Multistatic 3D Whole Body Millimeter-Wave Imaging for Explosives Detection

Northeastern University

ALERT
AWARENESS AND LOCALIZATION OF EXPLOSIVES-RELATED THREATS

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IEEE Distinguished Lecture, Qualcomm, December 6, 2019

Outline

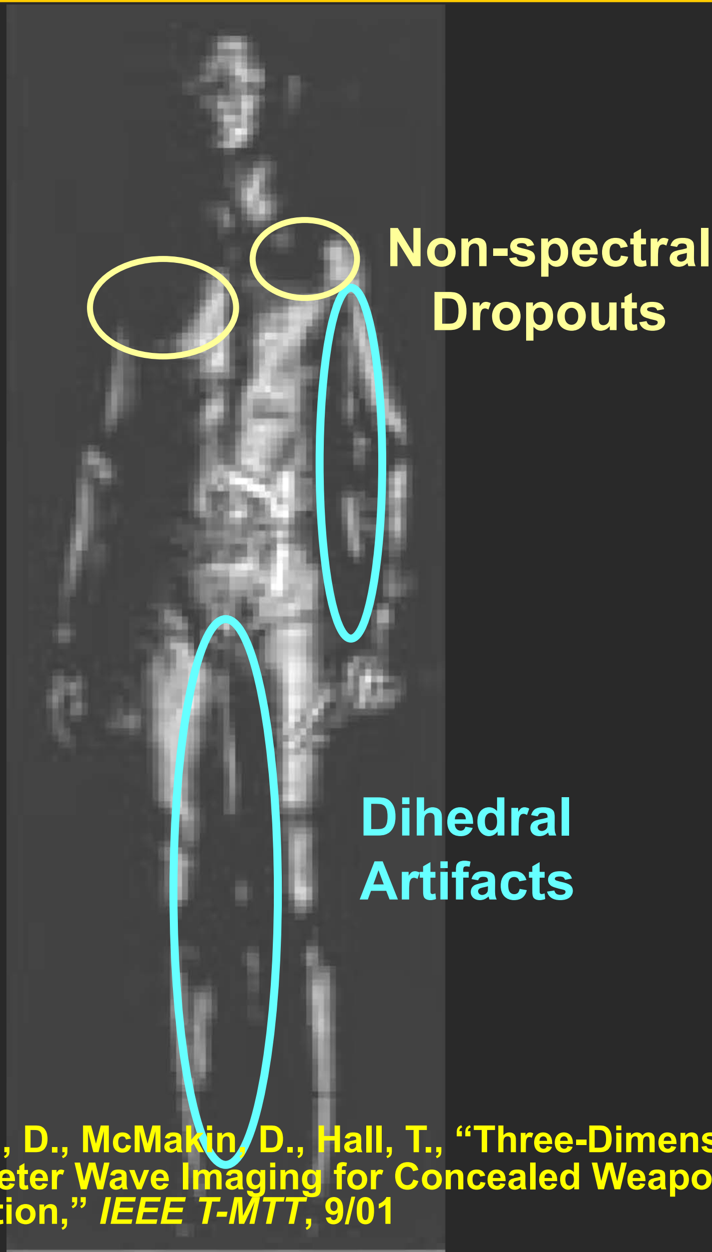
- State of the art
- Multistatic radar
- Blade beam reflector
- Elliptical toroidal reflector
- Penetrable dielectric imaging
- Experimental results

Mm-Wave Imager: Current State-of-the-Practice – L3 ProVision

- Detects many types of materials based on shape (metallic and non-metallic): liquids, gels, plastics, metals, ceramics

- Limitations
  - "Dead Spots"
  - No chemical info
  - Limited views
  - Poor penetration through leather and metallic clothing
  - No penetration through skin or into body cavities

State of the art



Current mm-wave scanners are based on monostatic radar:

•Presents specular reflection only – no depth encoding

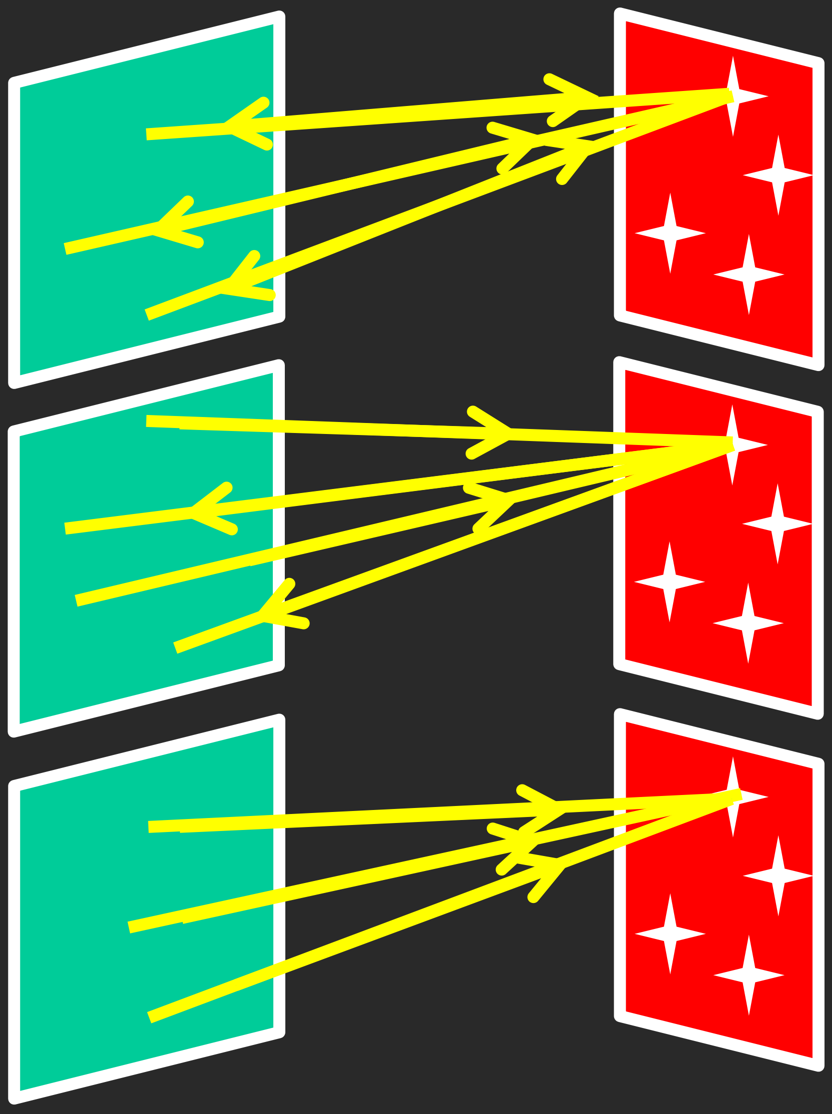
•Uses Fourier inversion – fast, but not best for close imaging.

•Shows shapes of metallic objects, but does not fully consider reverse imaging of weak dielectrics (i.e. explosives).

Sheen, D., McMakin, D., Hall, T., "Three-Dimensional Millimeter Wave Imaging for Concealed Weapon Detection," *IEEE T-MTT*, 9/01

Monostatic / Multistatic Radar

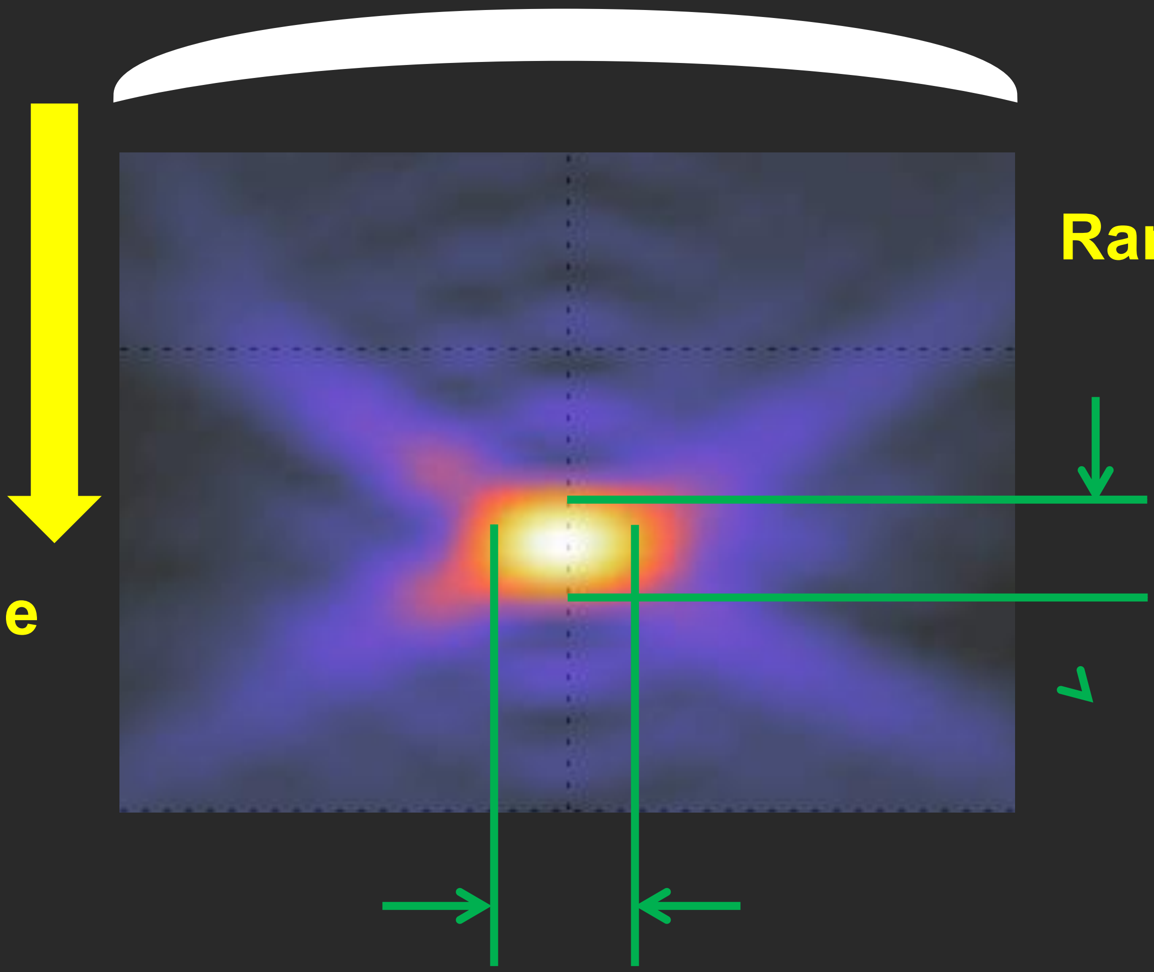
- Monostatic
  - Multi-monostatic
- Bistatic
  - Multi-bistatic
- Multistatic



Radar Focusing Resolution –Point Spread Function

Aperture width *d*

Range
r

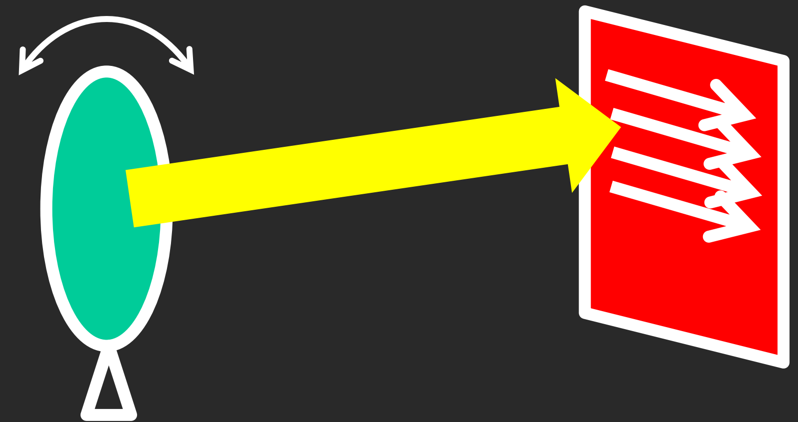


Range resolution:
~ *c / 2BW*

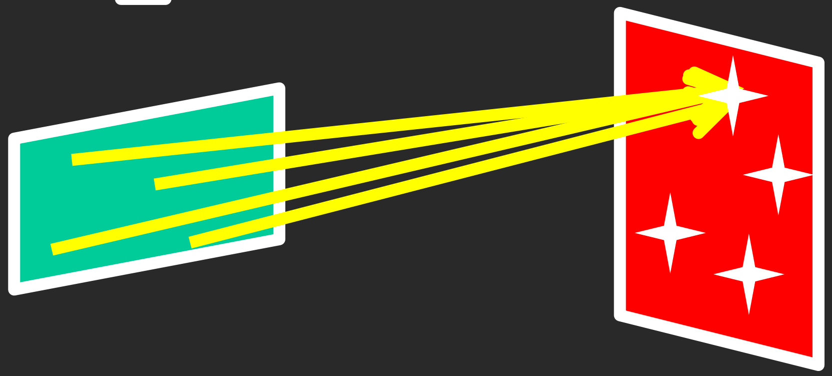
Cross range resolution: ~ $r \lambda / d$

Imaging with Mm-Wave Radar

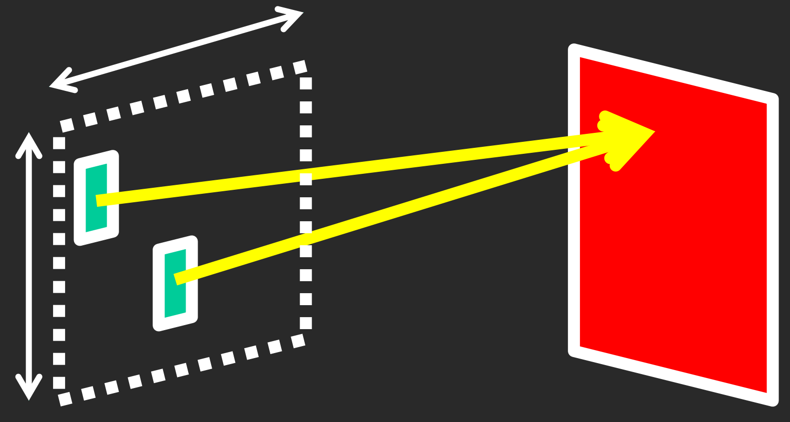
- Raster scanned focused point



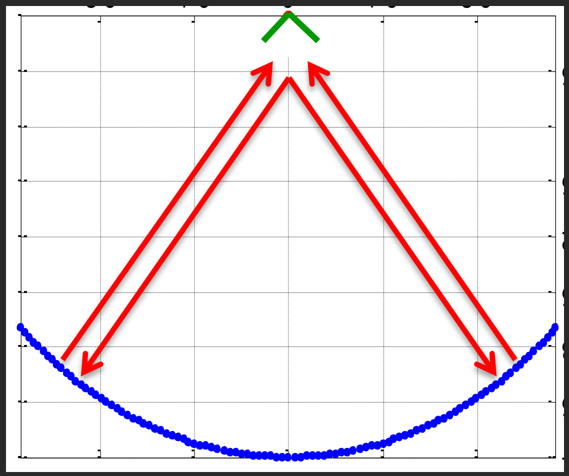
- Electronically scanned phased array

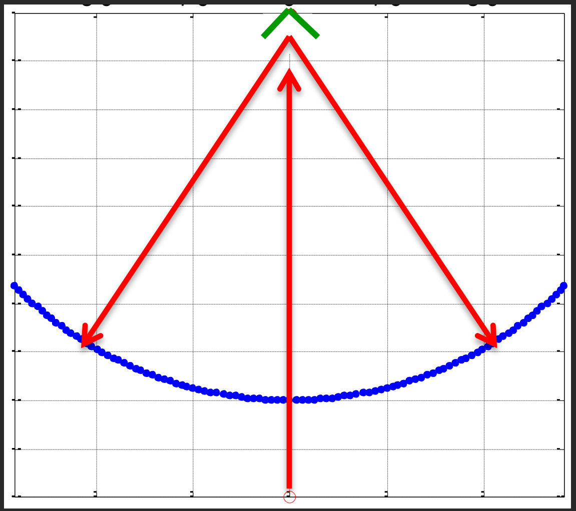


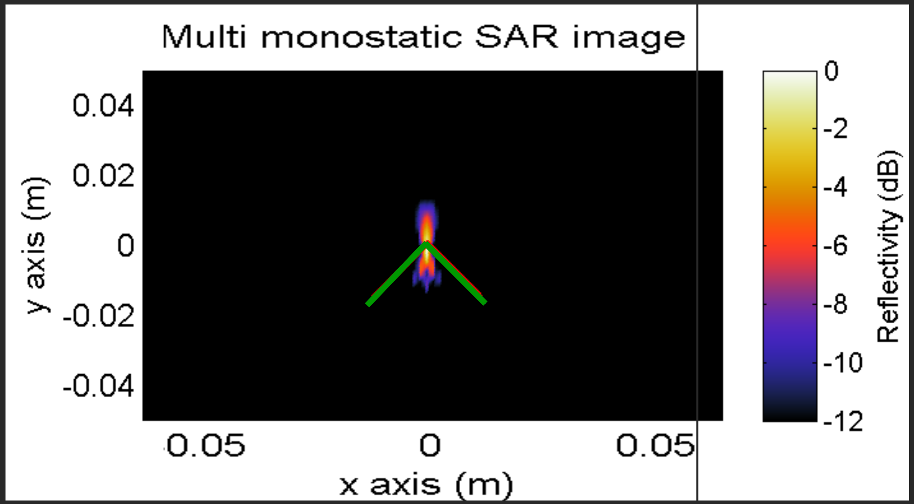
- Synthetic aperture radar



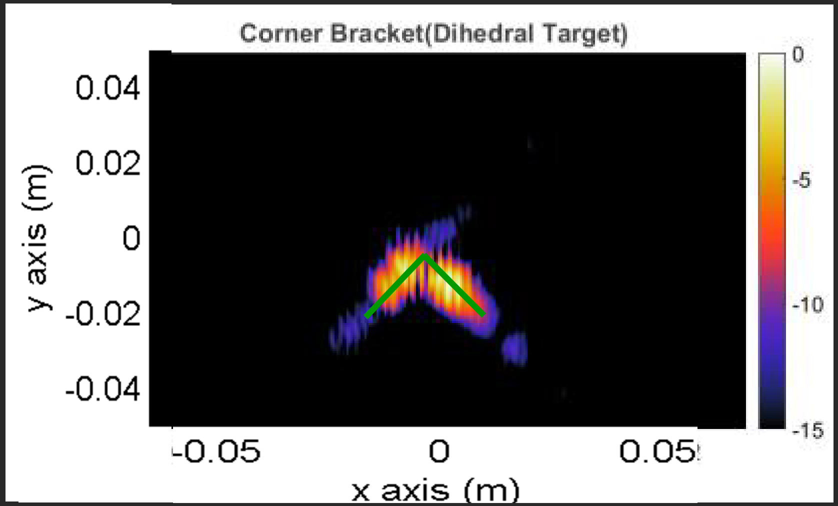
Multi-Monostatic vs. Mulitstatic Mm-Wave Radar Imaging Example







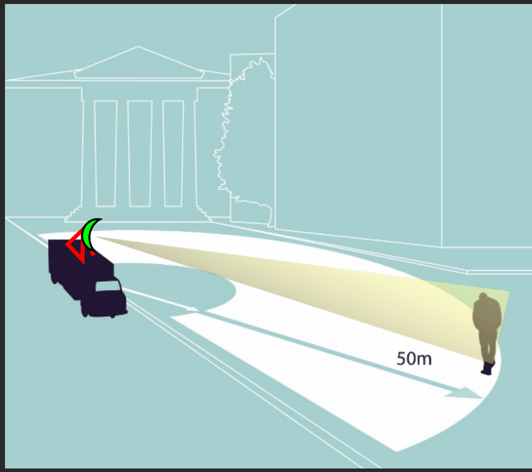
<u>Multi-Monostatic:</u> Dihedral images to a point



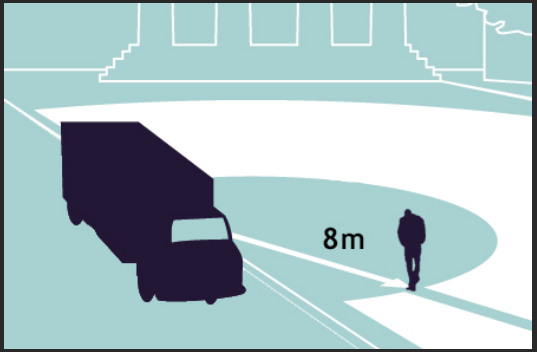
<u>Multistatic:</u> Dihedral images to correct corner scatterer

Detection Regimes

- Distant targets (10 m to >100 m),
  - Stand-off detection of hazards
  - Far enough away to minimize threat



- Mid-range targets (3 to 10m)
  - Enhanced sensing discrimination
  - Not explicitly surrounding target

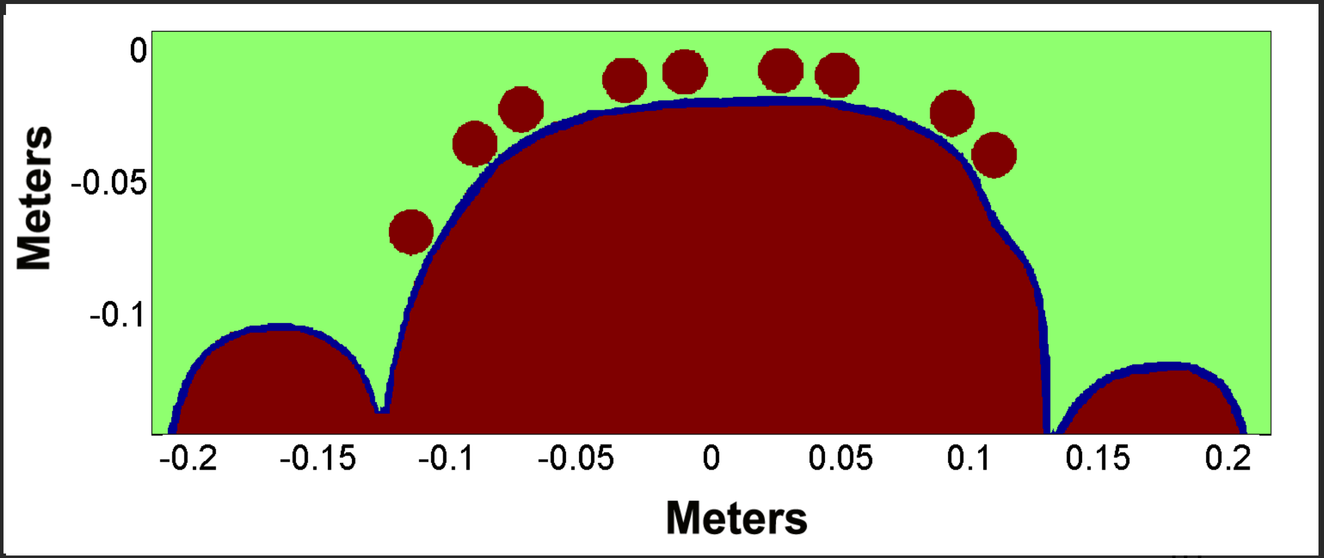


- Intimately near targets (< 3 m)
  - Non-invasively examined
  - Mostly portal sensors

Full-Wave Modeling of Radar Scattering from Accurate Anatomic Geometries

www.nlm.nih.gov/research/visible/visible_human.html

Threat Case with 9 Pipe Bombs

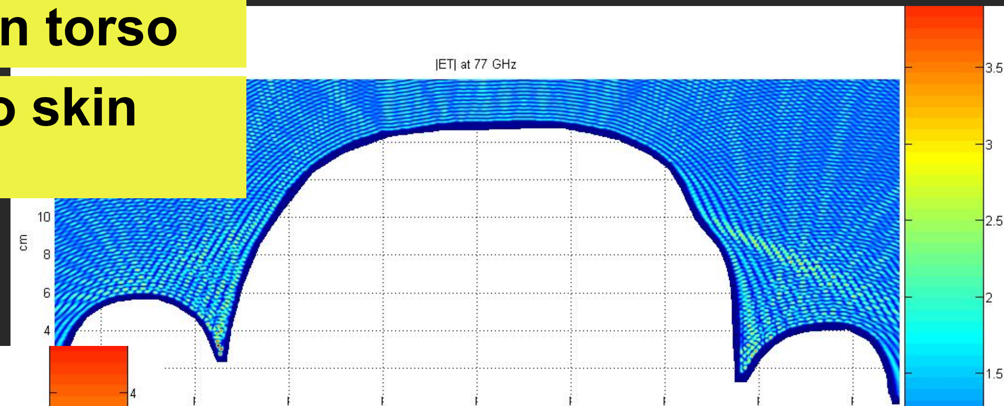


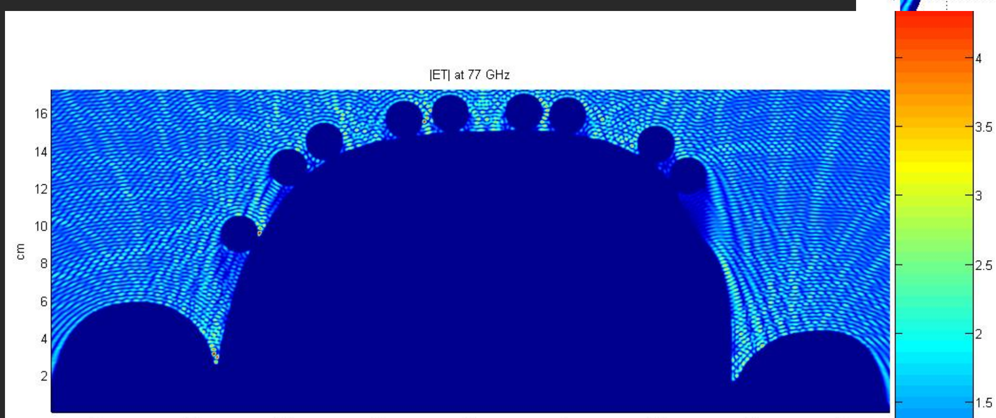
Snapshot of Waves Interacting with Scatterers

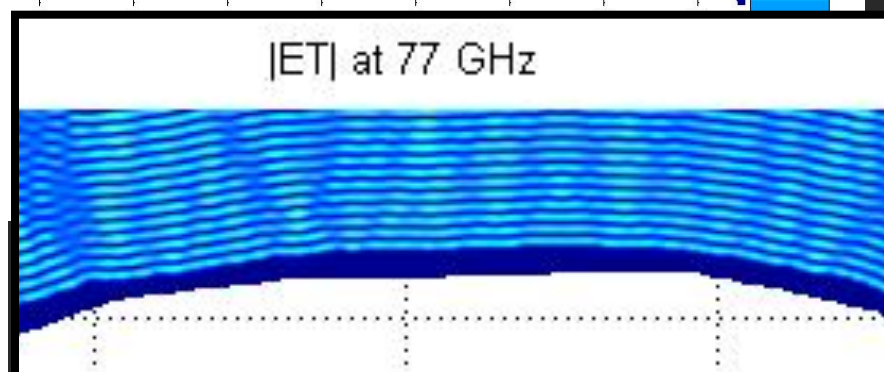
77 GHz TM Uniform Plane Wave Scattering from Torso with and without Pipes

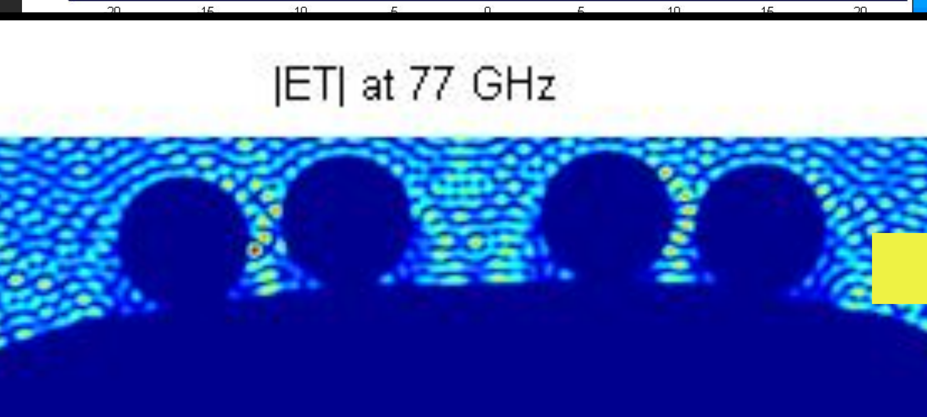
Considerable interference from various scattering points on torso

But variation across torso skin surface is slow









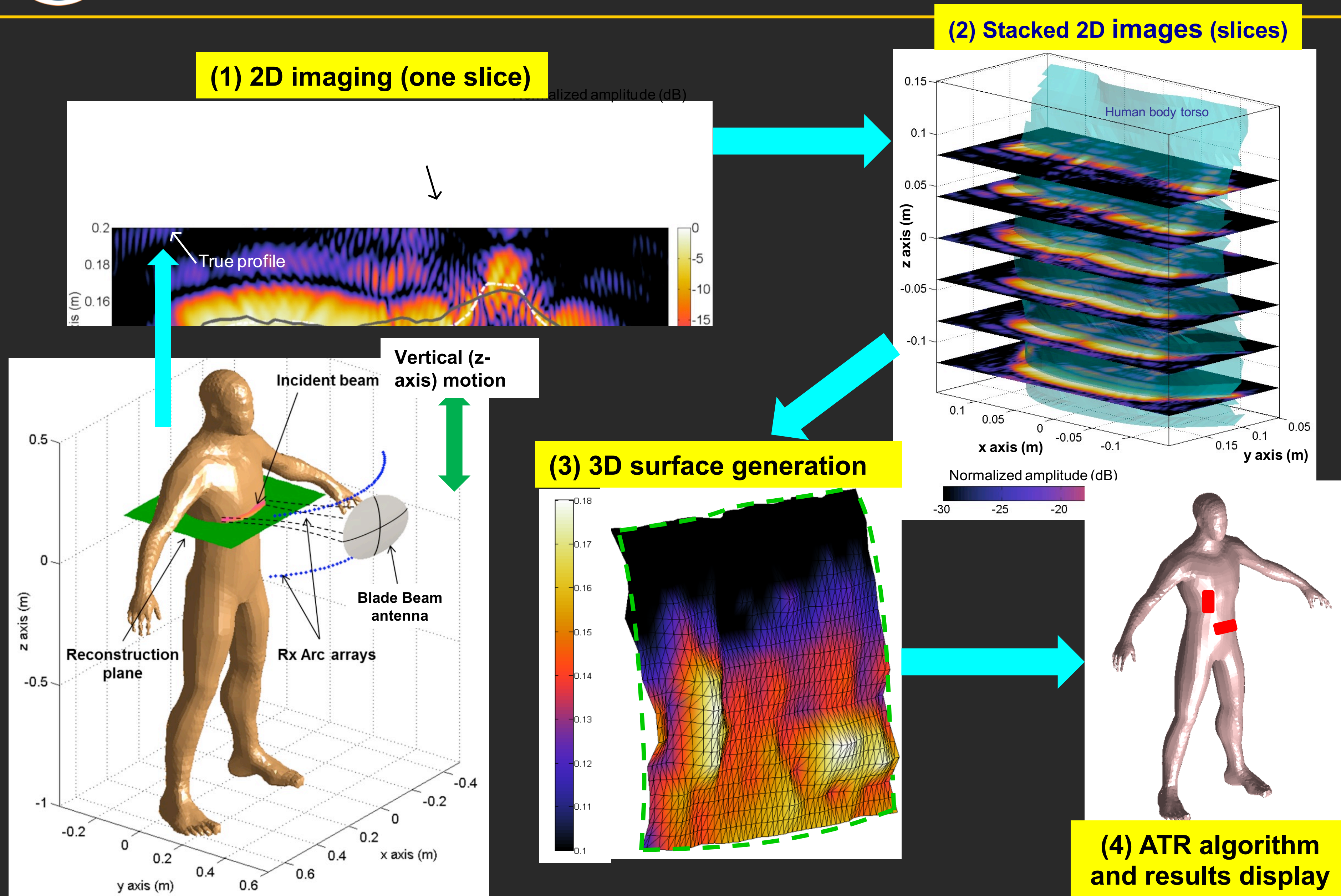
Pipes further confuse scattering

And variation is rapid

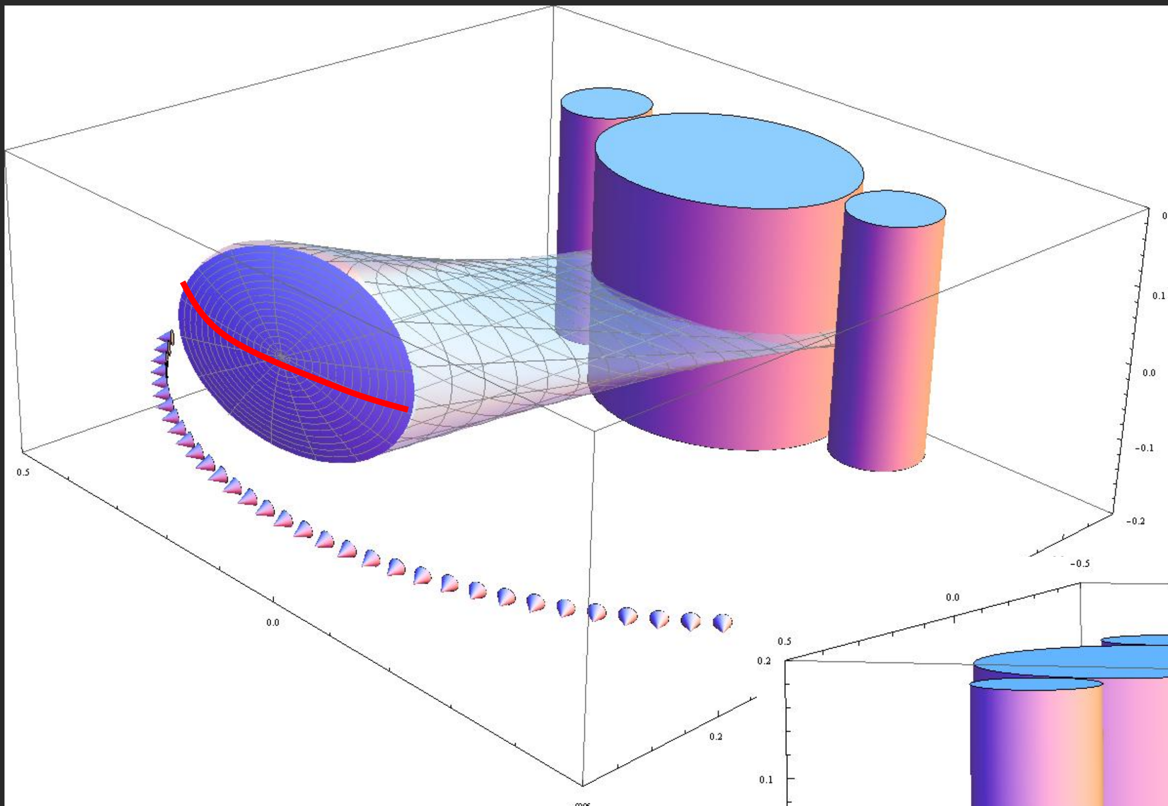
Overview & Technical Approach

- Custom designed elliptical torus reflector allows multiple overlapping beams for focused wide-angle illumination to speed data acquisition and image inclined body surfaces.
- Multiple transmitters provide horizontal resolution and imaging of full 120 deg. of body.
- Multistatic Tx and Rx array sensing avoids dihedral artifacts from body crevices and reduces non-specular drop-outs.

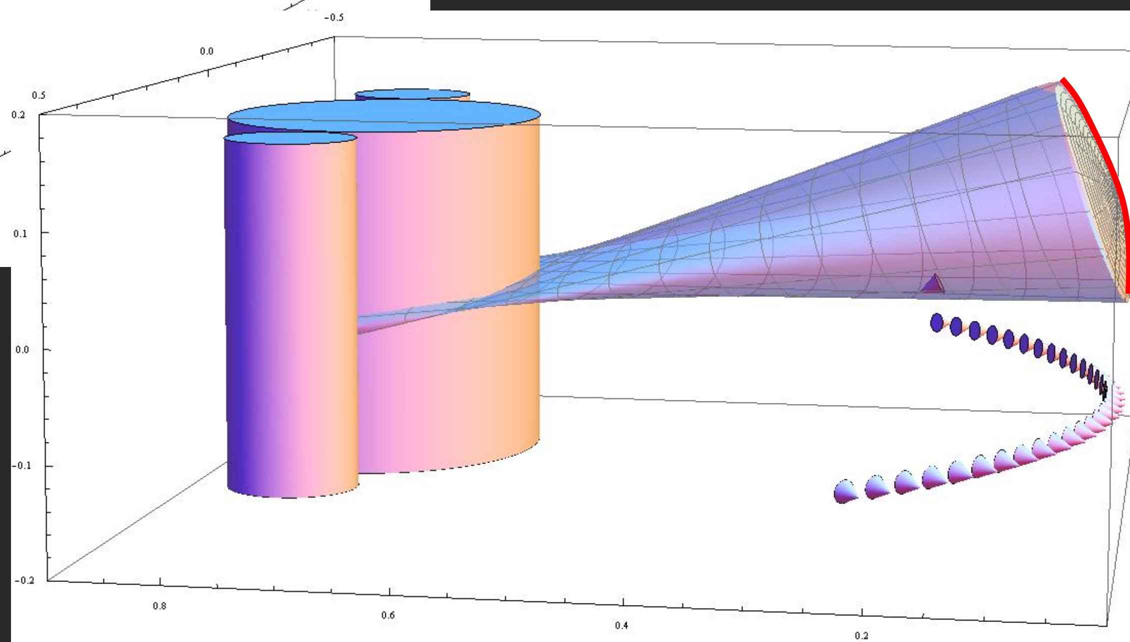
Operational Concept: Stack 2D Slices to Generate 3D Surface – Minimize Hardware, Simplify Calculation



System setup: Specially Designed Elliptical Parabolic Reflector Focuses to a Thin Slice on Body

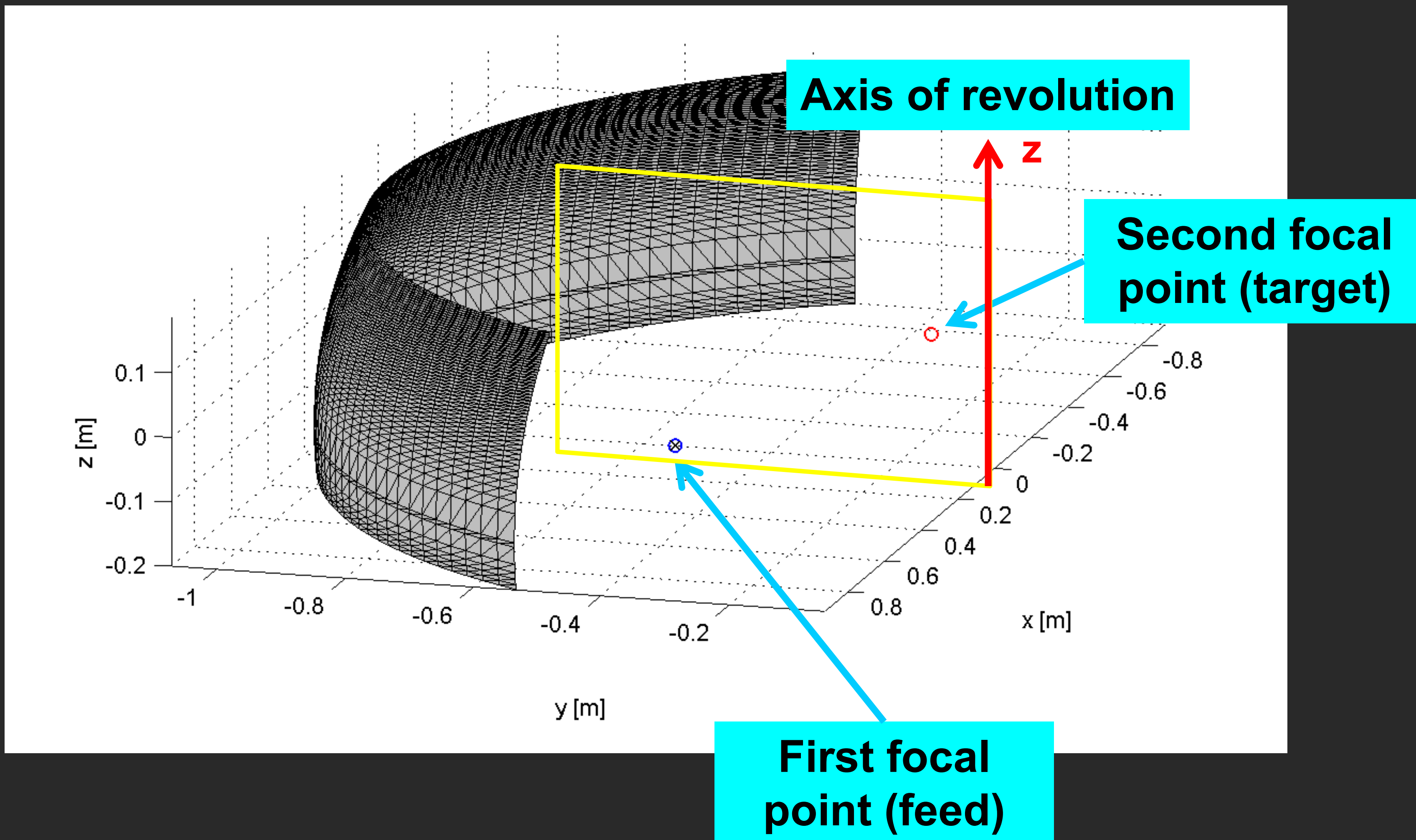


Parabolic in azimuth
- Gives wide beam
- Parallel incident rays

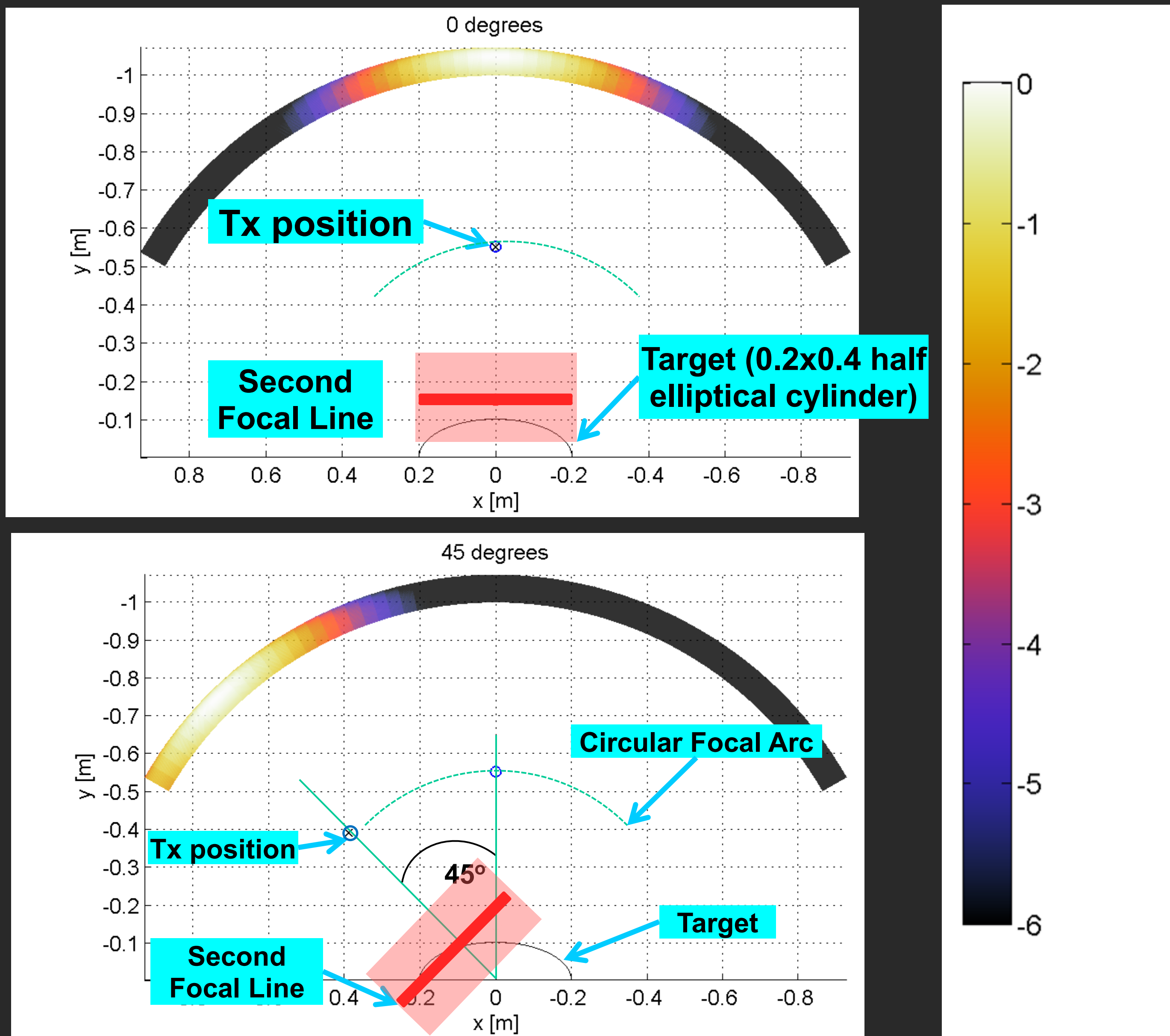


Elliptical in elevation
- Tight "Blade Focus"
- Illuminates narrow slice

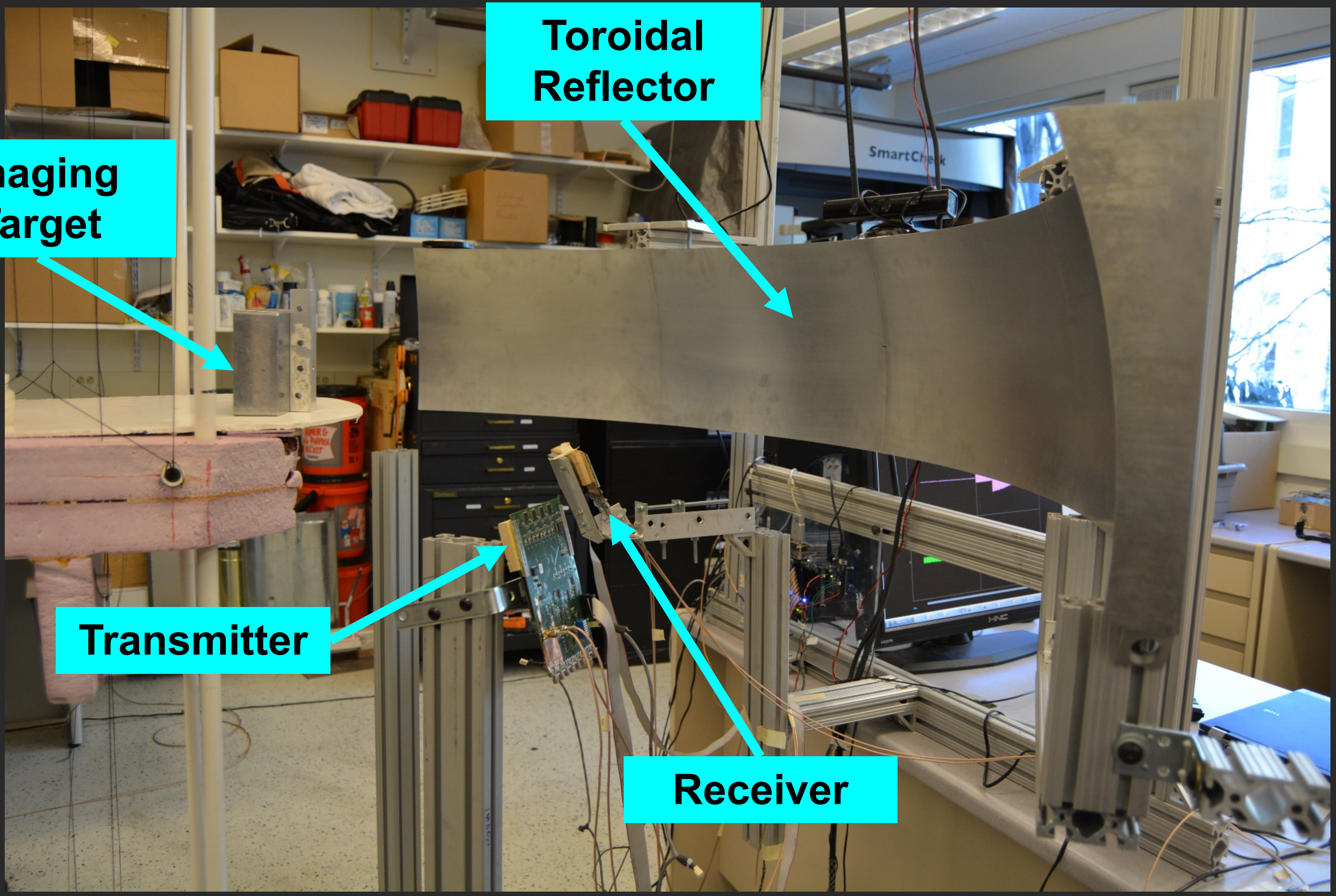
Elliptical Torus Reflector – Surface of Revolution Allows Multiple Scanned Transmitters



Reflector View from Above for Two Feed Positions 0 and 45°

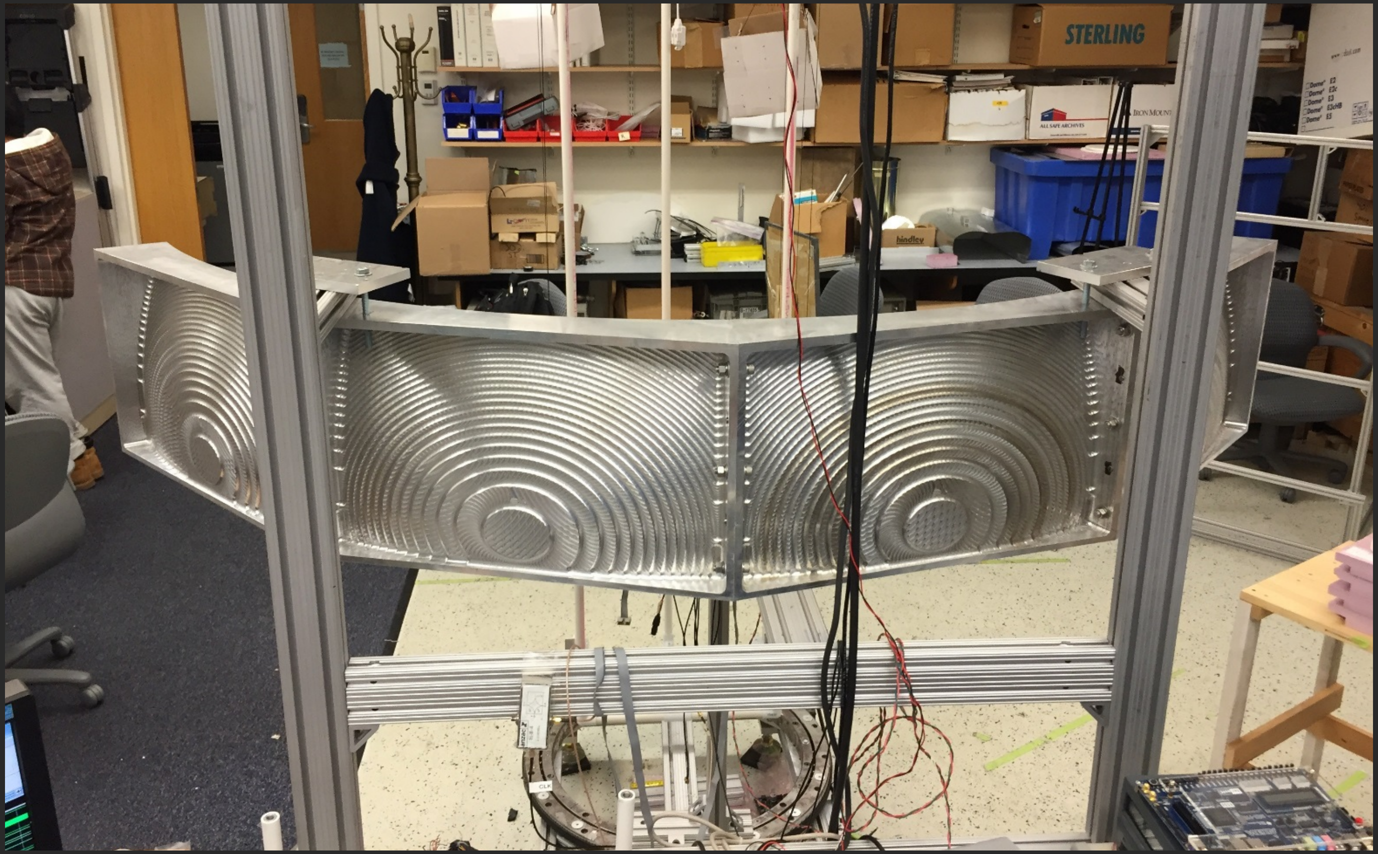


Torus Reflector Configured with Both Transmit and Receive Elements on Focal Arc, Facing Torus



Aluminum Reflector Machined with CNC Milling Machine – 0.0001m Surface Tolerance

- 4 Identical panels
- 8 kg per panel
- Elliptical vertical profile X circular arc horizontal profile



Back view, showing rough cuts for weight reduction

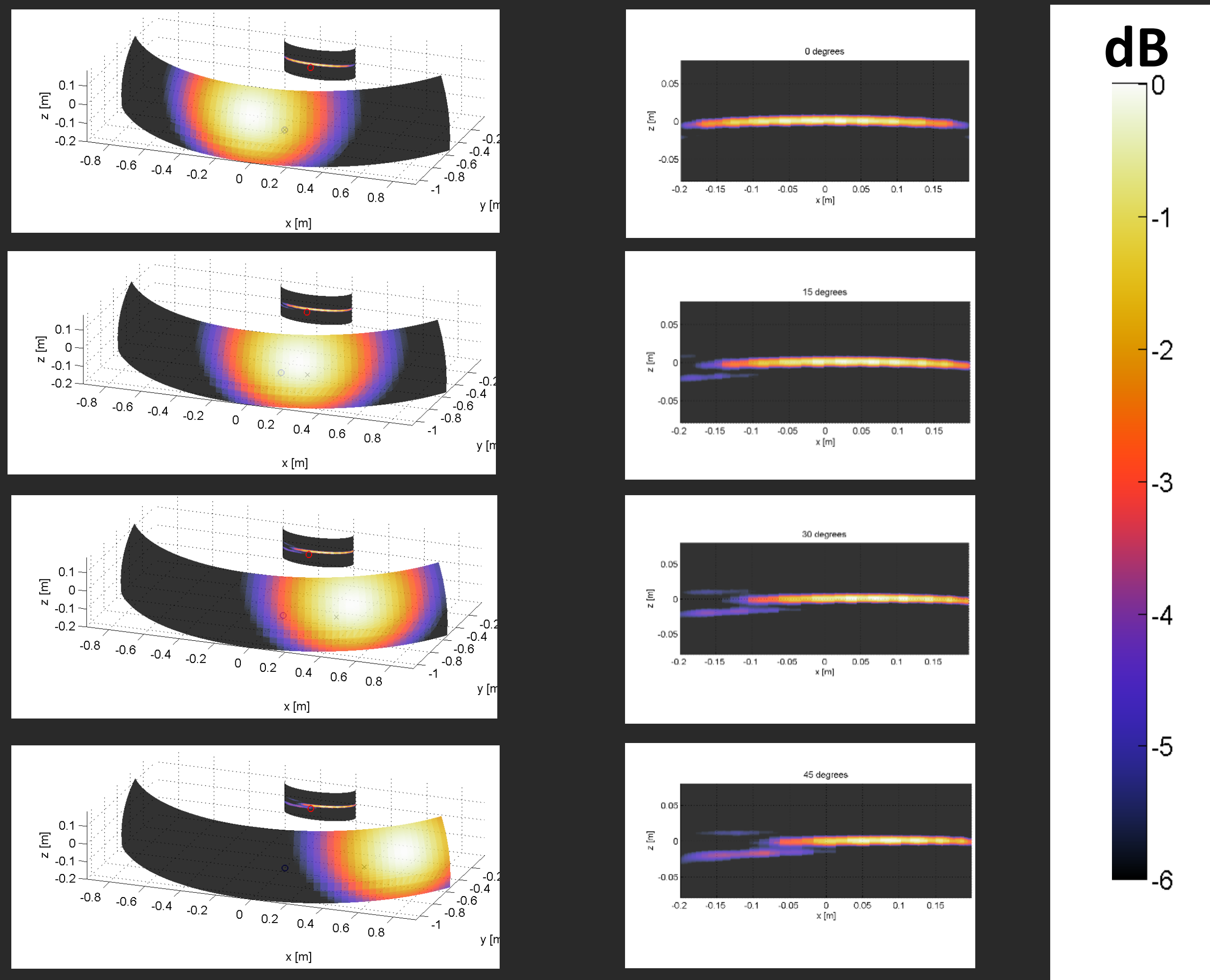
Reflector / Cylinder Target Illumination for Scanned Transmitters --Simulation

0°

15°

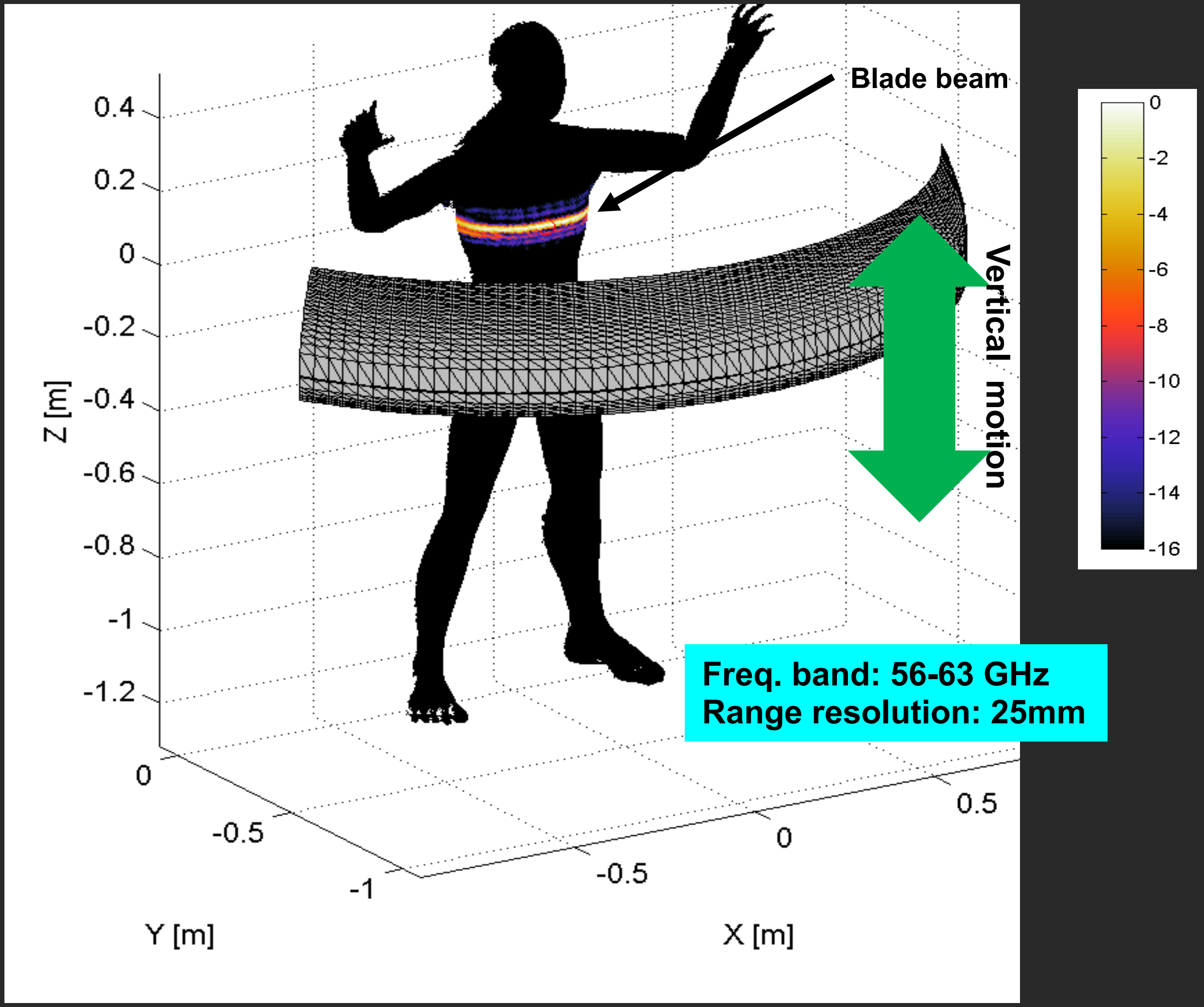
30°

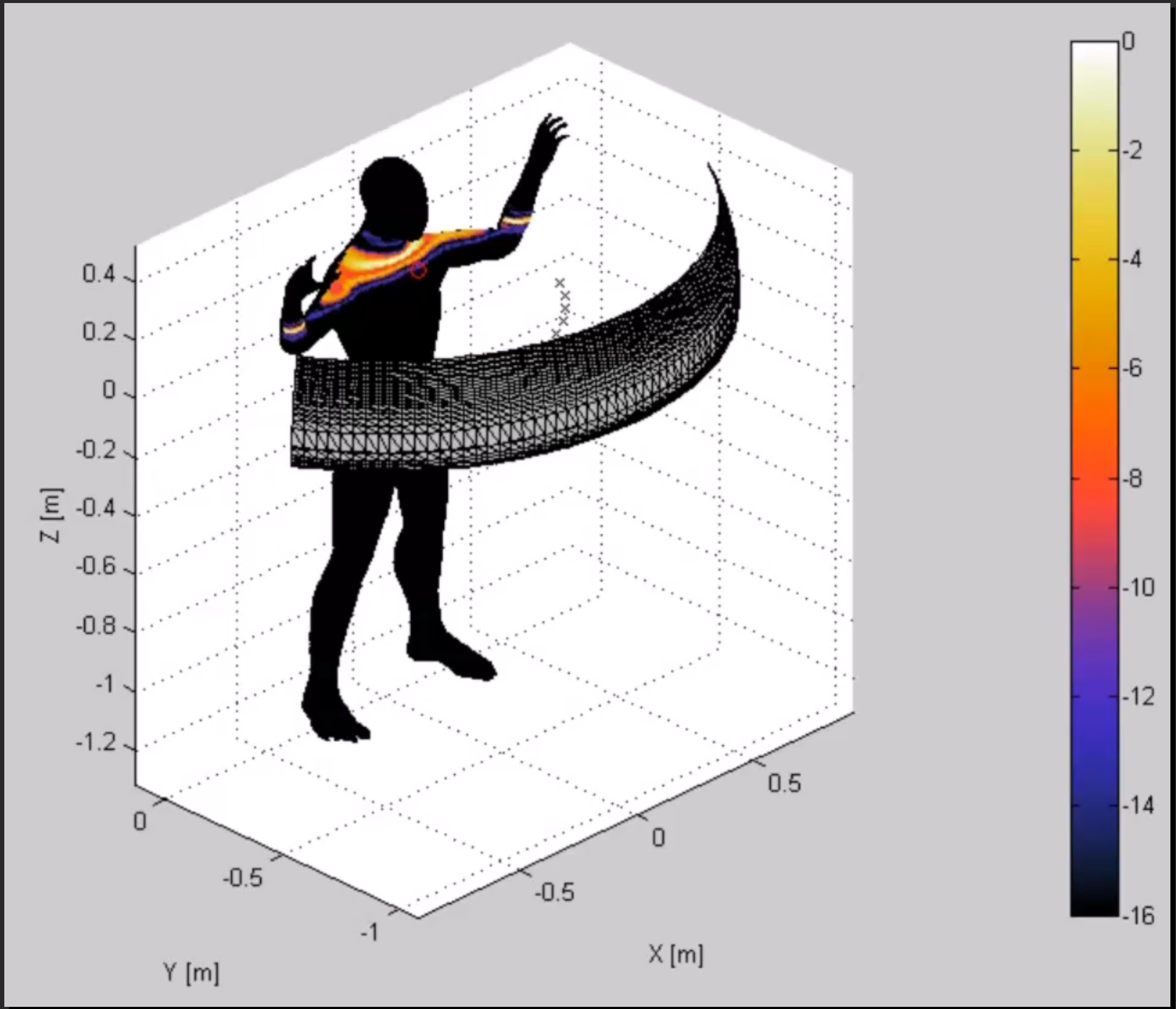
45°



Tx Position | **Reflector Illumination** | **Target Illumination**

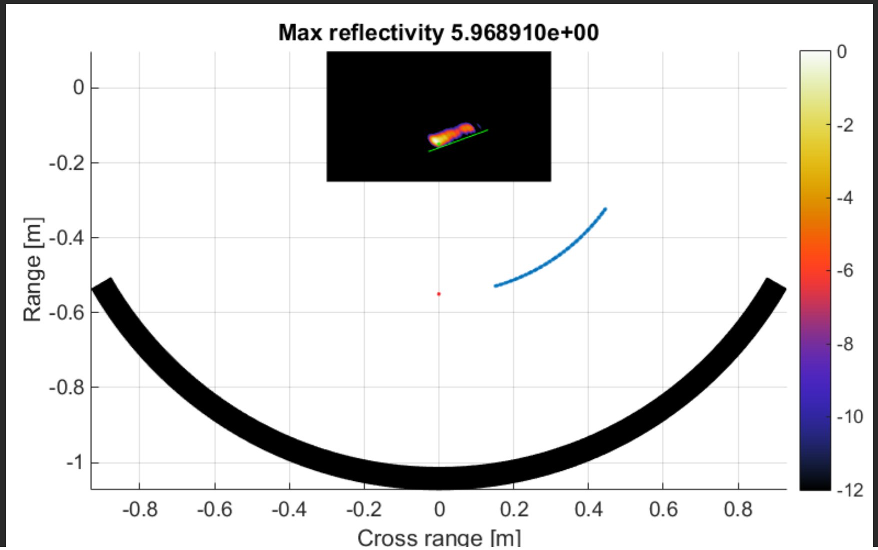
Computed Illumination from Vertically Translating Toroidal Reflector





Z [m]
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Y [m]
0
-0.5
-1
X [m]
-0.5
0
0.5
0
-2
-4
-6
-8
-10
-12
-14
-16

Multistatic Imaging with Torus Reflector – 20 deg. Inclined Metal Box, Half Receiver Arc



Ground Truth in Green

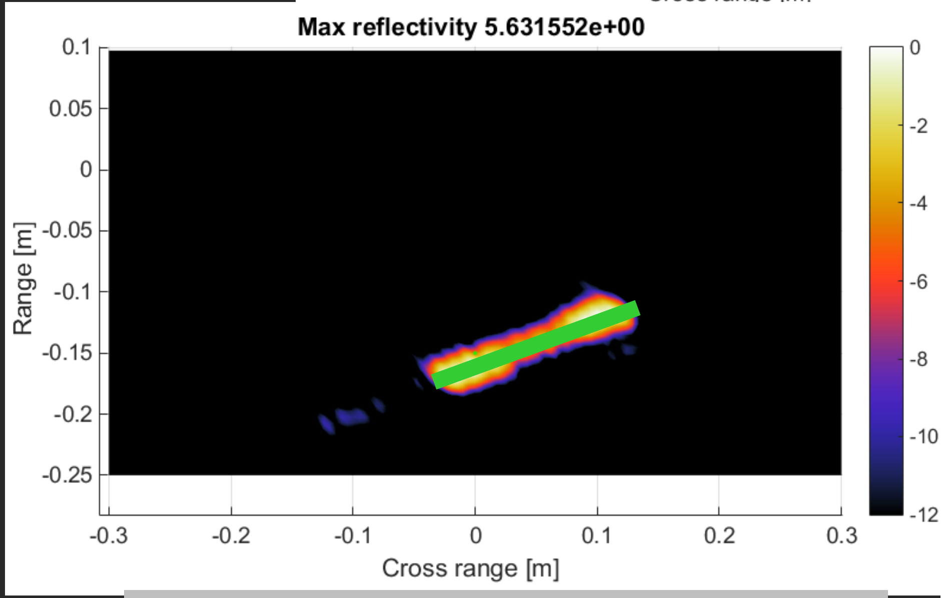


Image from Measured Data

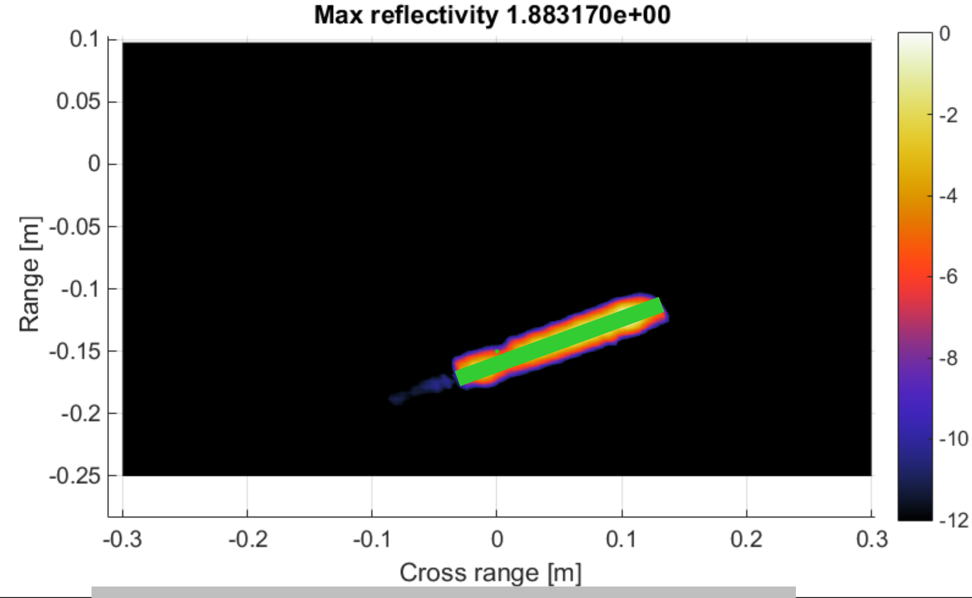
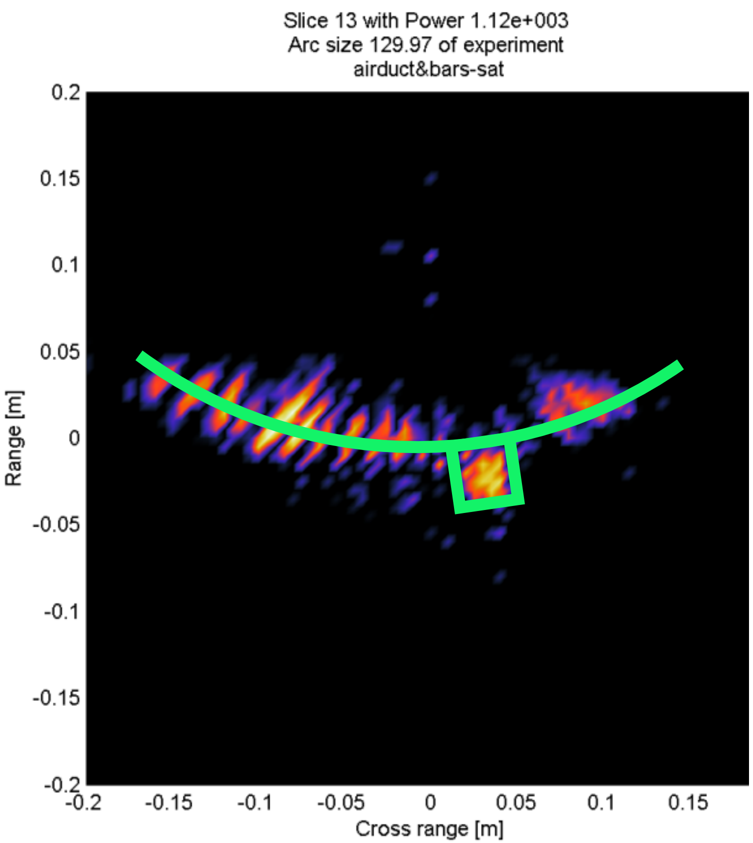


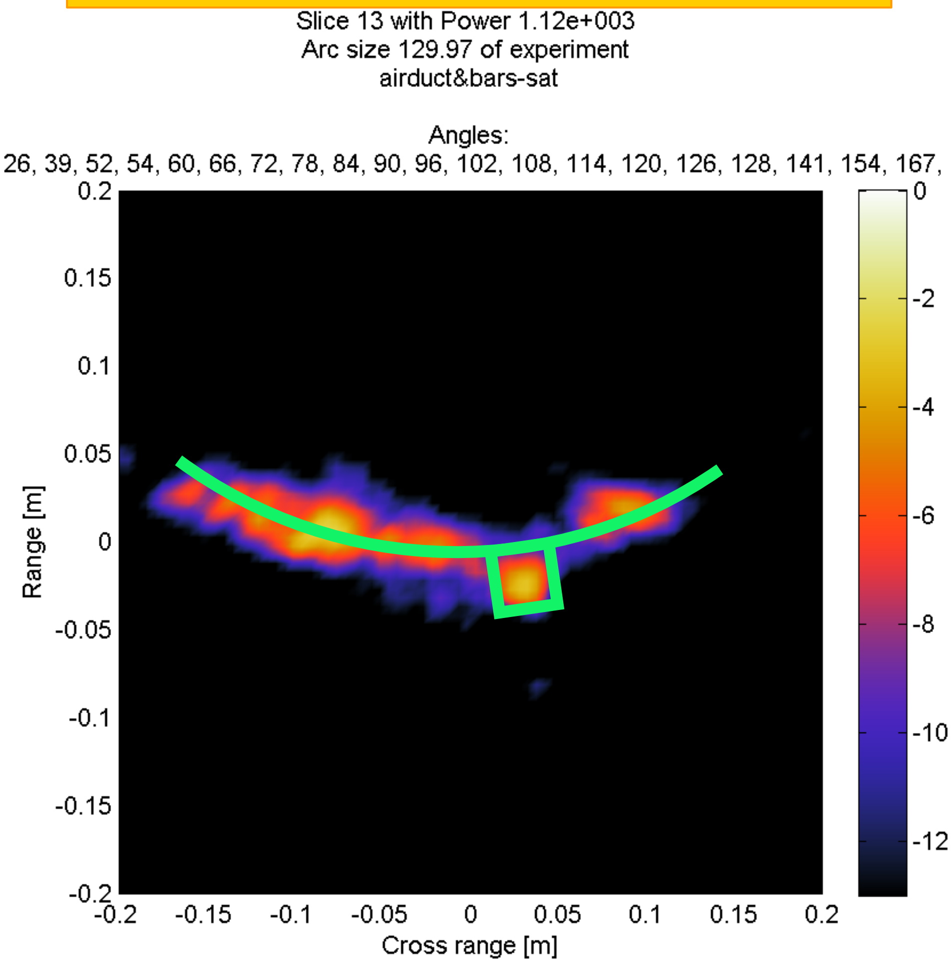
Image from Modeled Data

SAR Reconstruction of Mm-Wave Radar Measurements

Original Reconstruction



Radon / Inv. Radon processing



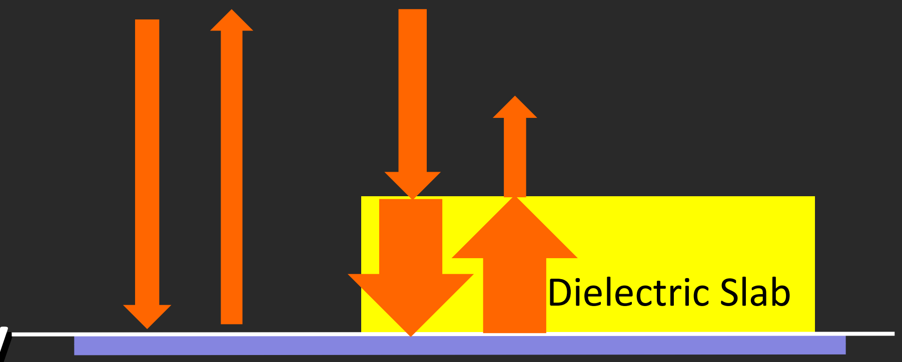
Curved metallic torso surrogate with attached square pipe

Dielectric (Explosive) Slab on Skin Characterization

Waves travel more slowly through dielectric:

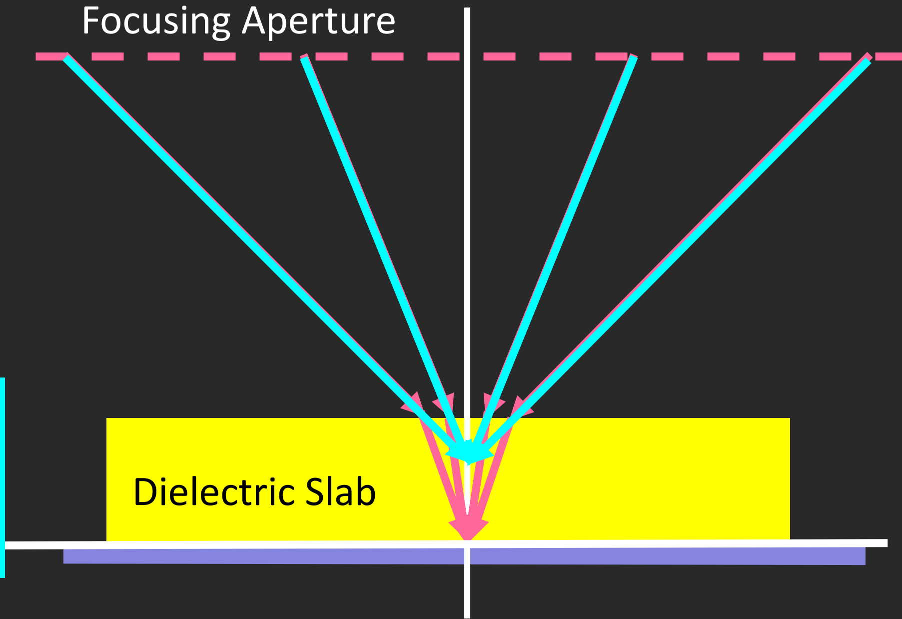
- Slab delays response from back surface (skin reflection), making primary image look farther away (L3 Provision, Rohde & Schwarz)

  Wideband, Time Domain, Impulse



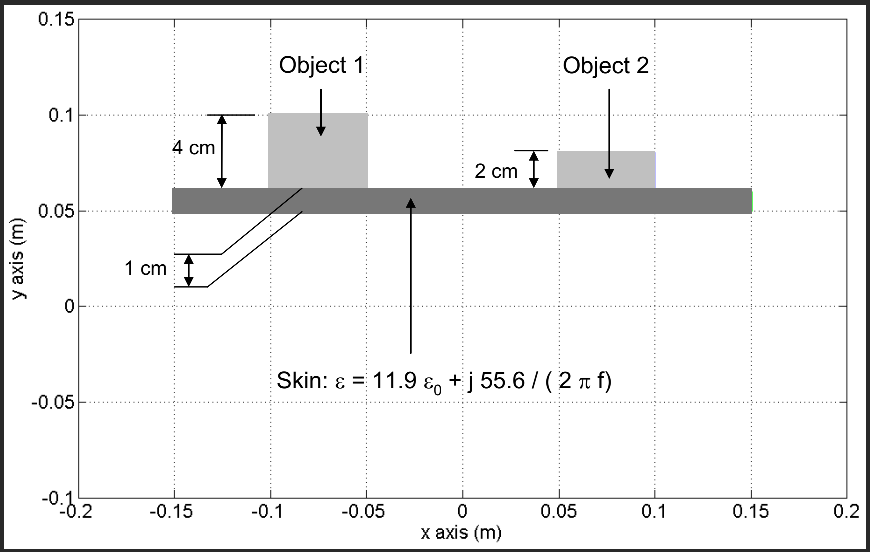
- Slab refracts focused rays, making response appear closer to sensor (Smiths)

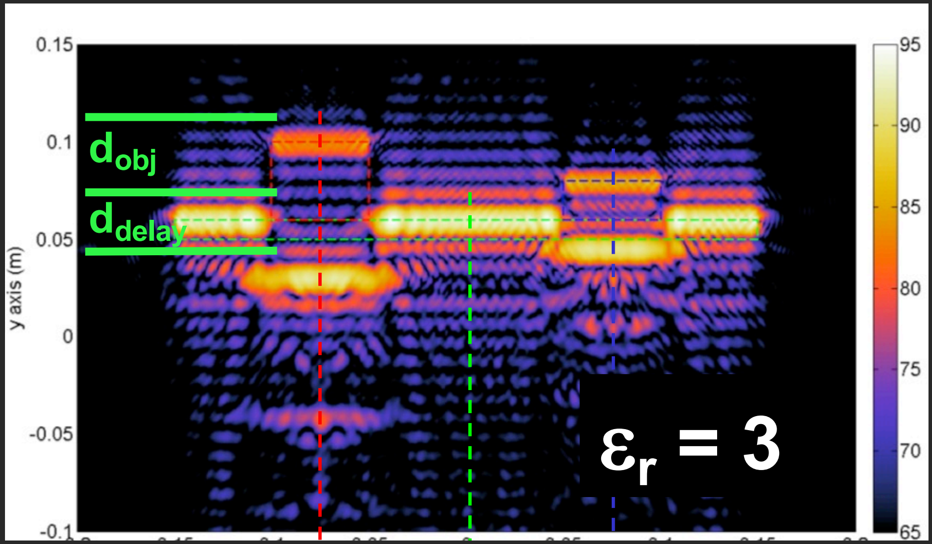
  Frequency Domain -- CW



Determine Thickness and Dielectric Constant

Determining Slab Dielectric Constant with Wideband Imaging, Using Depth (Range) Response





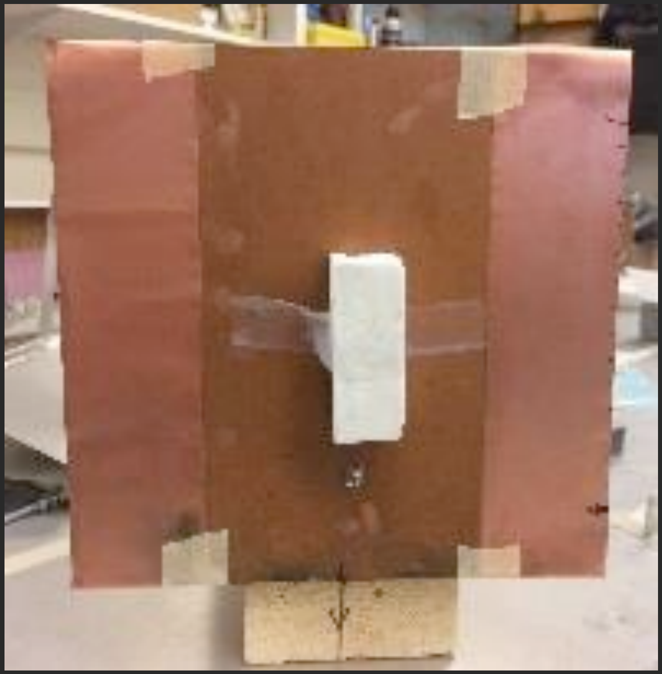
$$\varepsilon_{r\ Est} = \left(1 + \left(\frac{d_{delay}}{d_{obj}}\right)\right)^2$$

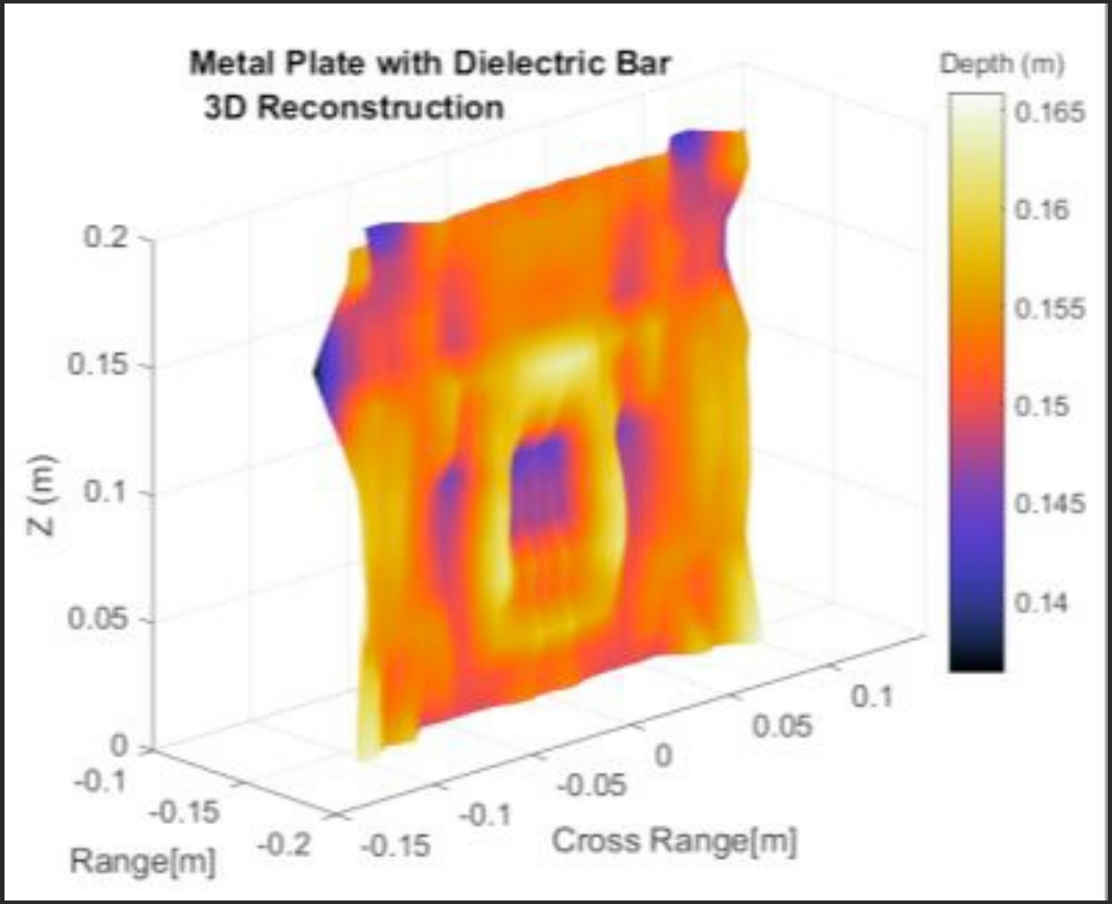
$$\varepsilon_{r\ Est} = (1 + 3/4)^2 = \mathbf{49/16}$$

Álvarez, Y., Gonzalez-Valdes, B., Martínez-Lorenzo, J., Las-Heras, F., & Rappaport, C., "SAR Imaging-Based Techniques for Low Permittivity Lossless Dielectric Bodies Characterization," *IEEE Ant. Prop. Mag*., 4/2015, pp. 267 - 276.

US Patent 9,575,045, 2/15/2017, Rappaport and Martinez, "Signal Processing Methods and Systems for Explosive Detection and Identification Using Electromagnetic Radiation"

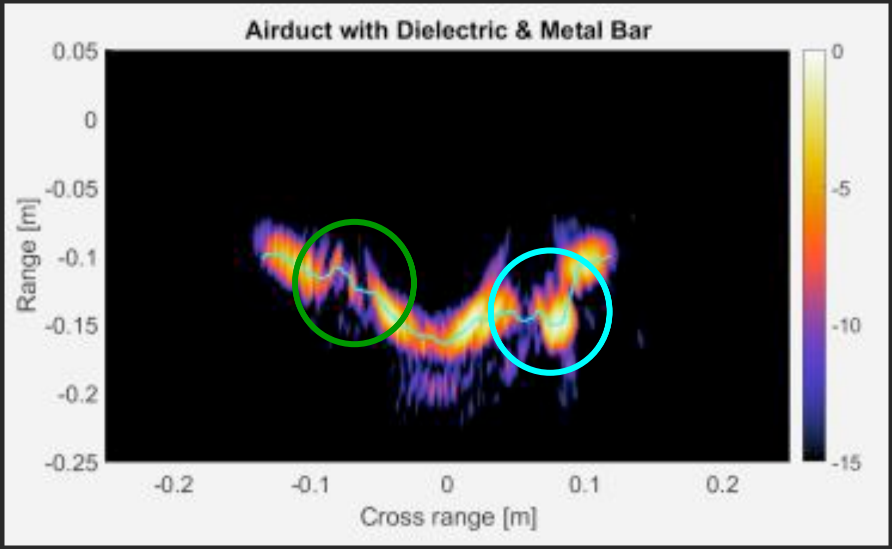
Metal Plate Skin Simulant with Small Affixed Explosive Simulant Bar

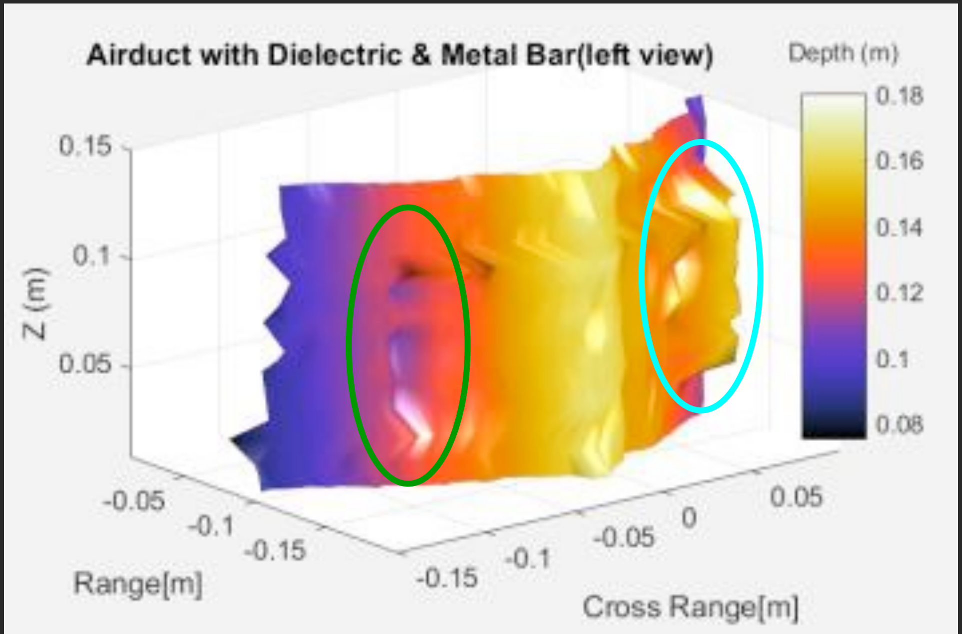


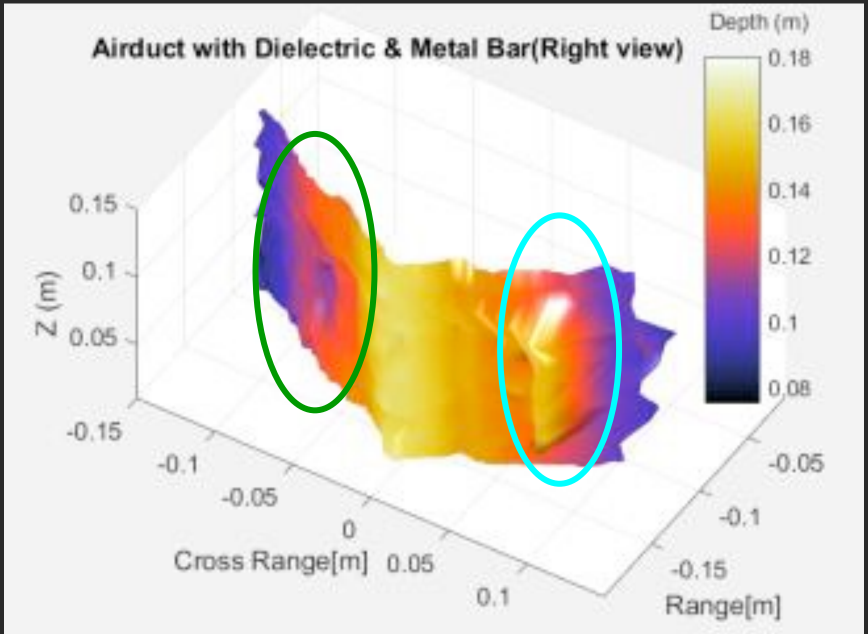


Penetrable affixed dielectric images as a depression

Metal Torso Simulant with Small Affixed Metal and Explosive Simulant Bars

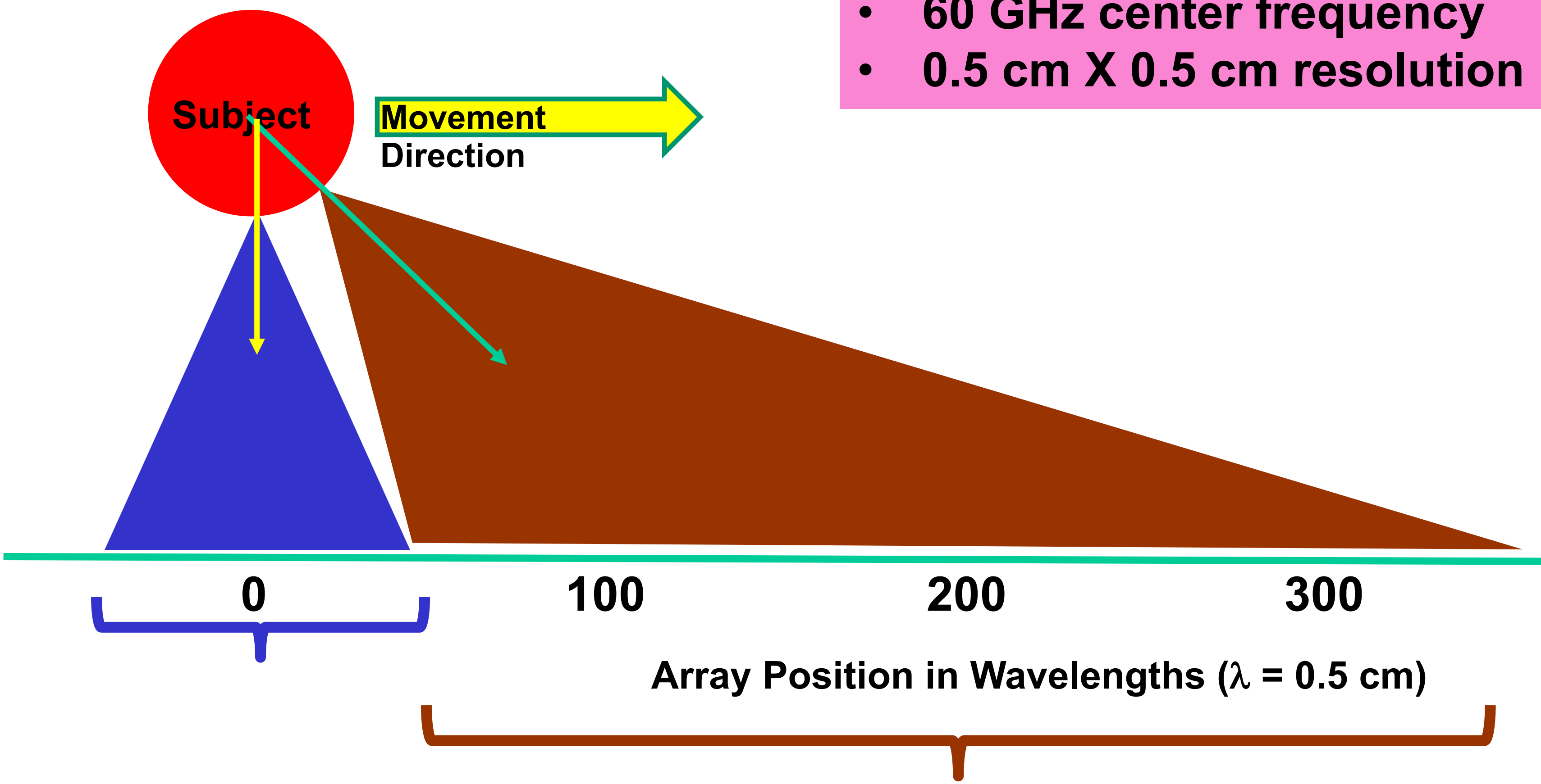




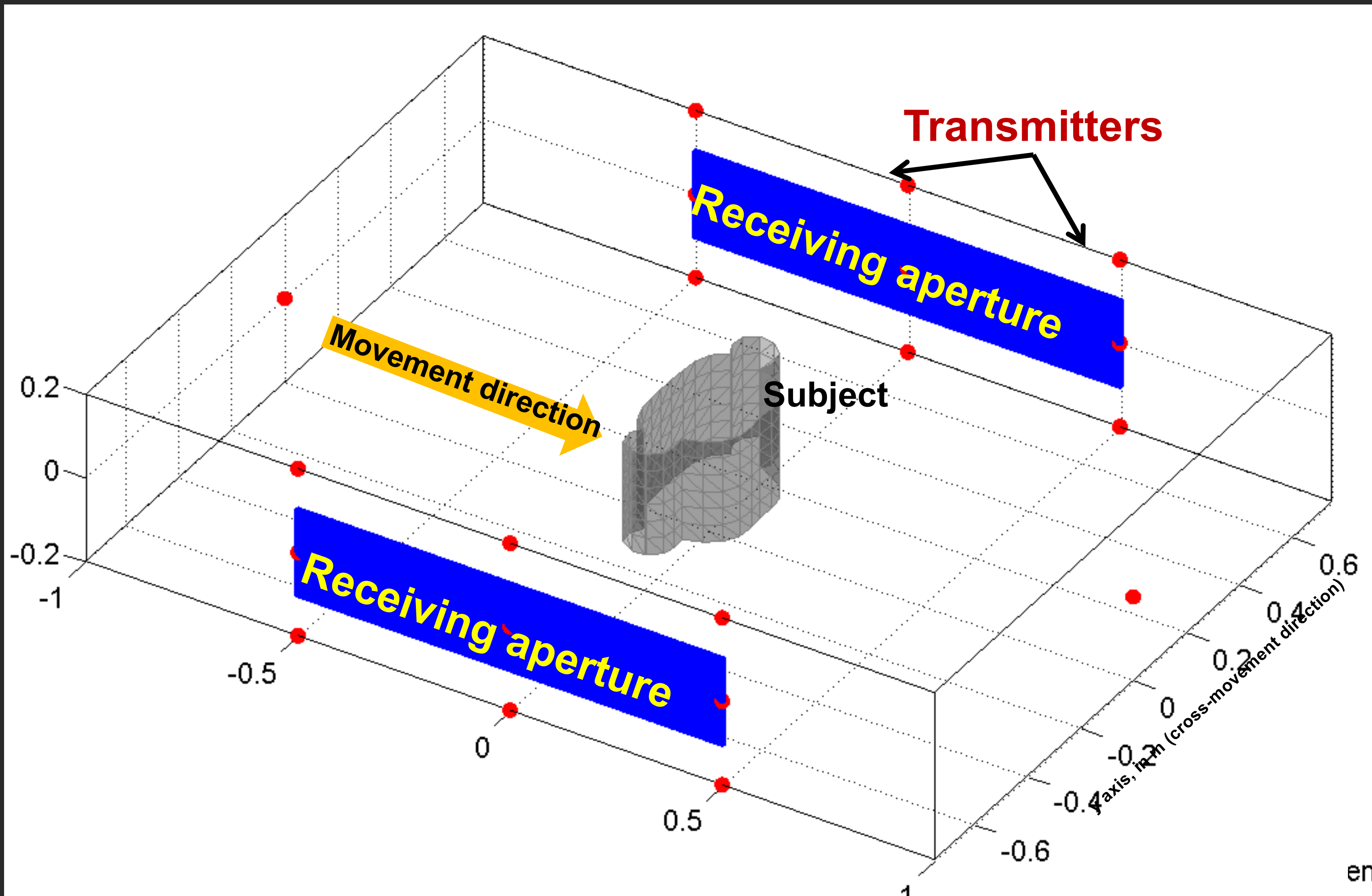


Hallway Detector Paradox: Single Planar Array Requires Unrealistically Wide Aperture for Reasonable Resolution

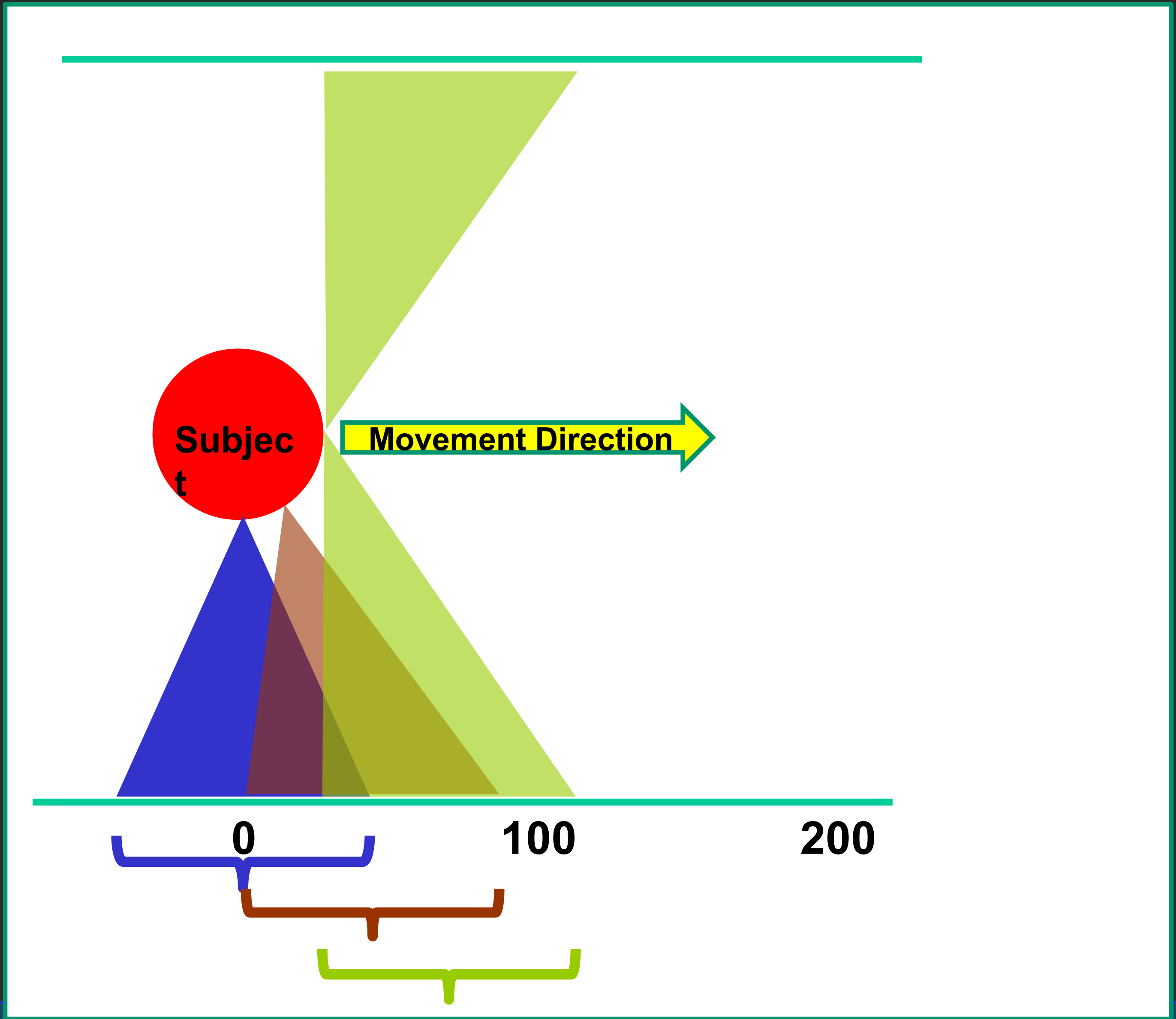
- 30 GHz bandwidth,
- 60 GHz center frequency
- 0.5 cm X 0.5 cm resolution



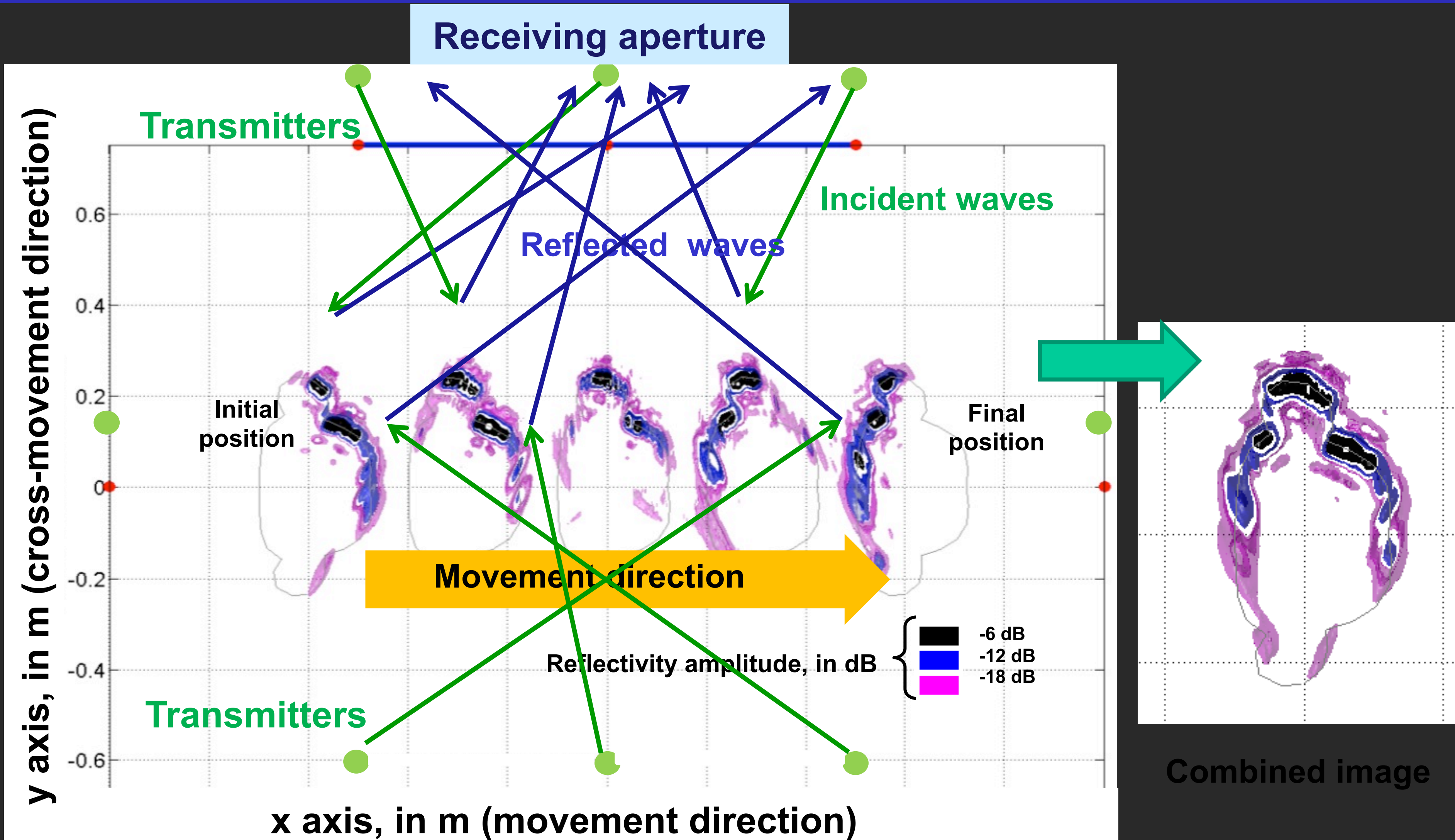
Hallway, "On-the-Move" Person Scanning Concept – Imaging Subject's Front and Back



Hallway Detector Solution: Dual Planar Arrays (or Apertures) Capture Non-Specular Scattering with Reasonable Resolution



Hallway Wideband Radar – Left Side Receiving Aperture Only



Provisional Application No. 61/912,630, "On the Move Millimeter Wave Interrogation System with a Hallway of Multiple Transmitters and Receivers," Gonzalez, Rappaport, and Martinez.

Conclusions

- Extension of Blade Beam Reflector into Elliptical Torus for multiple overlapping high quality beams
- Illumination and receiver focusing on narrow slice for fast computation
- Fabrication, testing, optimization of wideband 60GHz multistatic radar
- Novel reflector antenna, stacked 2D reconstruction, and fast inversion for real time processing
- Minimal artifacts from dihedrals, full depth information and advanced visualization

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