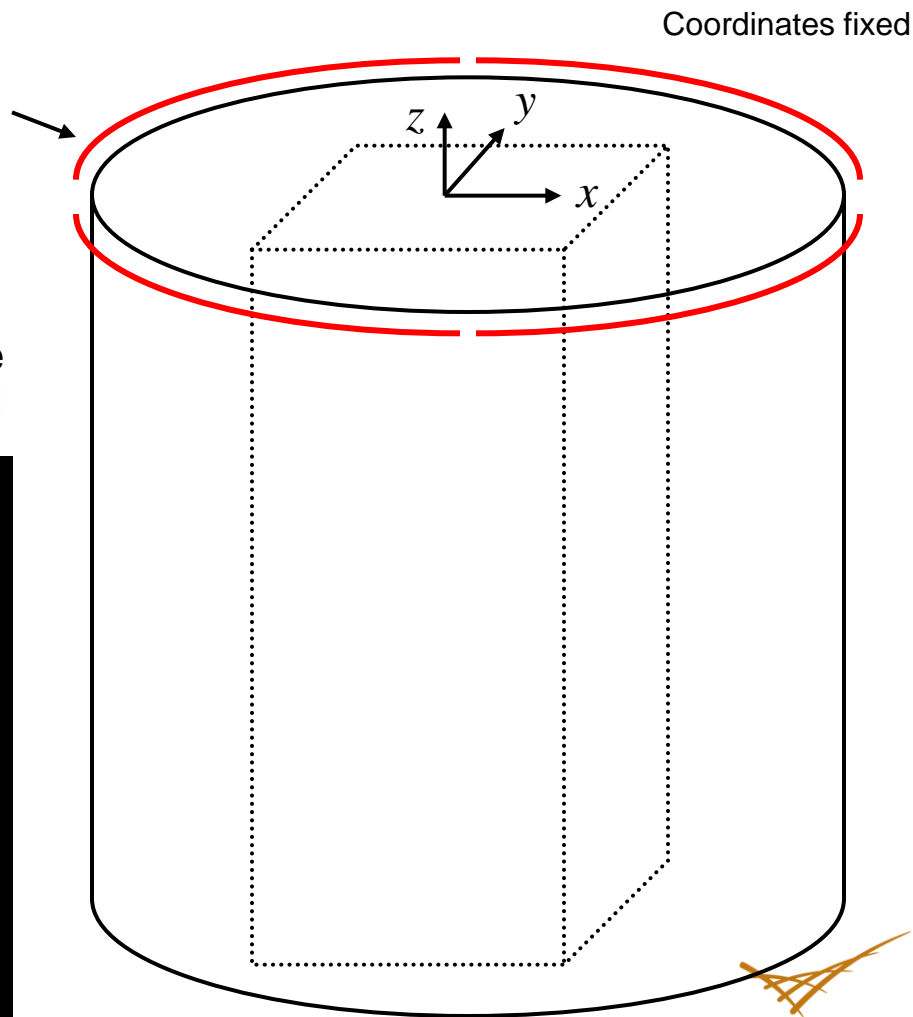

10 – 20 GHz

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Combined Cylindrical 3-D Reconstruction

- ▶ Reconstruction angular segment shifts relative to fixed (x, y, z) volume

- ▶ 3-D (x, y, z) images are combined from 8 overlapping 90 degree arc segments to form complete reconstruction

- ▶ Bandwidth should be as wide as possible for depth resolution comparable to lateral resolution
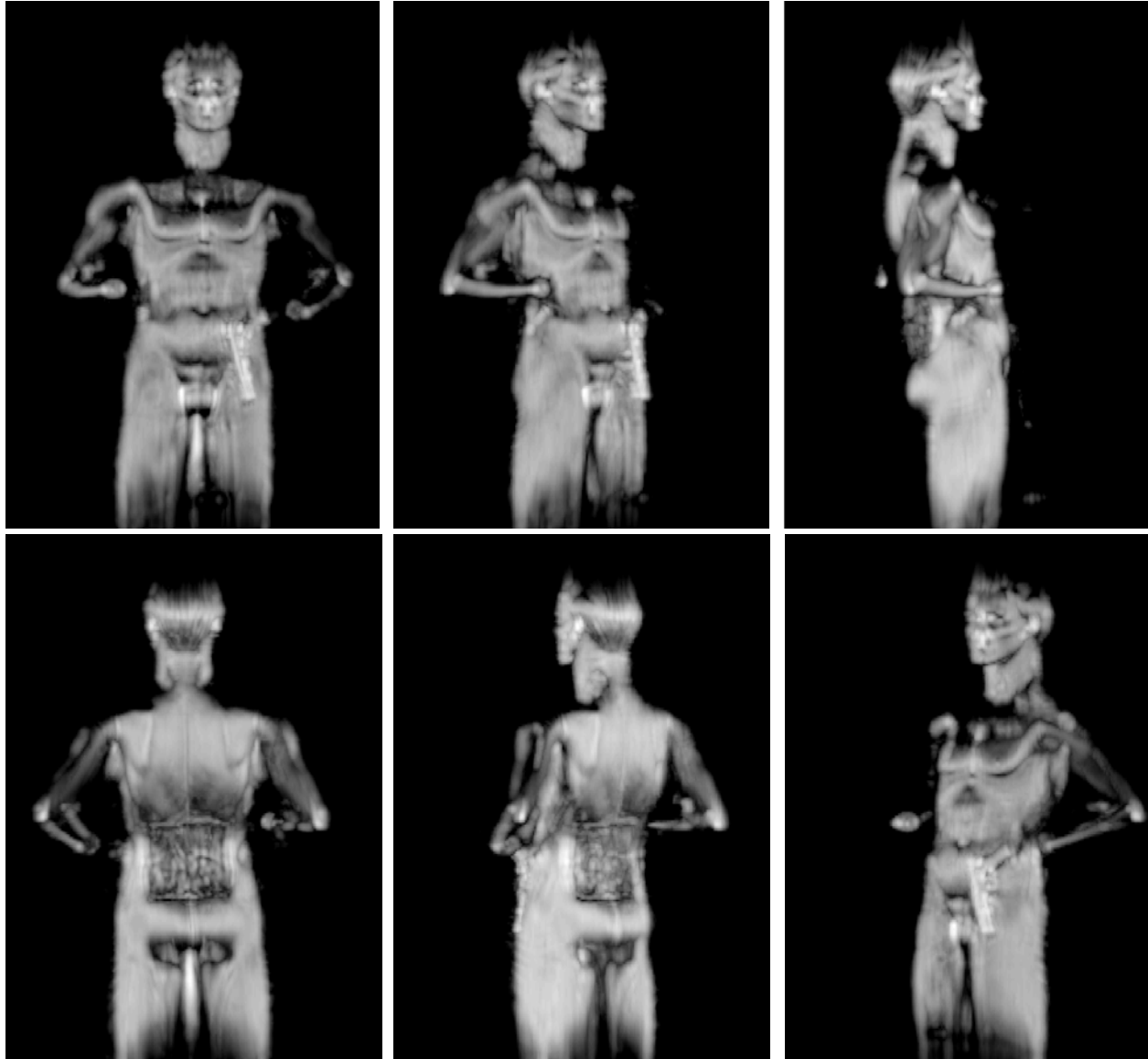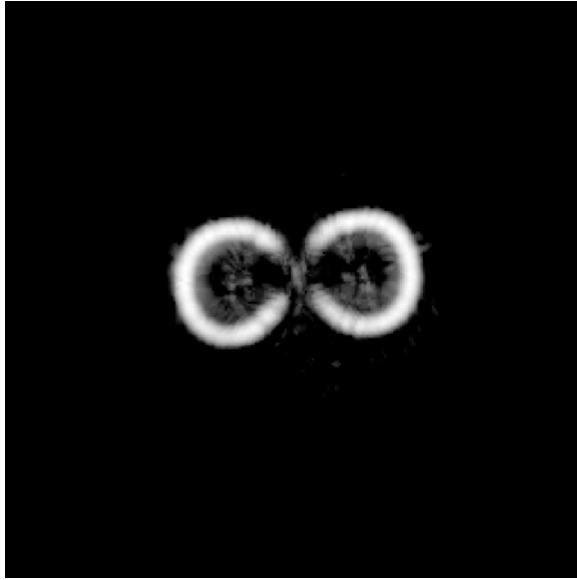
10-20 GHz cylindrical image reconstructions

Weapon Detection with Combined Illumination (10 – 20 GHz)

Combined illumination reconstruction rendered with APR

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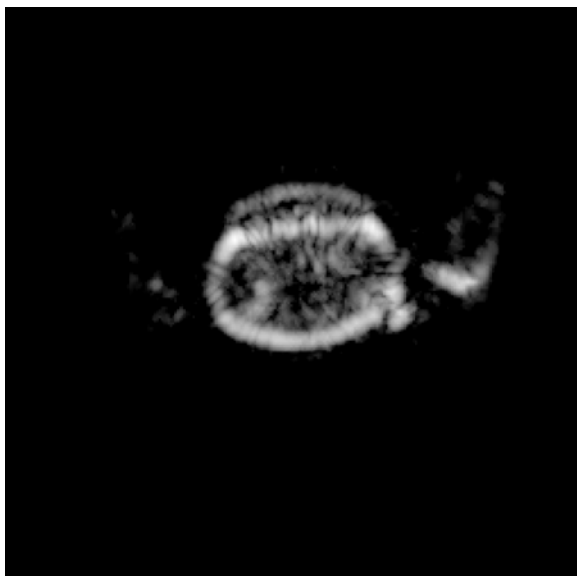NATIONAL LABORATORY

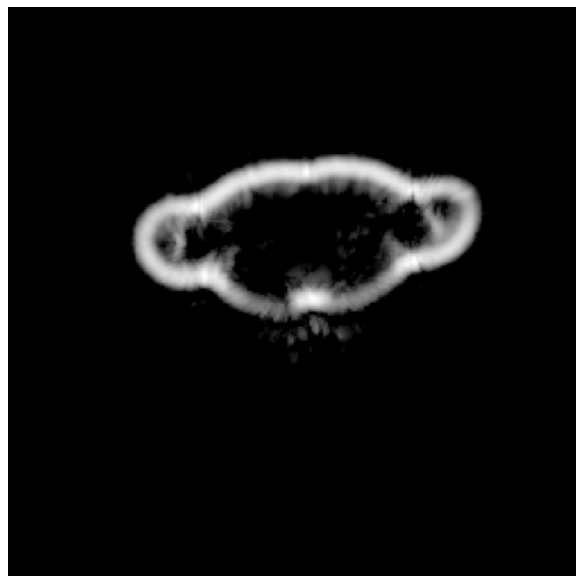# Combined Cylindrical – Cross Sectional Analysis (LR Polarization)

Thigh level
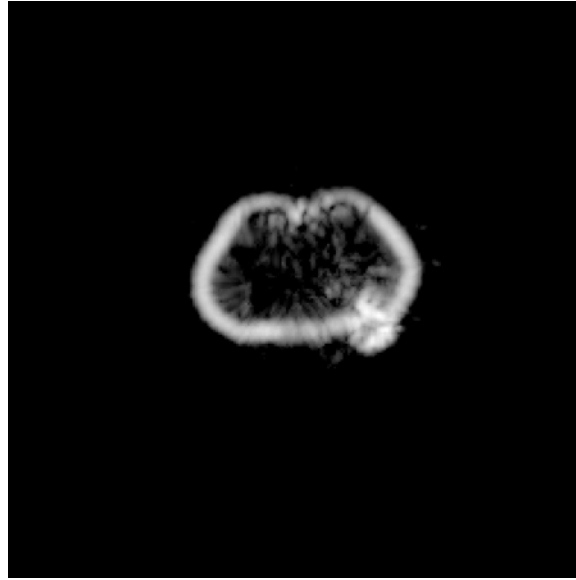
Near/below waist level

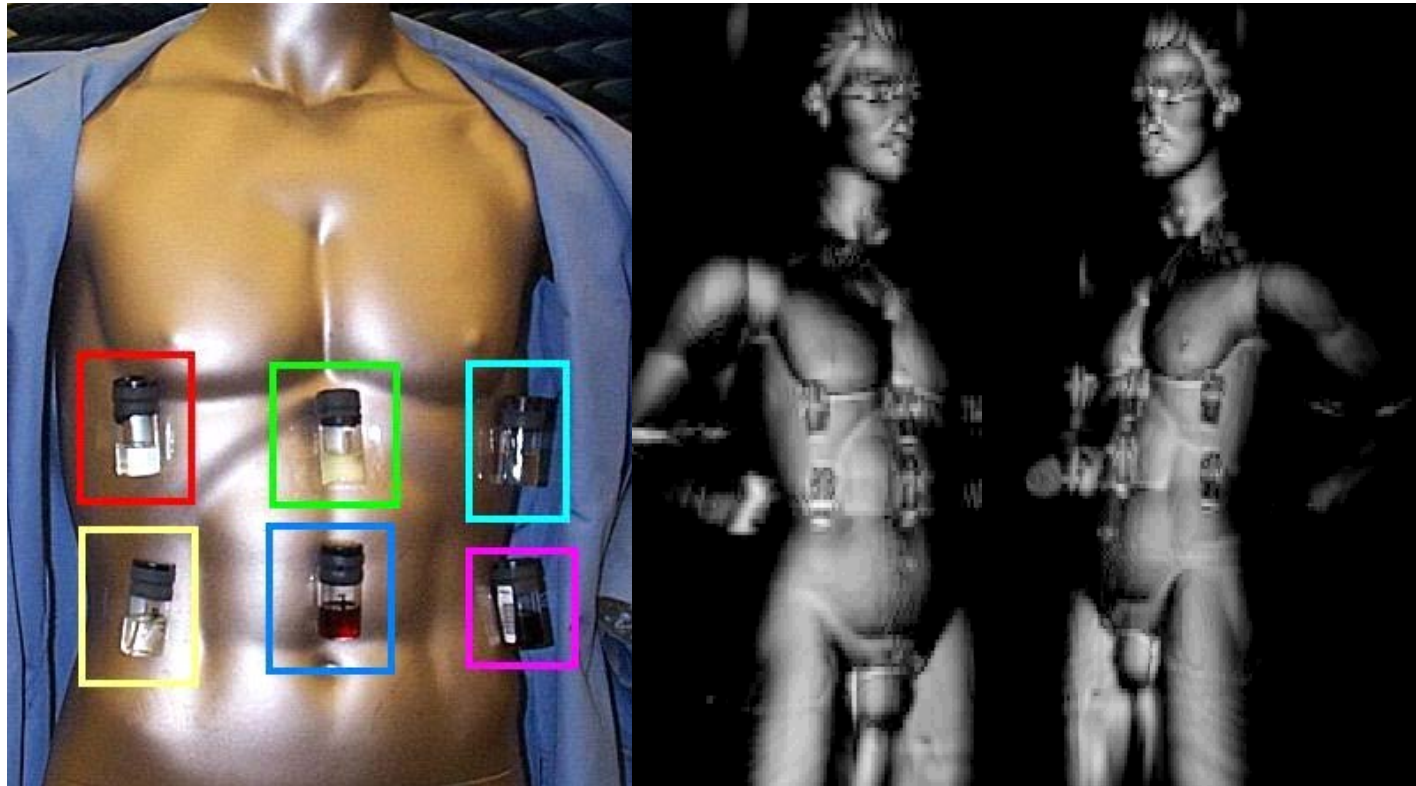Above waist level – partially transparent on lower back

Chest level

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Ka Band Images of Mannequin and Concealed Glass Vials
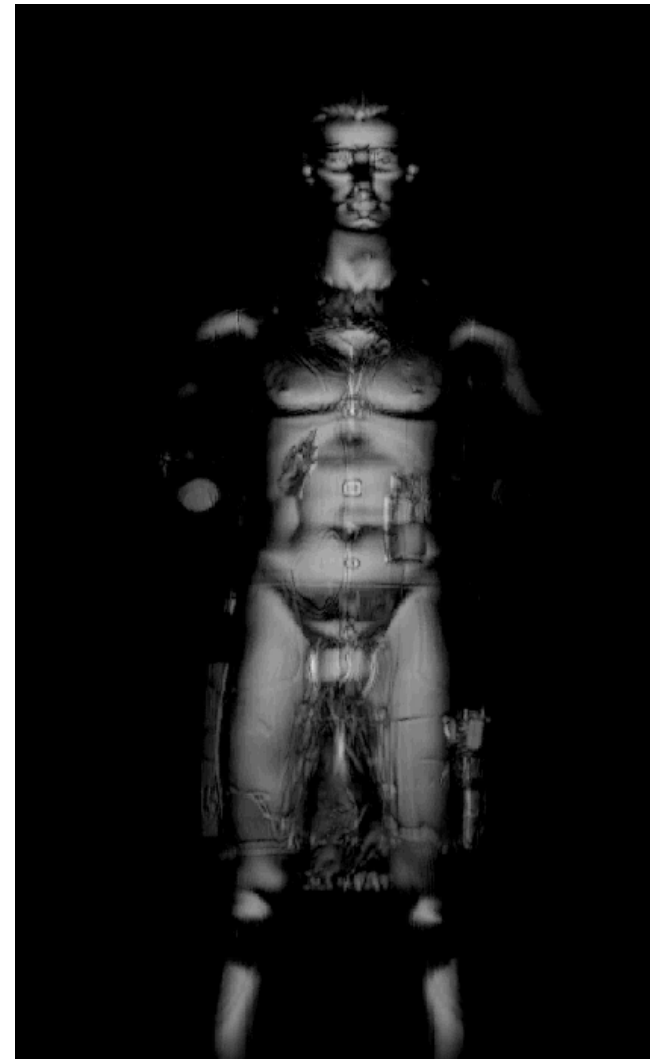

Optical

22 – 33 GHz Images

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Cylindrical Holographic Radar Imaging Results (40 – 60 GHz)

Mannequin with Concealed Threats

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Conclusion

▶ Active mm-wave imaging is effective for security screening

- Cylindrical portal imaging technology is becoming widely deployed
  - Excellent illumination properties due to the 360 degree (or wide angle) illumination
  - Allows inspection from multiple viewing angles
  - High-resolution
  - Excellent clothing penetration at in the lower mm-wave band
  - Scanning is rapid (several seconds), with throughput of over 400 people/hour possible
  - Cost effective
- 3-D imaging provides additional information
  - Preserves focus (depth of field)
  - Allows exploitation of depth information or layered reflections for additional target detection techniques

▶ Standoff imaging is being explored using sub-mm imaging

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