ALERT: Awareness and Localization of Explosives-Related Threats

Fusing Millimeter-Wave Technologies for Advanced Imaging Technology

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Conclusions

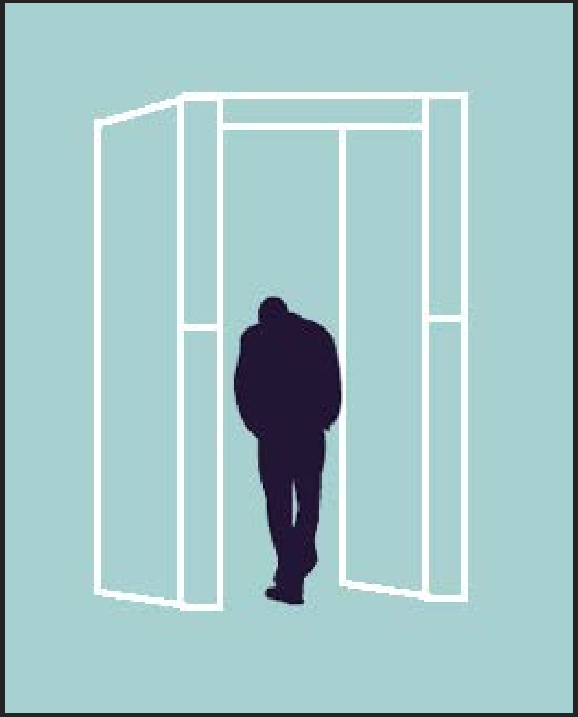
- Established detection regime and parameters
- Described why fusion necessary
- Showed potential challenges and considerations with fusion with mm-waves
- Described the ALERT AIT Testbed (ScanBED)
- Explained how advanced simulation and modeling saves lots of time and money
- Presented a specific example of the potential of fusing x-ray backscatter with mm-wave sensing
- Described the plans for ScanBED multi-modal fusion

Outline

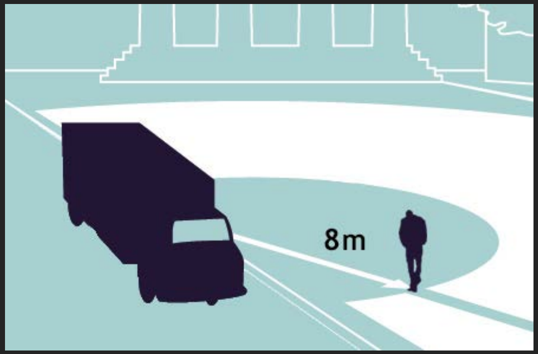
- What detection regime is examined?
- Why is fusion necessary?
- Why is fusion problematic?
- What must be considered for fusing with mm-waves?
- What is the ALERT AIT Testbed (ScanBED)?
- How can advanced simulation and modeling save lots of money?
- What is the specific potential of fusing x-ray backscatter with mm-wave?
- What are our plans for ScanBED multi-modal fusion?

Advanced Imaging Technology Problem Space

- Intimately near targets (< 3 m)
  - Portal sensors
  - Non-invasive examination
  - Fast sensing, real time processing
  - 99.997% detection probability
  - *Manageable* false alarm rate
  - Safe
  - Publicly acceptable



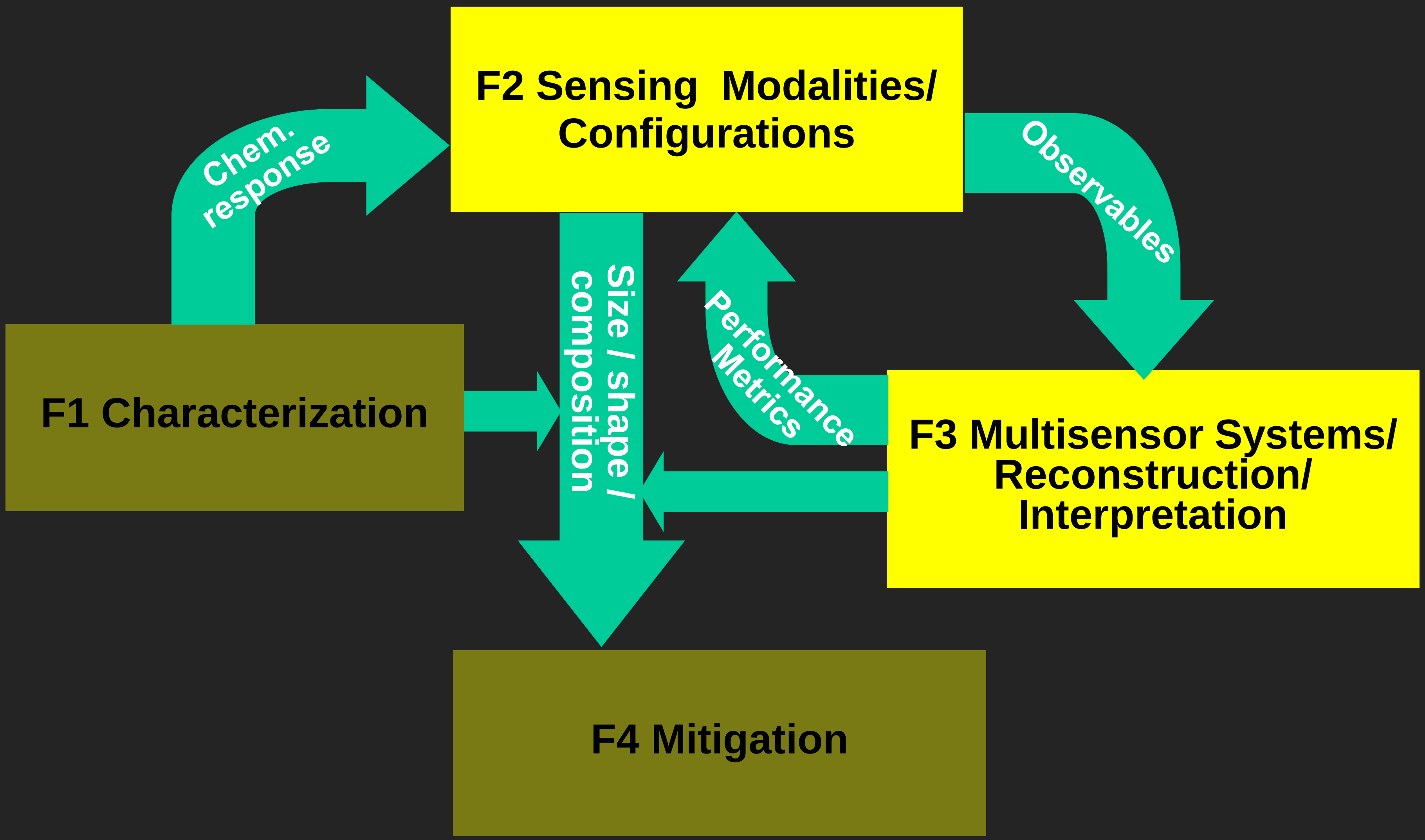
[Mm- wave sensing can also be fused with X-ray, THZ, video, trace for Mid-range targets (3 to 10m)]



Detecting and Identifying Explosives

- Sense within hidden / concealed / shielded / non-stationary environments
- Optical imaging to detect suspicious shapes/size (video, patterned video)
- Wave-based imaging to detect suspicious shapes/size (mm-wave radar, X-ray, THz, acoustics)
- Chemical trace detection of suspicious materials (Mass Spec., Ion Mobility Spec., Gas Chrom., "Artificial Dog Nose")
- Material ID spectral response to characterize molecular structure (Hyperspectral, IR, UV, THz, NQR, LIBS , NMR)

Sensing Thrust couples with Systems Thrust in ALERT Center



Coordination both across discipline and among thrusts is essential

Fusion is Necessary

No non-invasive sensor is capable of unequivocal identification of all concealed threats in reasonable time

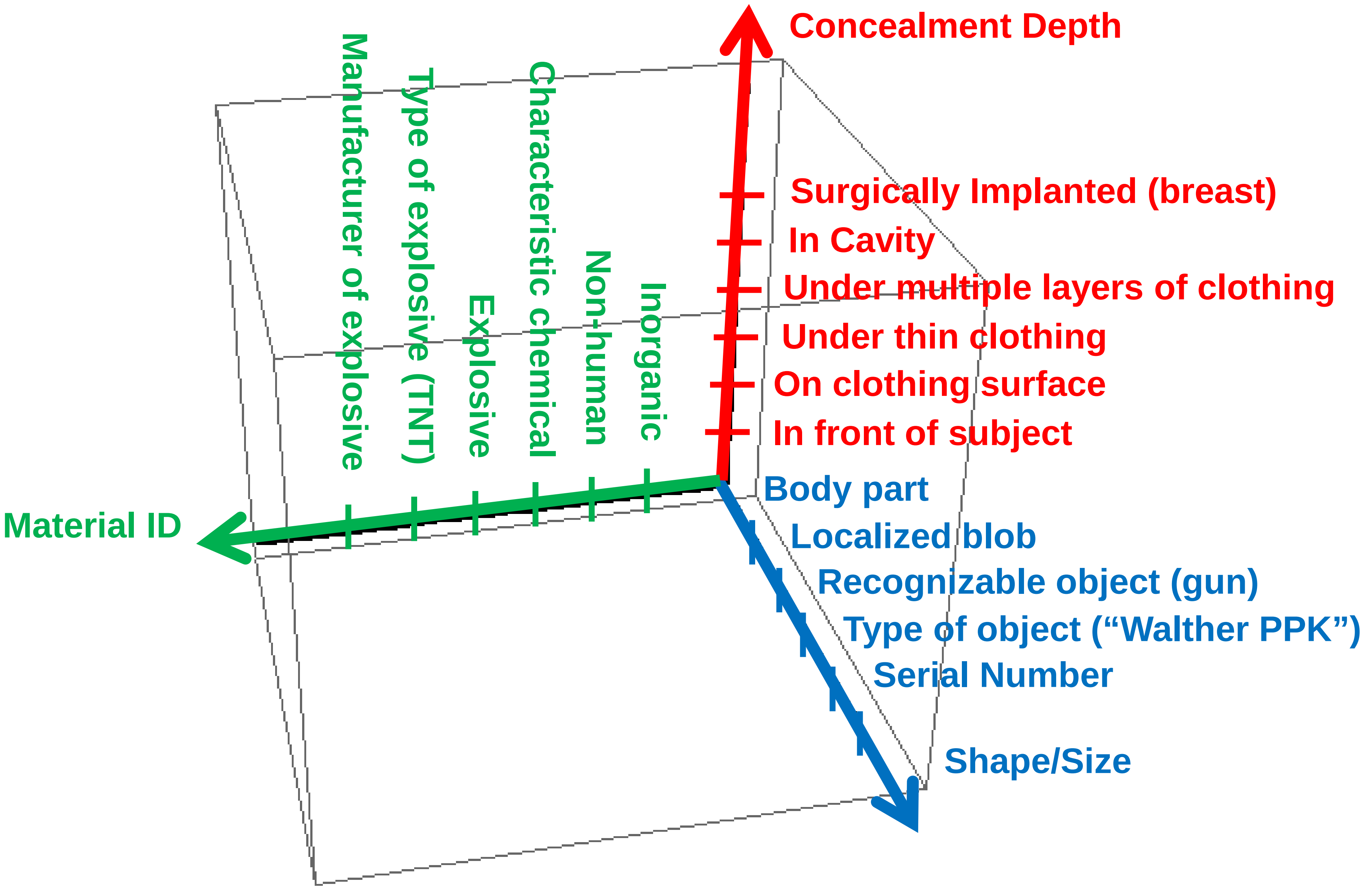
- Shape-based detection cannot determine composition: false alarms for canonical or non-specific shapes
- Chemical sensors cannot penetrate concealing layers: thick covering hides threat
- Material composition sensors are non-local or must be repeated: slow
- Various modalities are dangerous (not eye-safe), ionizing (x-ray)
- Sensors that are effective in the lab fail in the field

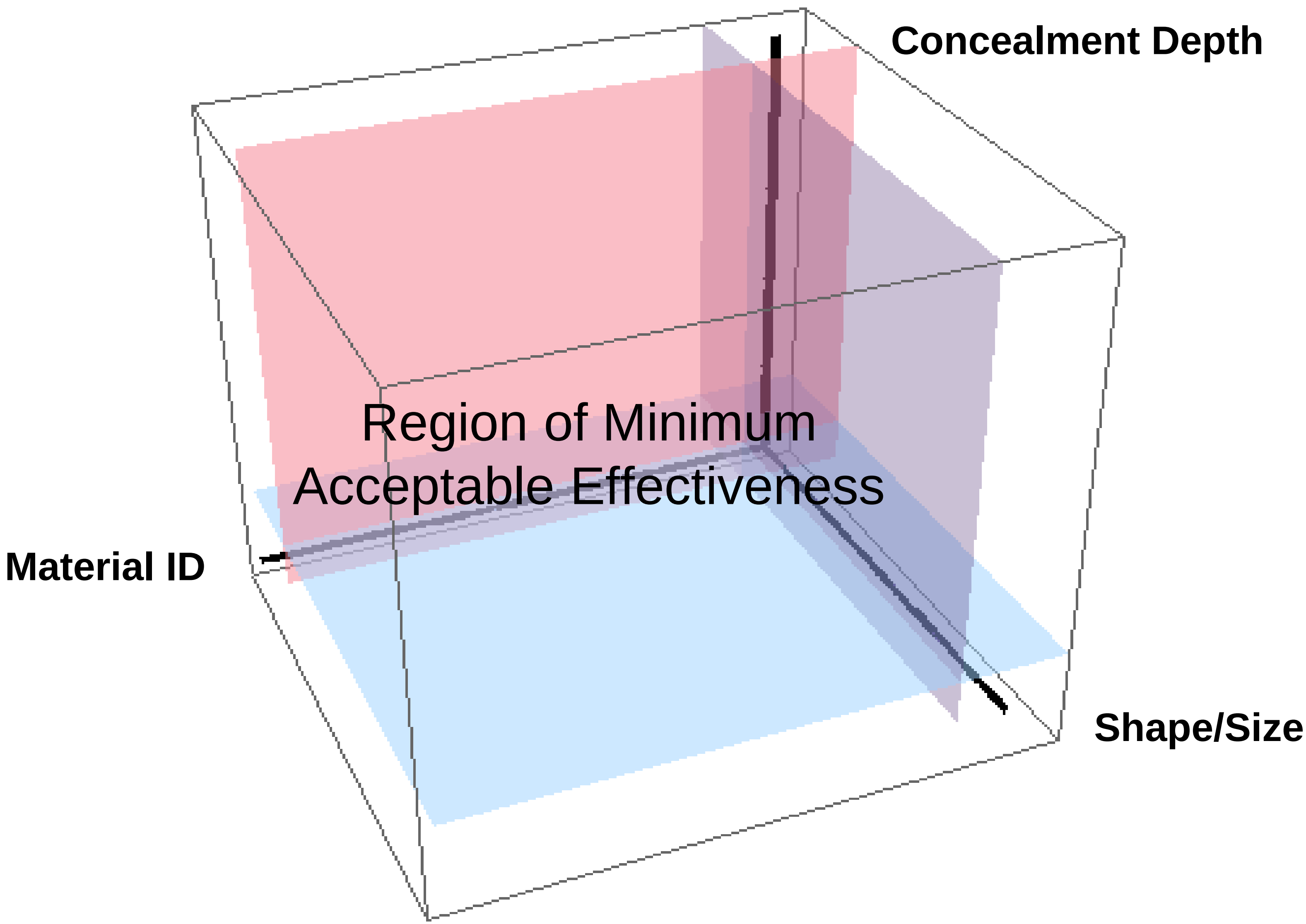
Fusion is Problematic

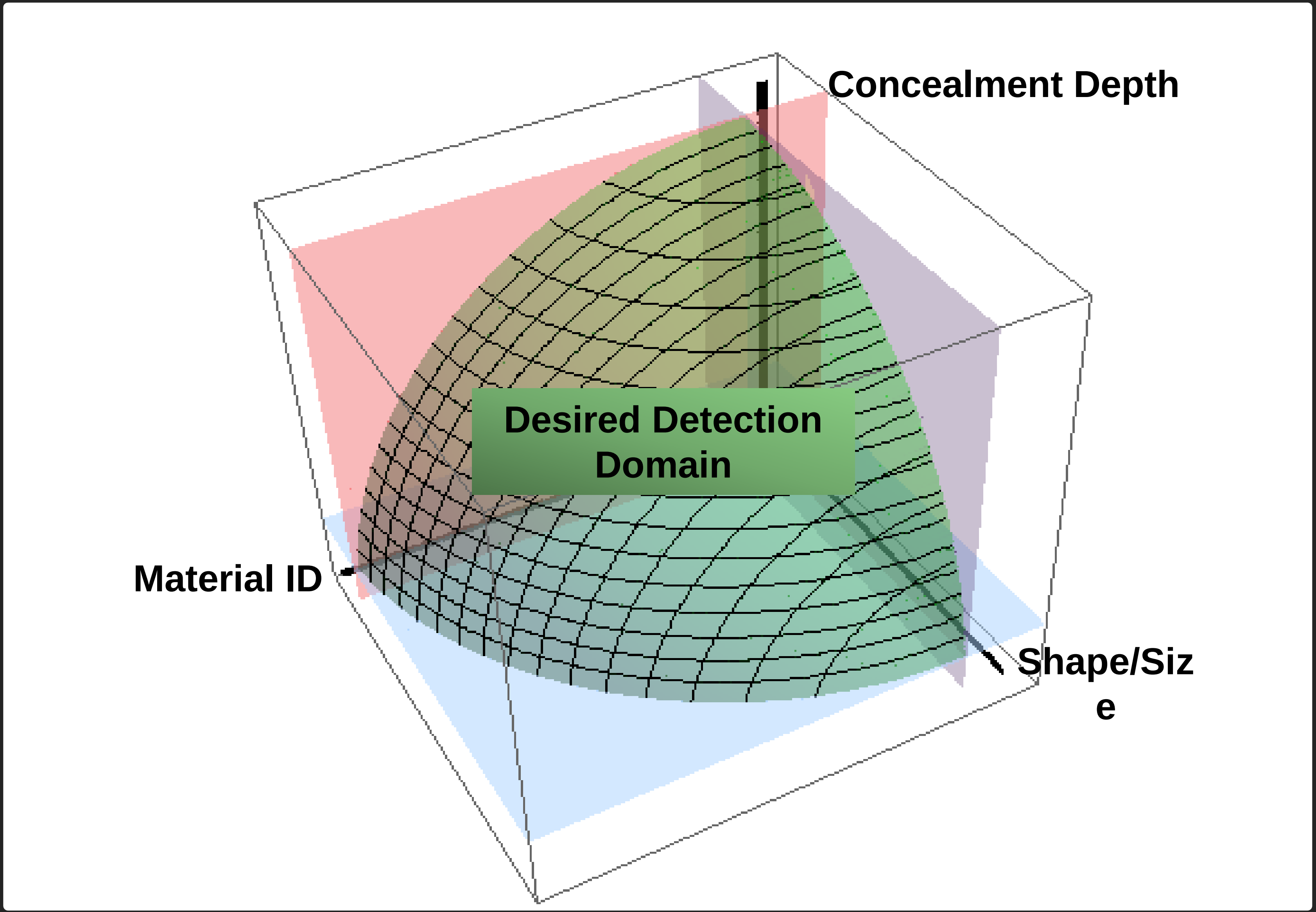
- More sensors do not guarantee more *useful* information
  - If second sensor is too similar: no addition information
  - If second sensor is too noisy: can obscure information
  - If second sensor is contradictory: hard to decide (3 clocks)
- Orthogonality of sensor information is worthwhile, but only if added information is useful for detection
  - Form factor is challenging
  - One physically sensor blocks others
  - Sensors interfere
- Additional sensors increases cost
  - Must justify higher cost for marginal additional information
  - Is a higher performance single sensor better than multiple fused sensors?

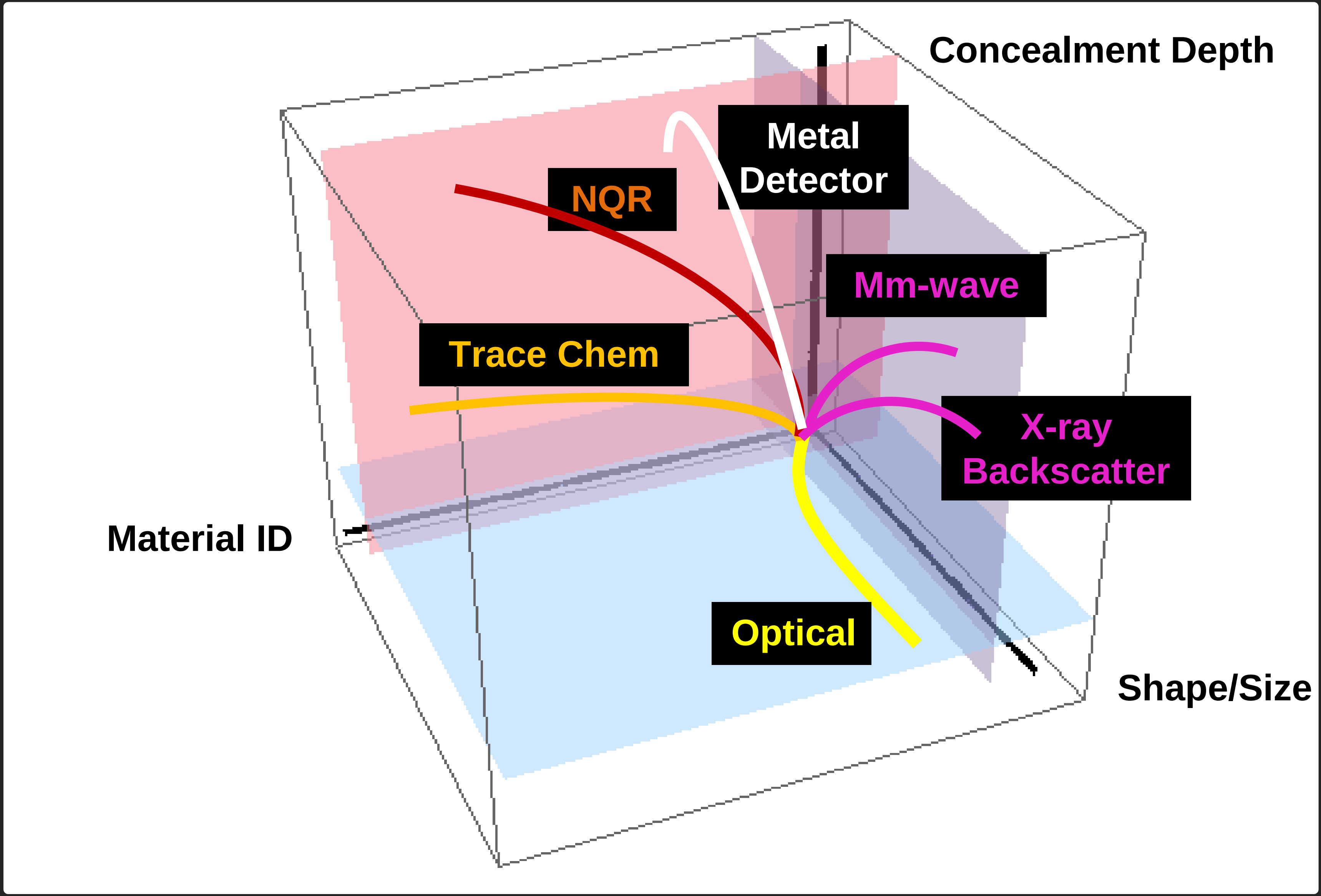
AIT Sensing Table (from White)

Sensor	Wavelength/energy	Signature	Detection Type
Metal Detectors	kHz	Eddy current induced in metals	Material ID
Active mm-wave	20-40GHz (15-7.5mm)	Dielectric scattering contrast	Shape/size
Passive mm-wave	30-300GHz (10-1mm)	Natural blackbody radiation	Shape/size
X-ray backscatter	50-125kVp	Differential scattering (Z_{eff}, ρ)	Shape/size
X-ray transmission	80-160kVp	Differential attenuation (Z_{eff}, ρ)	Shape/size
IR thermography	8-10μm	Thermal emission from body	Shape/size
IR spectroscopy	8-13μm	RF molecular vibration absorption	Material ID
Trace portal/puffer		IMS (or MS) spectral match	Material ID
THz imaging	0.1-3THz (3-0.01mm)	Attenuation /scattering from dielectrics	Shape/size
THz spectroscopy	0.1-3THz (3-0.01mm)	RF molecular vibration absorption	Material ID
NQR	0.5-5MHz	RF resonance (molecular/N environ.)	Material ID
NMR	kHz	Characteristic RF decay from ^1H	Material ID


Concealment Depth
Surgically Implanted (breast)
In Cavity
Under multiple layers of clothing
Under thin clothing
On clothing surface
In front of subject
Material ID
Manufacturer of explosive
Type of explosive (TNT)
Explosive
Characteristic chemical
Non-human
Inorganic
Body part
Localized blob
Recognizable object (gun)
Type of object (“Walther PPK”)
Serial Number
Shape/Size


Concealment Depth
Region of Minimum
Acceptable Effectiveness
Material ID
Shape/Size


Concealment Depth
Desired Detection Domain
Material ID
Shape/Size


Concealment Depth
Metal Detector
NQR
Mm-wave
Trace Chem
X-ray Backscatter
Material ID
Optical
Shape/Size

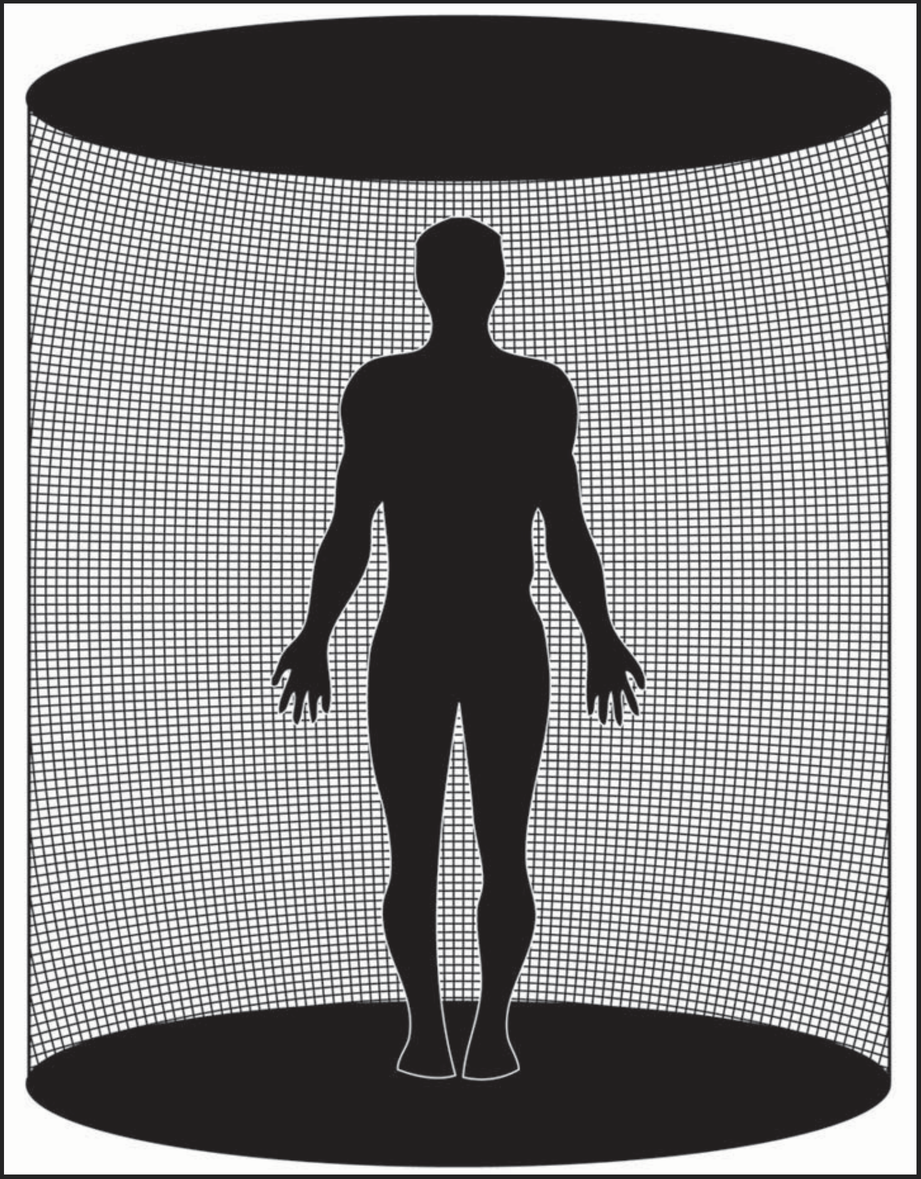
Considerations for Fusing Technologies with Mm-Wave Sensing

- Compensate for deficiencies of mm-wave sensing
  - Low resolution
  - No skin penetration
  - No material identification
  - Heavy computation
- Establish minimum desired sensing requirement
- Consider completely orthogonal sensor
  - No joint inversion – simple union of sensor info
- Consider front-end fusion – joint inversion
  - Initial guess
  - Regions of particular interest

Whole Body Imaging Testbed at NEU

- Precision portal multi-axis sensor array positioning system
  - Designed to accommodate various types of sensors
    - Separately, for analysis
    - Together, to test fused sensor information
    - Built to be flexible for reconfiguration
- Provide access to raw measurement data
  - Allows specific, modality-based inversion
  - Allows joint modality reconstruction
- Ultimate Goals
  - Establish performance metrics for sensor modalities
  - Develop and evaluate novel inversion and multi-modal threat detection algorithms

Portal Provides the Possibility for Full Aperture Sensing



Huge 360 deg. Aperture

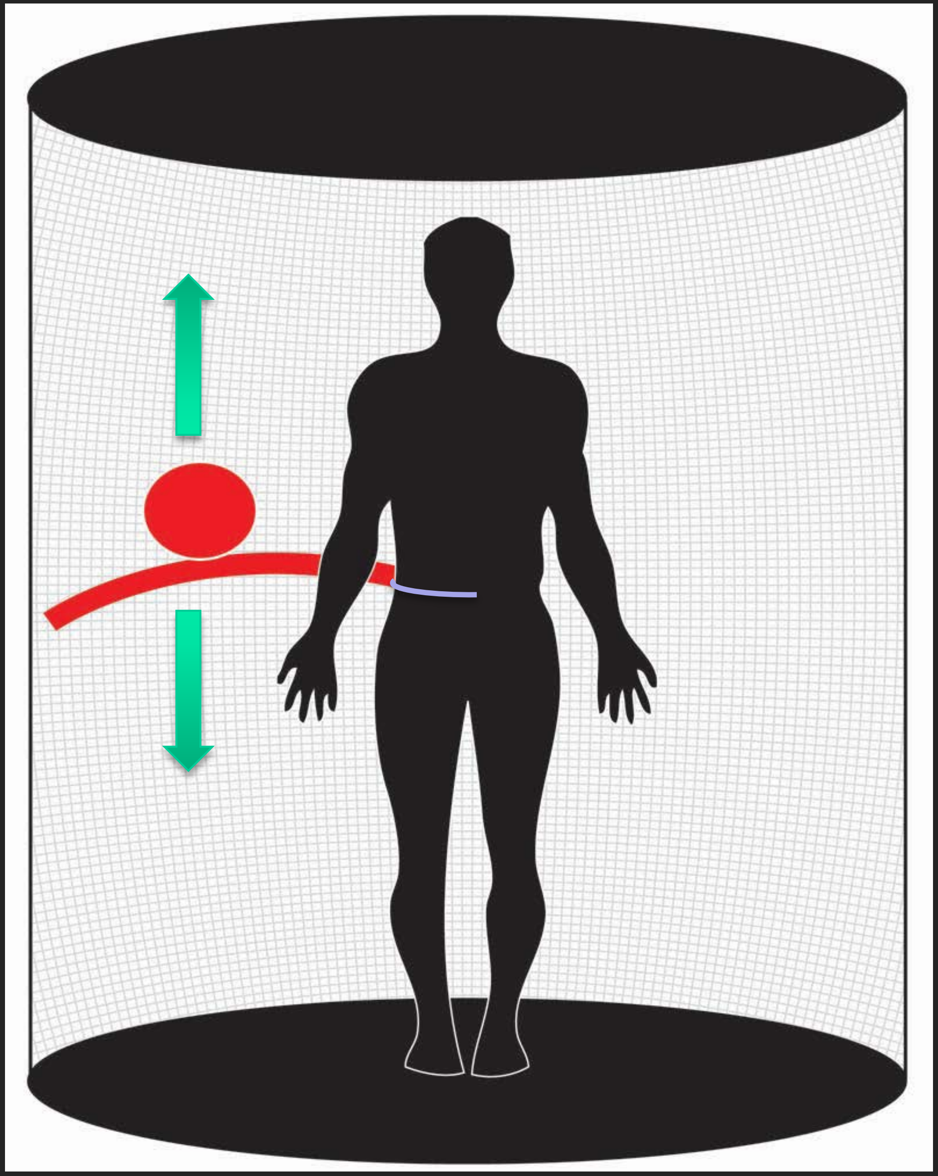
- **Almost perfect body surface reconstruction**
- **No motion artifacts**

However:

- **Very expensive**
- **Long acquisition time**
- **Long computation time and massive storage**

$(500 \times 1000)^2$ Tx/Rx
10,000 (cm^2) body pts.
= $2.5\ 10^{15}$ focusing calculations

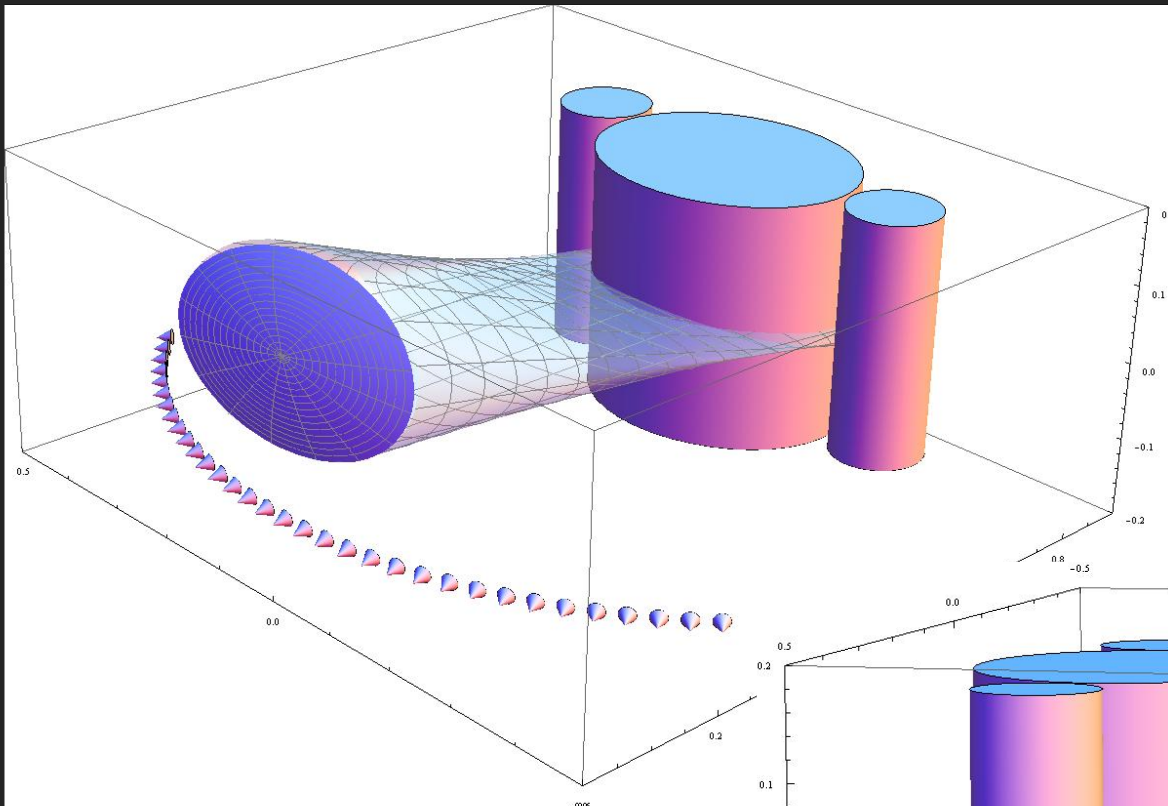
Expedient Alternative: Vertically Moving Focusing Reflector Antenna Trans./Arc Array Rec.



One transmitter
- Moves up/down
- Focuses on thin slice
- Allows multiple 2D processing
- Minimal motion artifacts

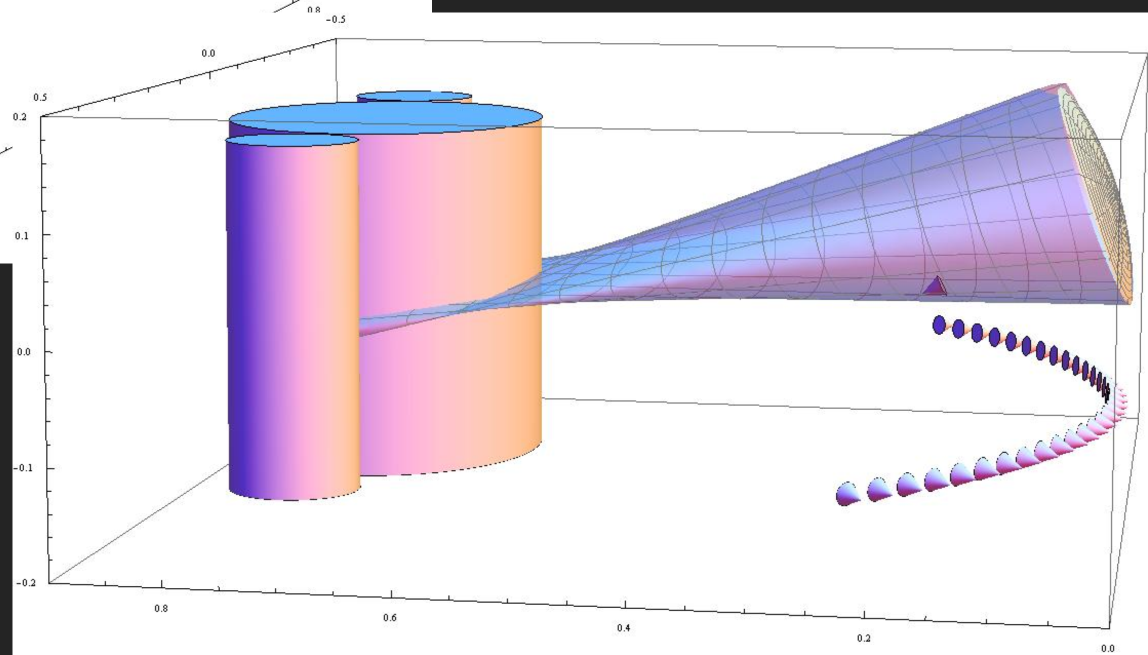
Arc Receiver
- Quarter circle
- Sparse element positions
- Moves up/down with transmitter
- Multistatic: no dihedral artifacts

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

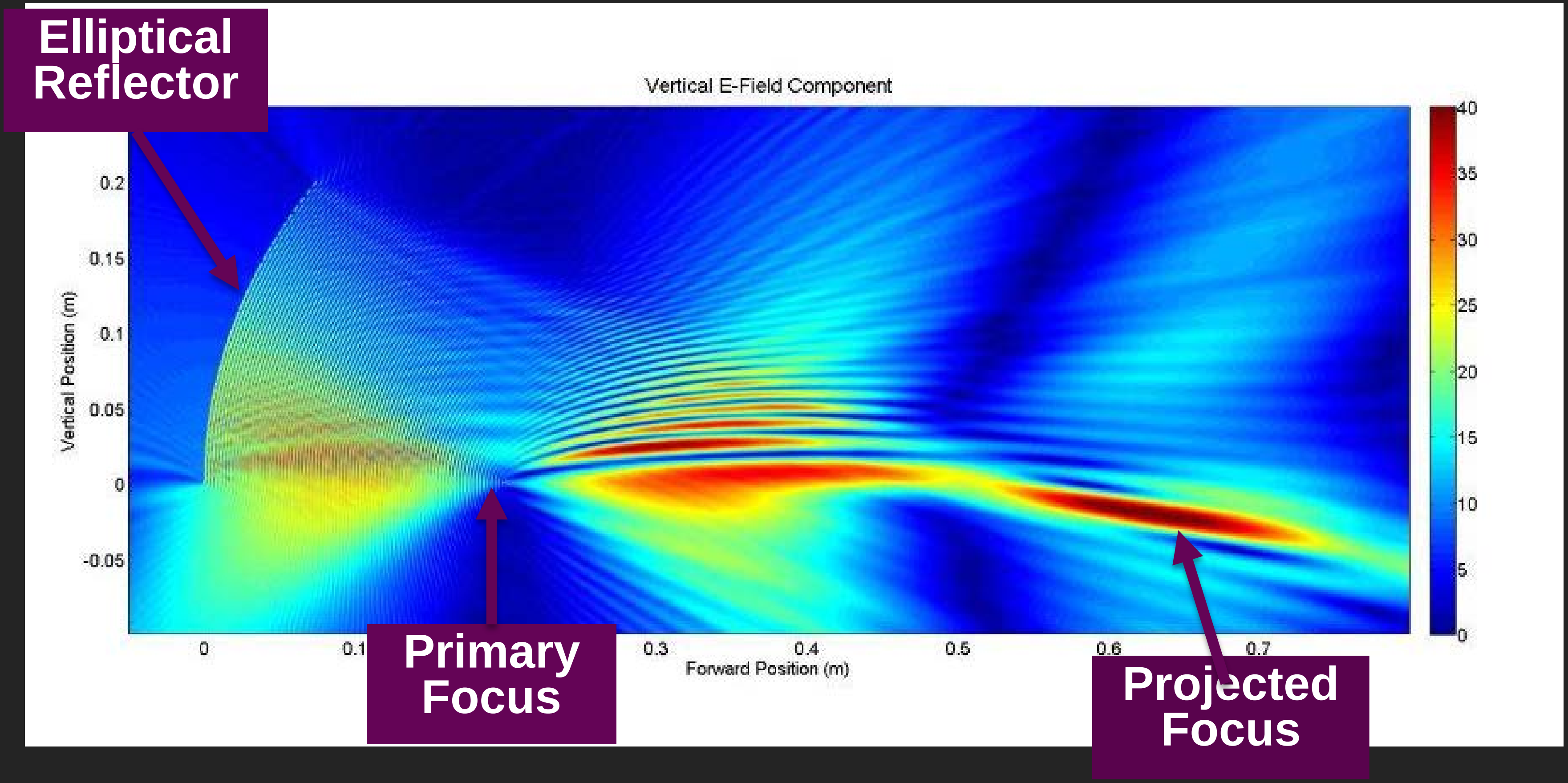


Parabolic in azimuth
- Gives wide beam
- Parallel incident rays

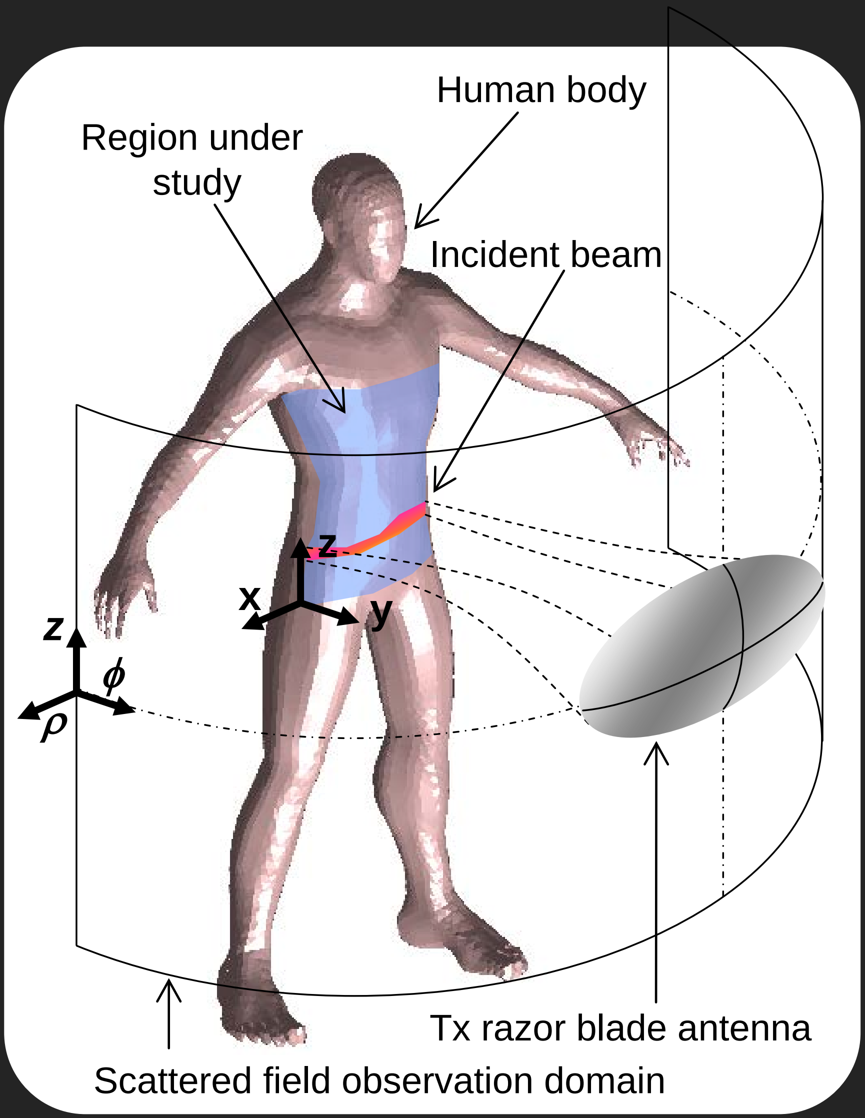
Elliptical in elevation
- Gives tight “Blade Focus”
- Illuminates narrow slice



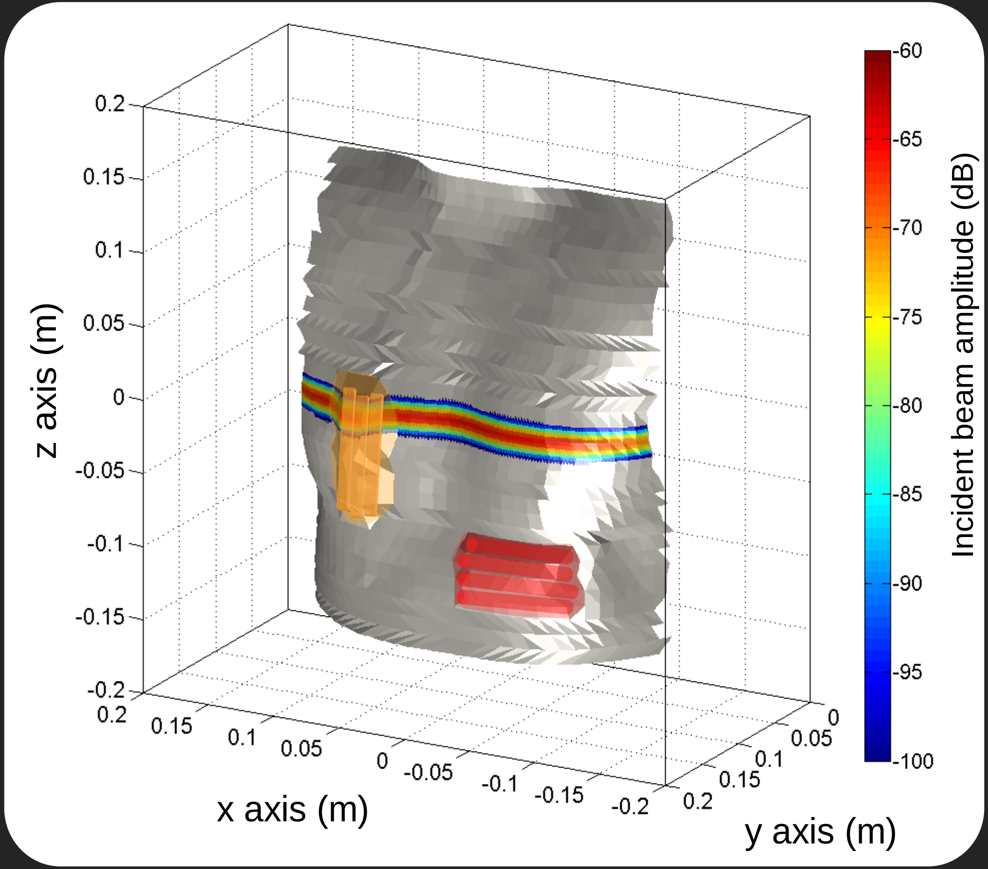
Full Wave FDFD modeling of Elliptical Reflector Focusing to a Thin "Blade Beam"



Specific 3D Human Modeling Geometry



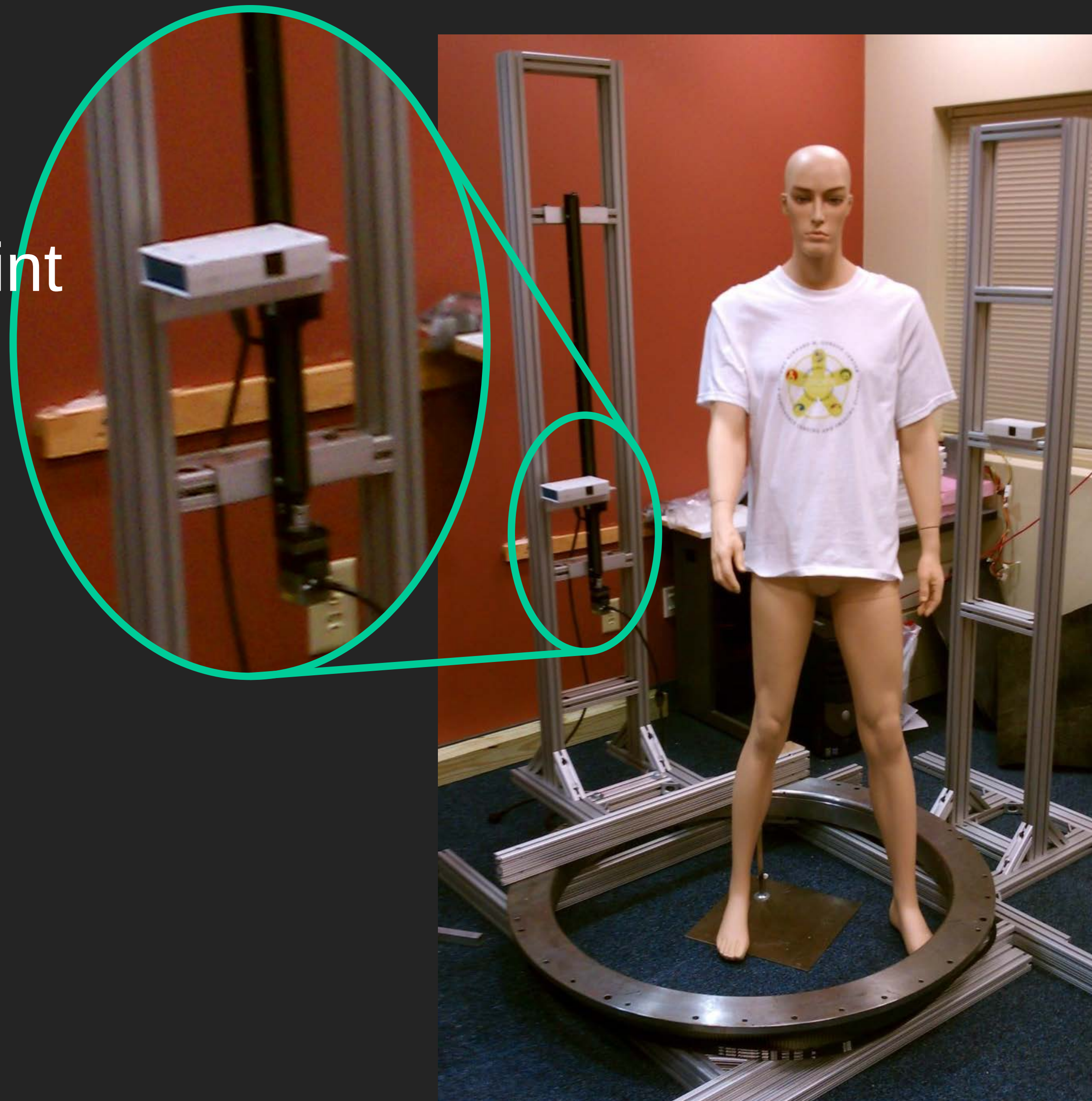
Resulting computed illumination on torso with foreign objects



Rotating / Variable Height Cylindrical Scanning Stage and Mounted 60 GHz Radar

- Independent multistatic experimentation
- Open support: joint x-ray sensor placement

* Circular bearing donated by Neurologica, Inc.



60 GHz Skin and Explosive Simulants

Skin simulant for combined mm-wave / x-ray phantom

- 0.75 cm thick hydrogel layer has very similar water content as skin
- Much better dielectric match than metalized mannequin
- Fully absorbs mm-waves to conceals internal metal parts
- Same transparency to x-ray backscatter as skin
- Workable, smooth, safe, cheap

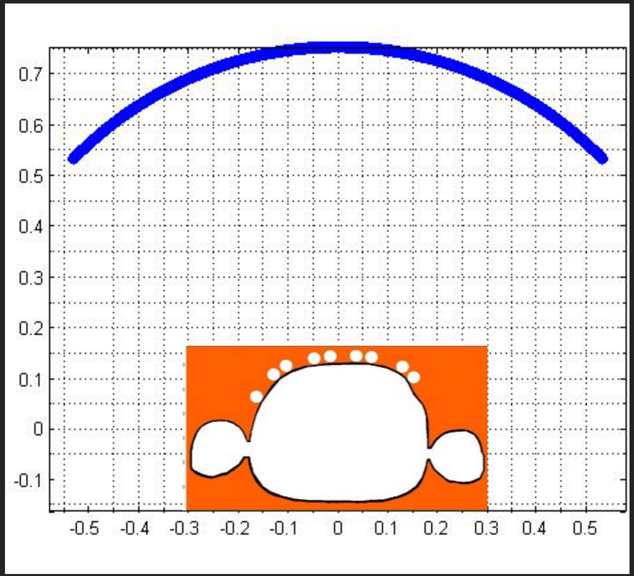
60 GHz Skin and Explosive Simulants

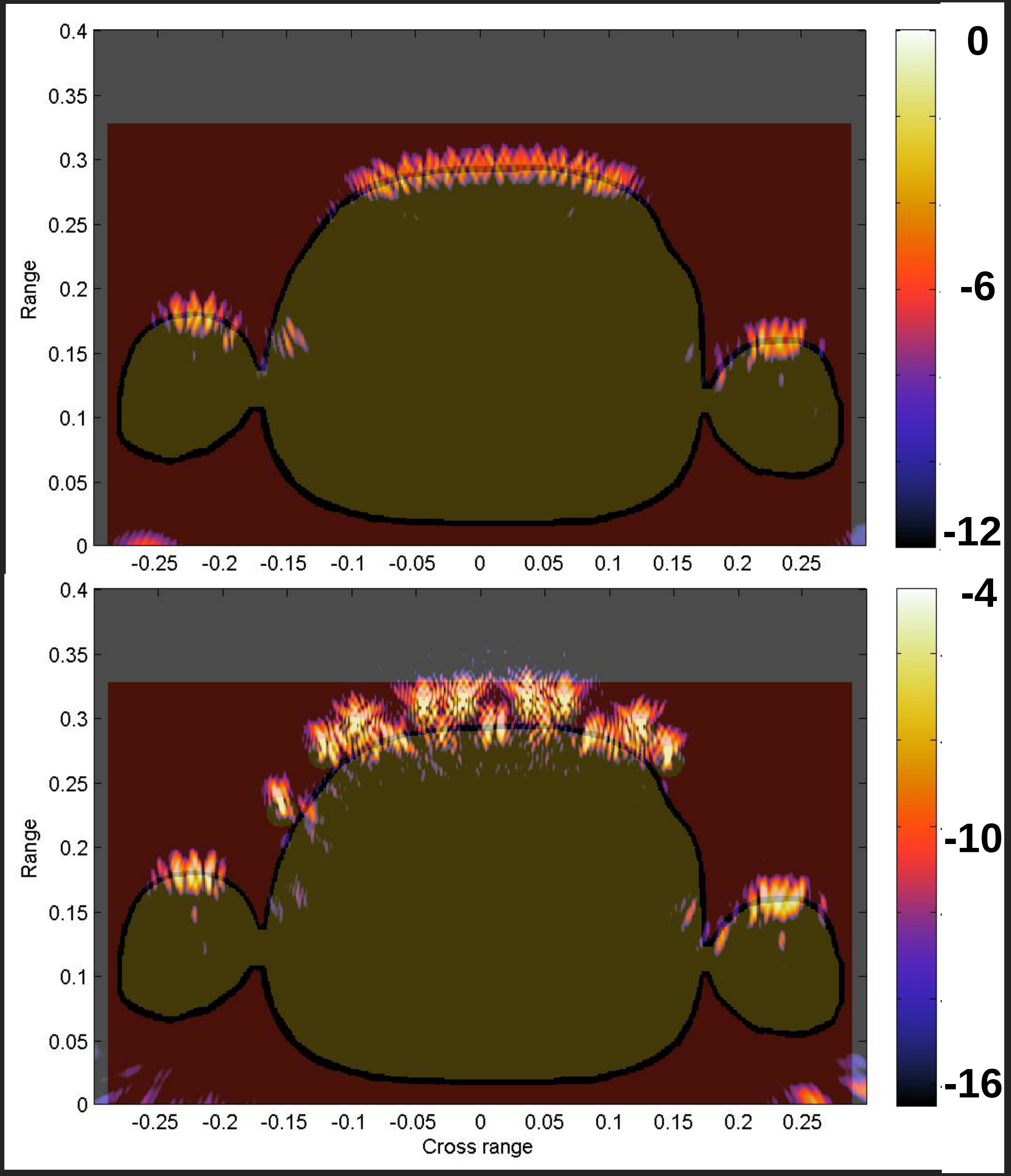
Explosive simulant for mm-waves

- Same electrical characteristics as TNT/RDX/PETN
- Paraffin and TiO_2
- Workable, stable, safe, cheap

Slice Reconstruction of Torso with and without metal pipe bomb simulants

- 2D Multistatic imaging
- Shows smooth innocent body contour
- No dihedral artifacts.

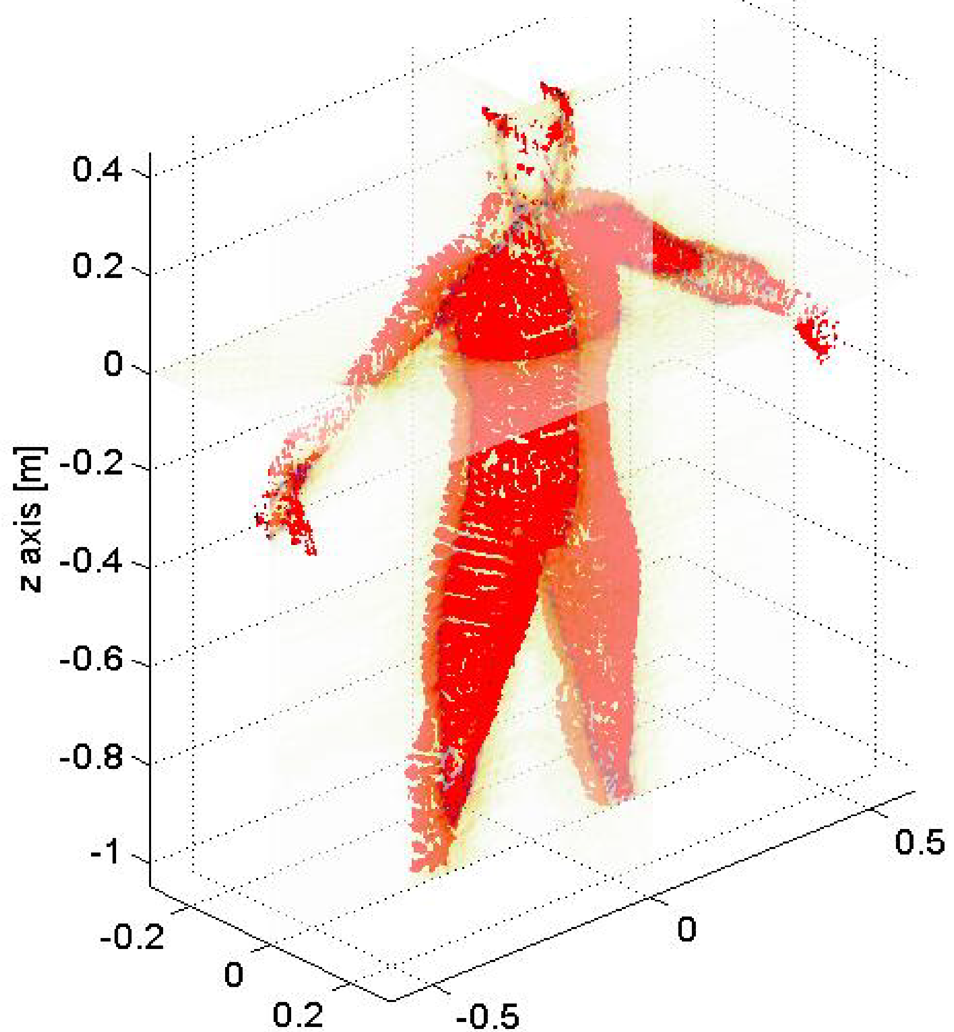




Stacked Slice 3D Reconstruction

- Fast multistatic model-based imaging
- Shows smooth innocent body surface curvature
- High resolution
- No artifacts / dropouts

Iso-surfaces

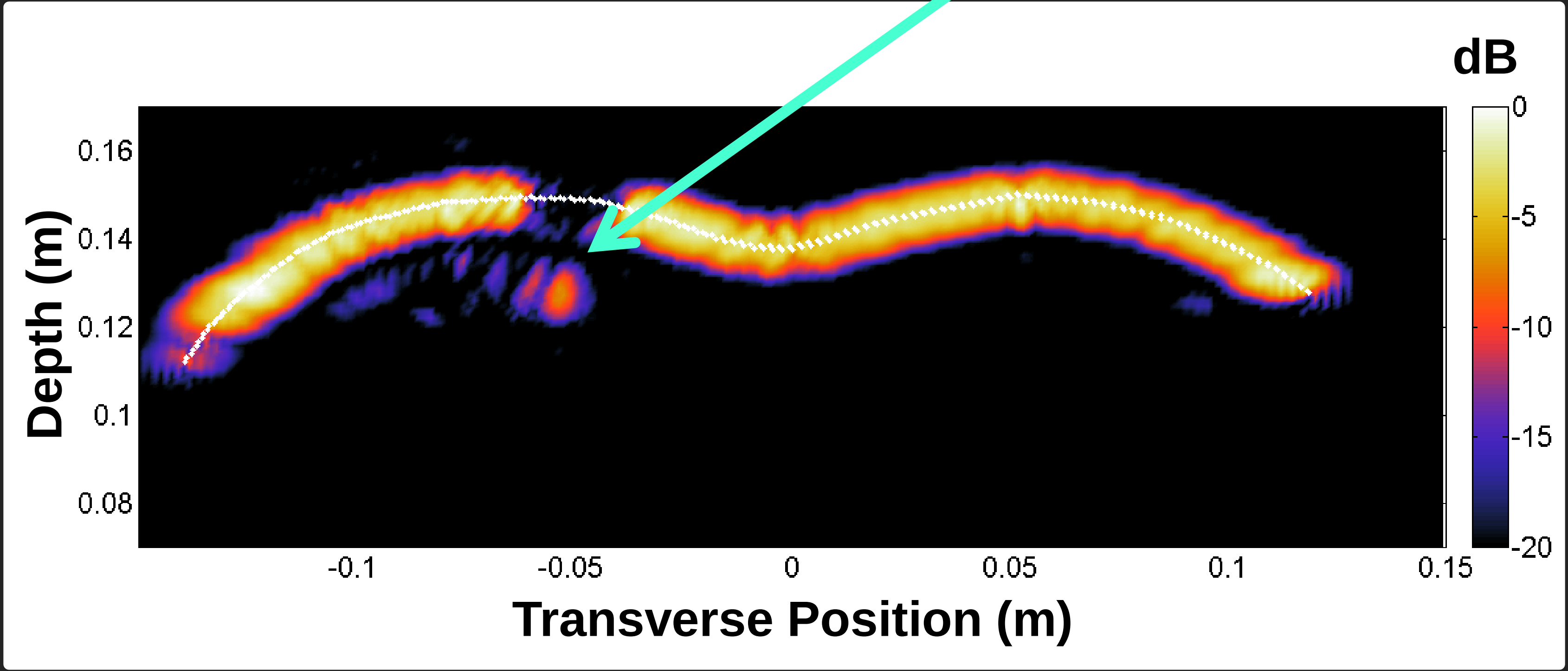


New model-based reconstructed 3D image (using synthetic data) with multistatic radar.

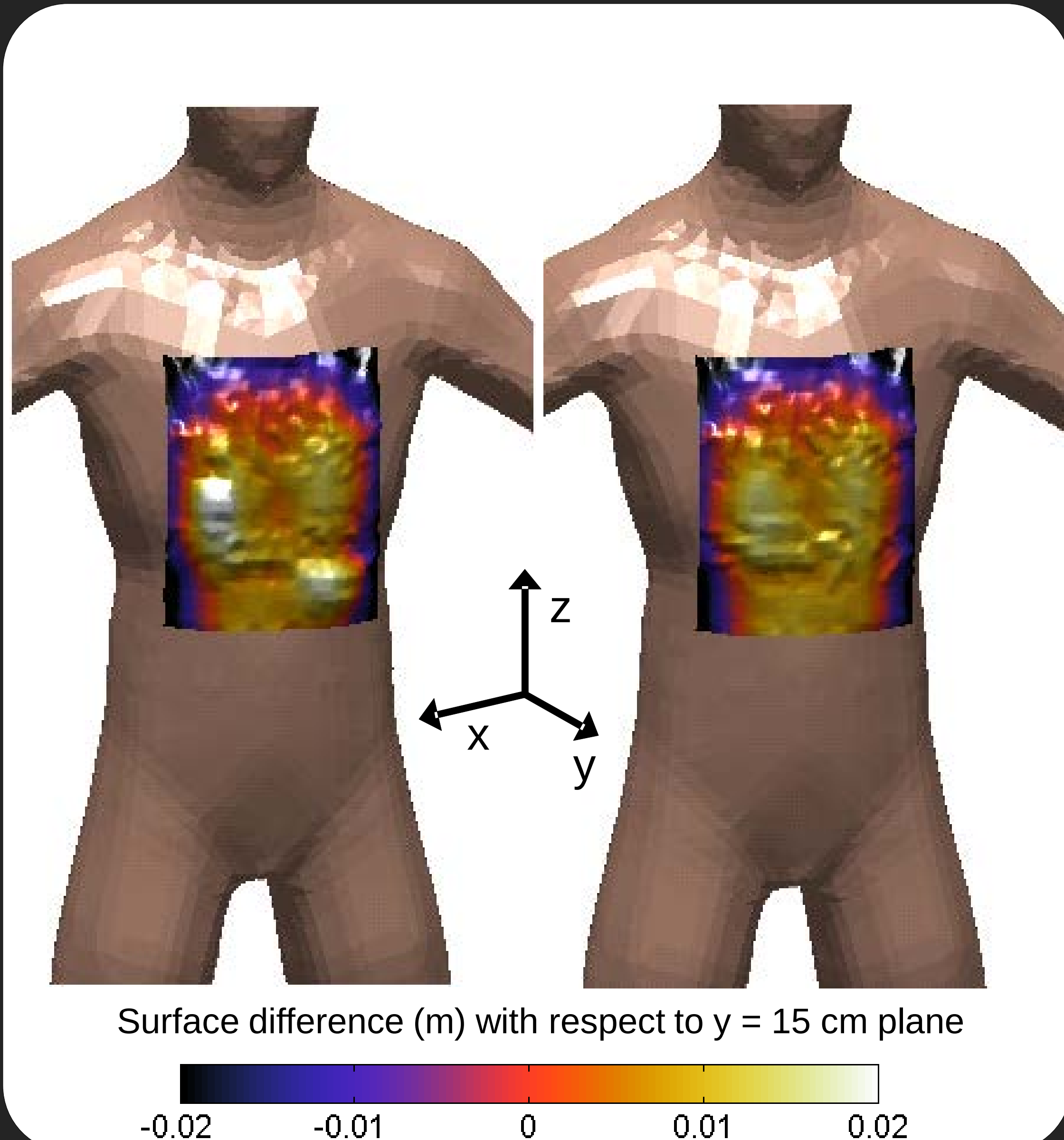
3D Reconstruction of Synthetic Data – Inverse Fast Multipole Method / SAR

- Adjust phase from radar antenna to each point in image space.
- Combine sources into a much smaller number of multipole sources
- High correlation indicates scattering center
- Display scattering centers as bright points – reflective surfaces

3 cm TNT rod (ε’ = 3) on skin gives anomalous response within torso

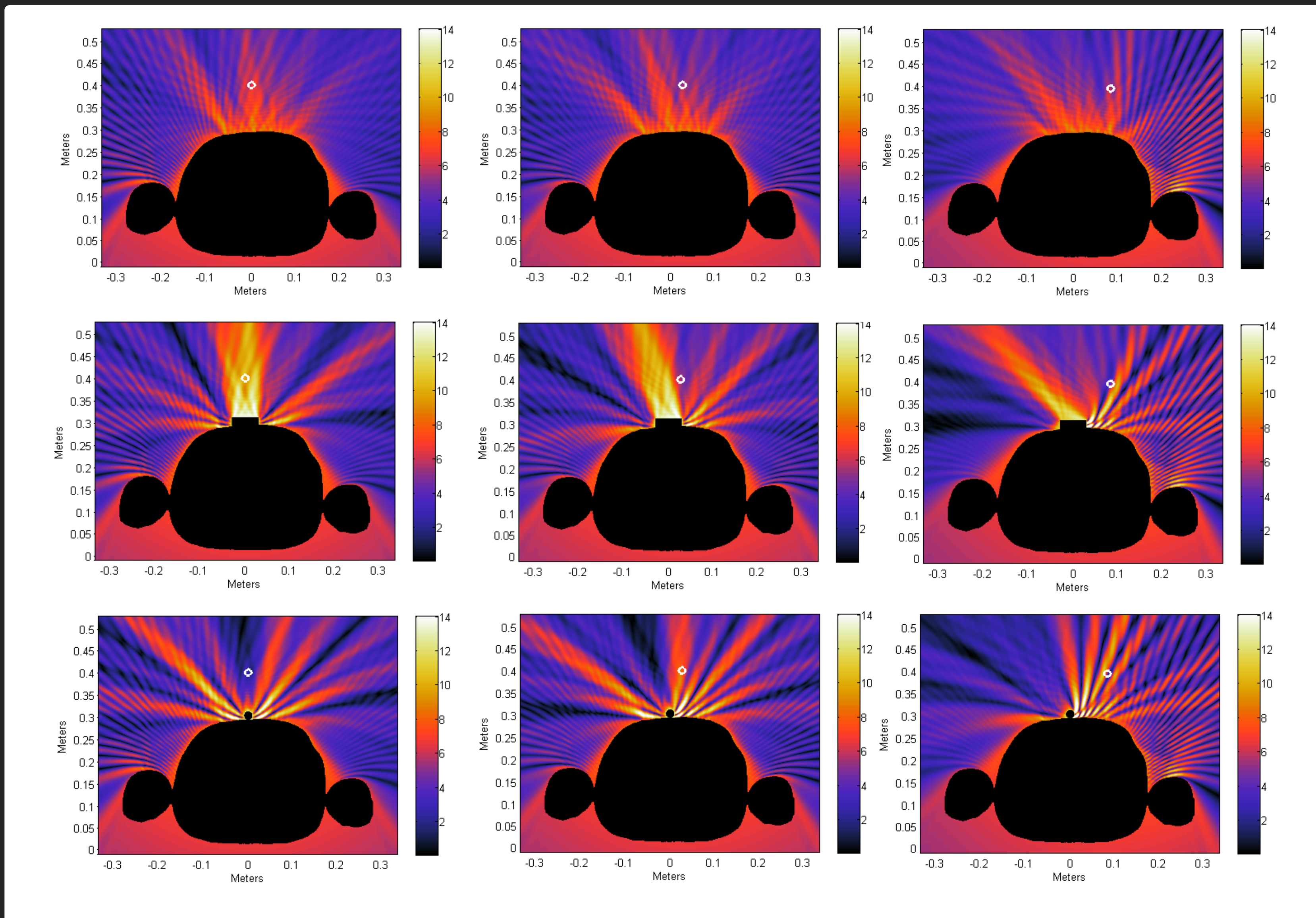


Iterative Field Method (IFM) used for High Resolution Surface Imaging



- Given estimate of range, estimate faceted surface
- Perturb surface facet positions based on linearized phase
- Iterate until convergence
- Surface reconstruction accuracy $\lambda/4 \sim 1$ mm

Finite Difference Frequency Domain Computational Model – Wand Scattered Field



Summary of Computational EM Models

Forward Models

- Finite difference Frequency Domain (FDFD) – 2D and 3D full wave with polarization: metal / dielectric
- Physical Optics (PO) – 2D and 3D surface scattering: metal
- Modified Equivalent Current Approximation (MECA): PO for dielectric
- Method of Moments (MoM) – 3D surface scattering: metal / dielectric

Inverse Models

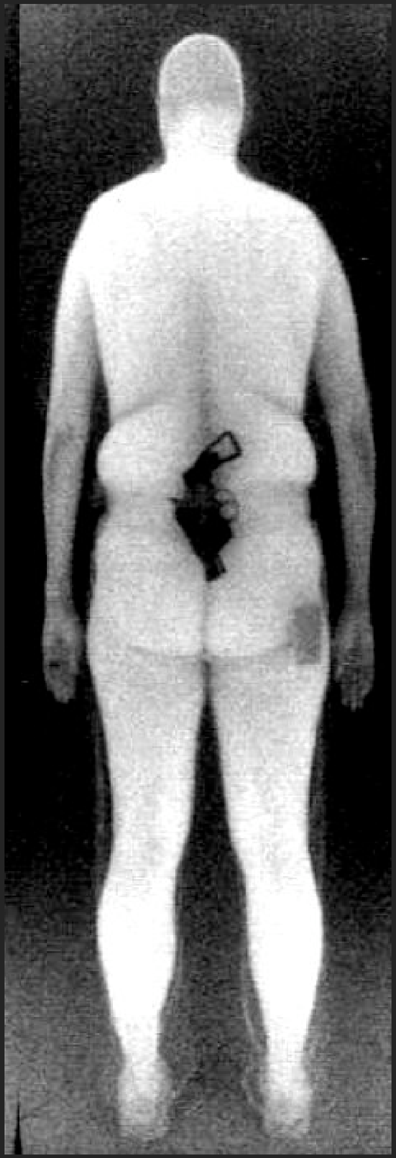
- Synthetic Aperture Radar processing (SAR) – Generalized, non-FFT based volume inversion
- Inverse fast multi-pole method (IFMM) – SAR accelerator
- Iterative Field Method (IFM) – Precise surface determination using center frequency

Fusion Example – X-Ray Backscatter with mm-wave

- XBS and mm-wave are NOT orthogonal
  - Both detect shape/size
  - Both sense material contrast relative to skin
  - Neither (appreciably) penetrates skin
- Both require sensor head movement

- XBS advantages
  - High resolution (wires, beads)
  - Fast
- Mm-wave advantages
  - Depth information (3D shape, thin layers)
  - Non-ionizing

X-Ray Backscatter Person Scan Images



- Skin is light
- Water is light

- Metal is dark
- Bone is dark
- Space is dark

- Minimal penetration into flesh

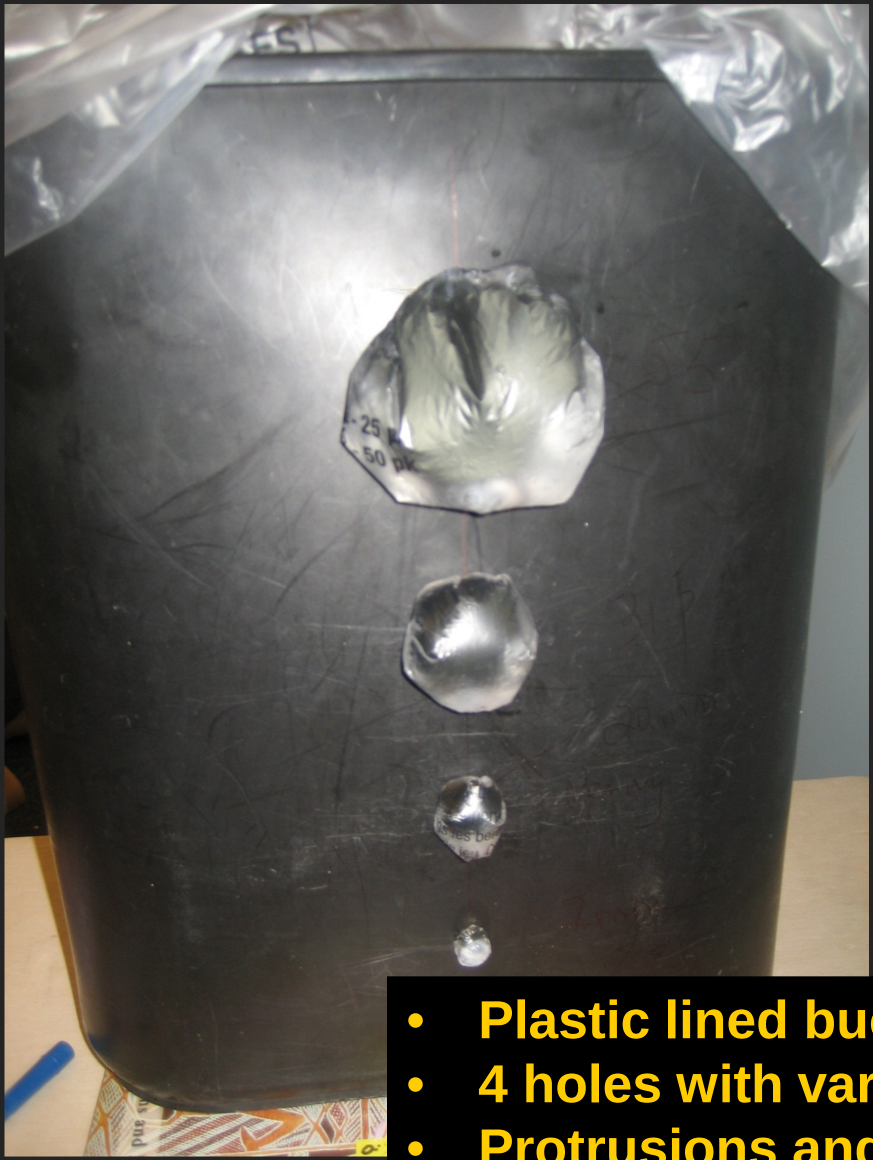
http://www.diagnosticimaging.com/news/display/article/113619/15211

AWARENESS AND LOCALIZATION OF EXPLOSIVES-RELATED THREATS

ALERT

DETECTION MITIGATION RESPONSE

Controlled X-Ray Backscatter Experiment

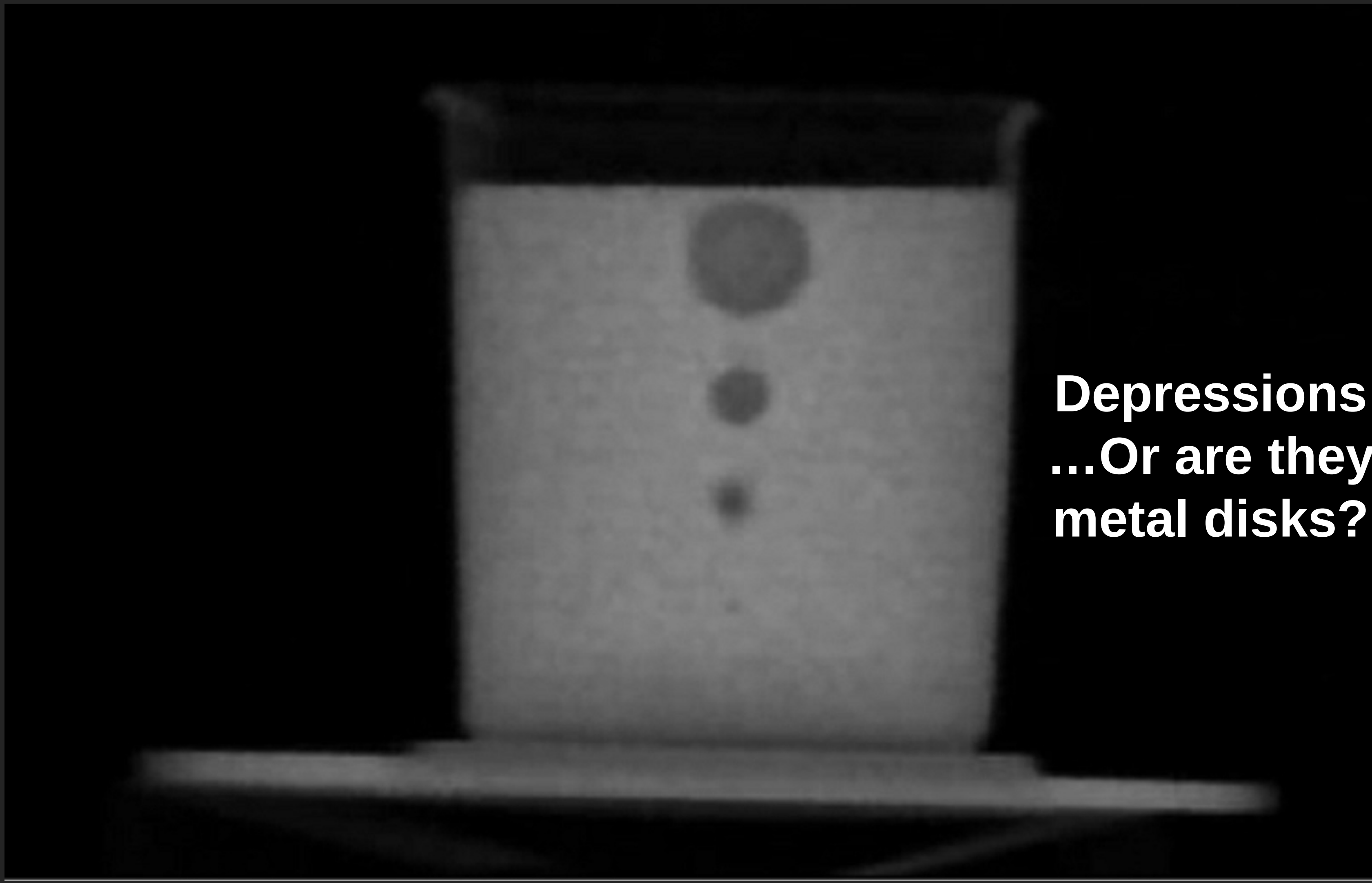


- Plastic lined bucket filled with water
- 4 holes with varying diameters
- Protrusions and Depressions

Controlled X-Ray Backscatter Experiment

- Interior view, plastic lined bucket
- 4 holes plugged with x-ray transparent styrofoam

Measured X-Ray Backscatter Image of Depressions in Water Volume

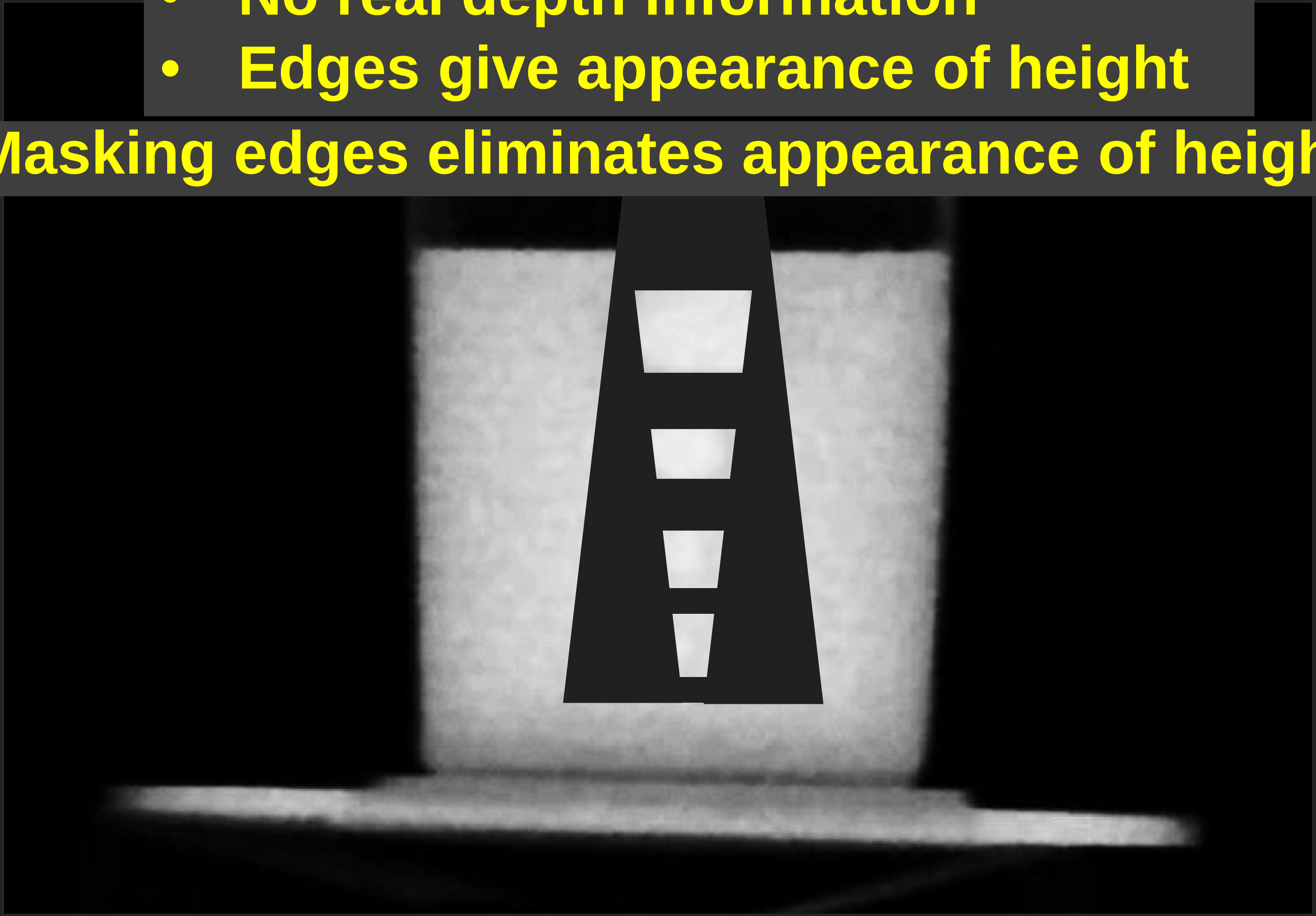


Rotating X-Ray Backscatter Video 1

Measured X-Ray Backscatter Image of Protrusions in Water Volume

- No real depth information
- Edges give appearance of height

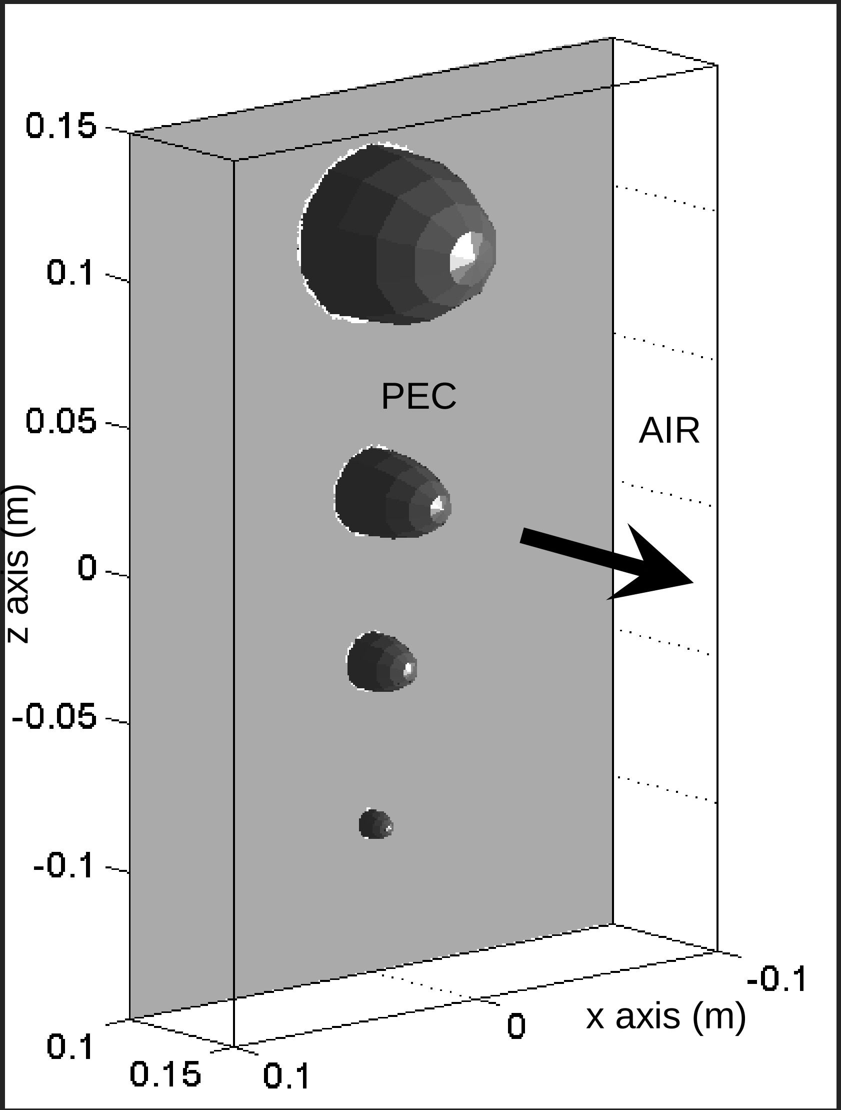
Masking edges eliminates appearance of height



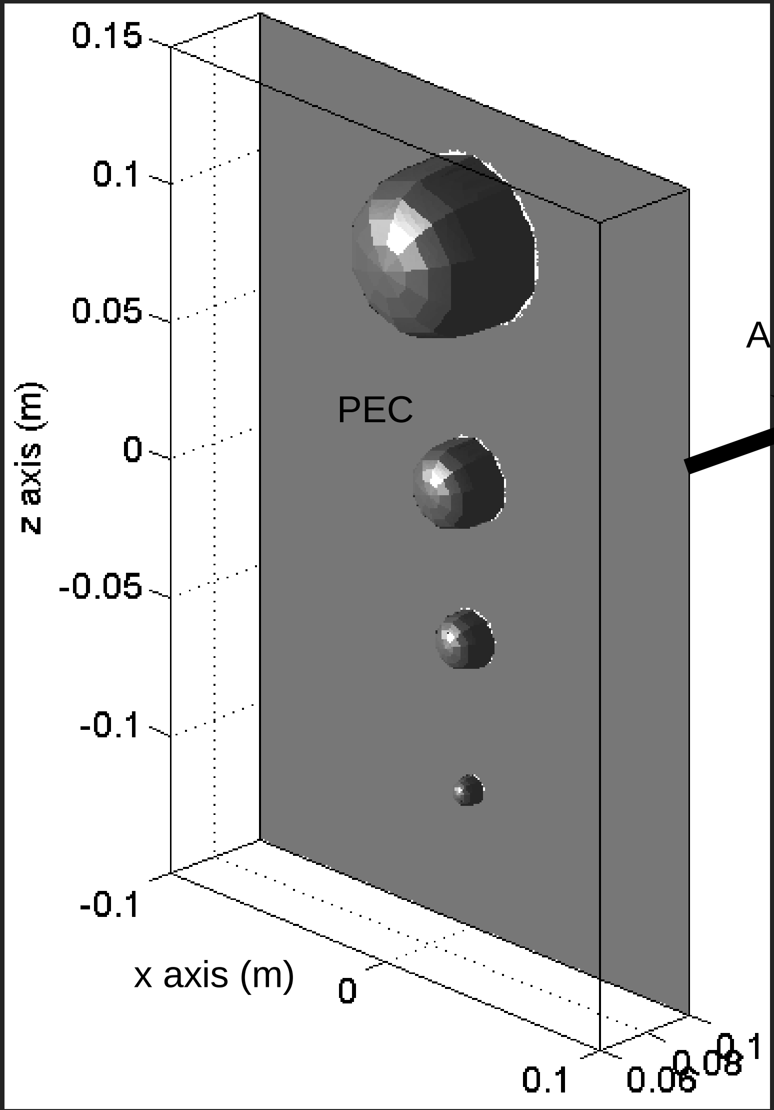
Rotating X-Ray Backscatter Video 2

MM-Wave Forward and Inversion Modeling of Hole Series

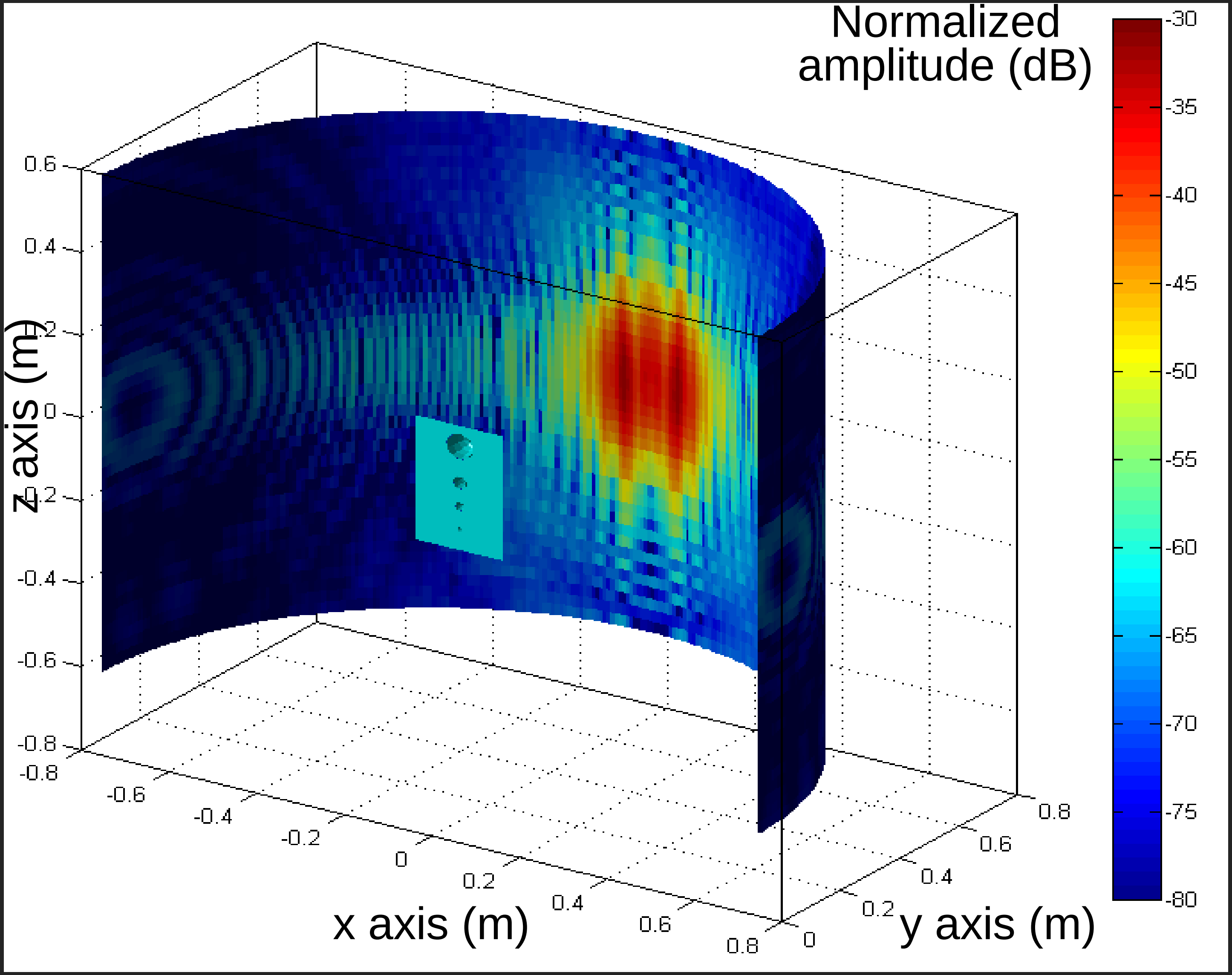
Protrusions– Modeled geometry



Depressions– Modeled geometry (inside view)

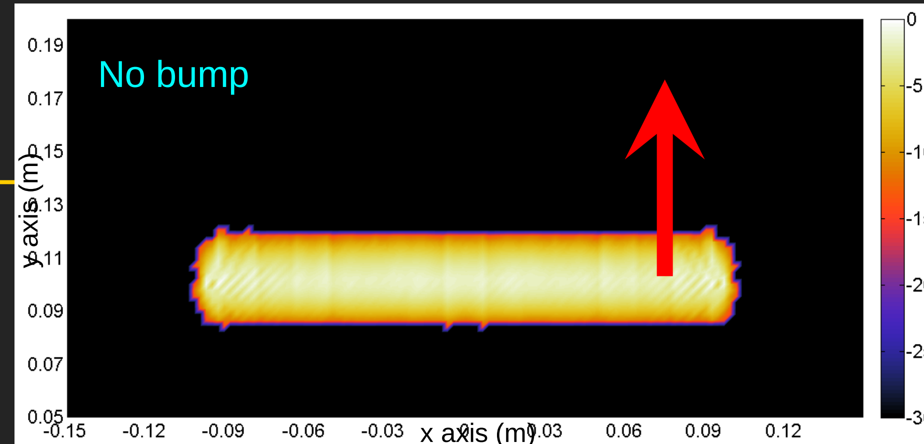


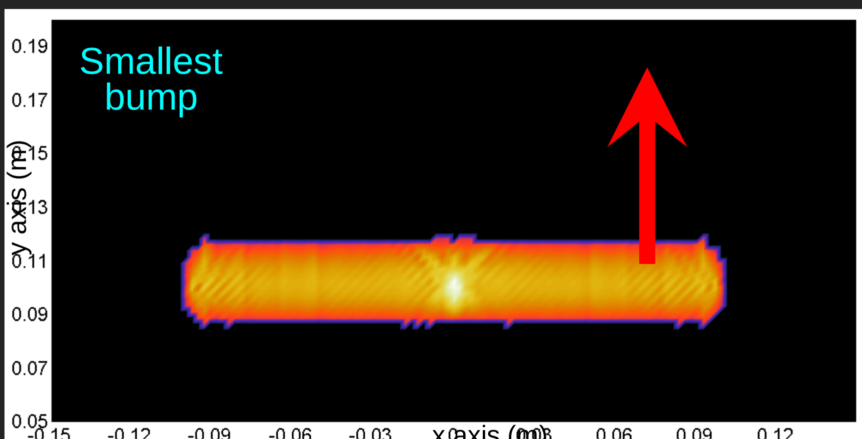
Scattered Field on the Cylindrical Acquisition Surface – Test Item with 4 Protrusions

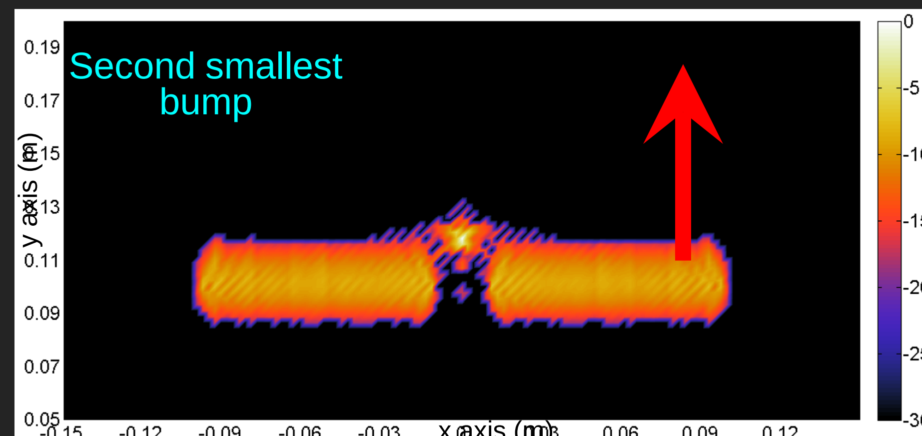


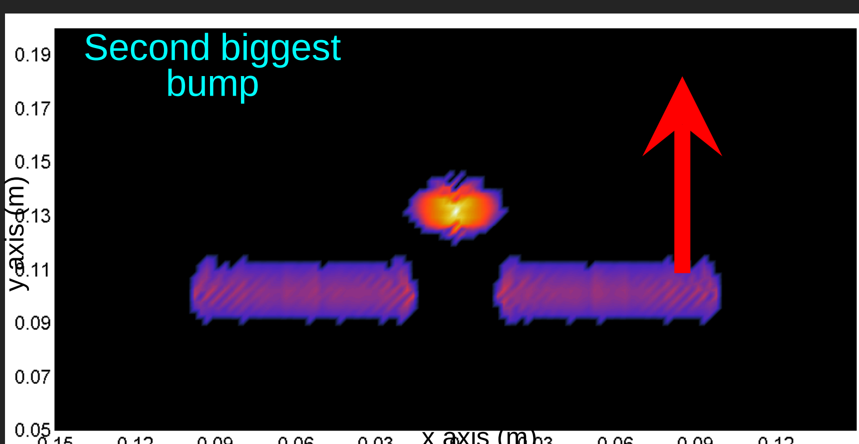
SAR Reconstruction of Protrusions

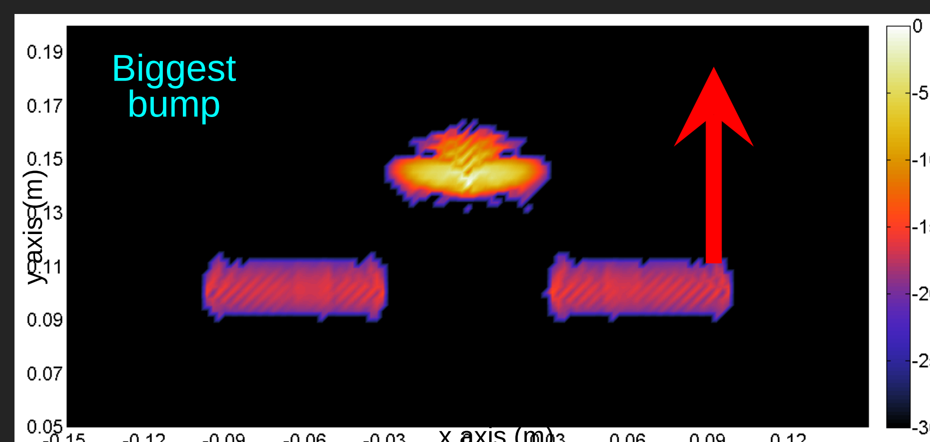
Range view, showing material closer to detector



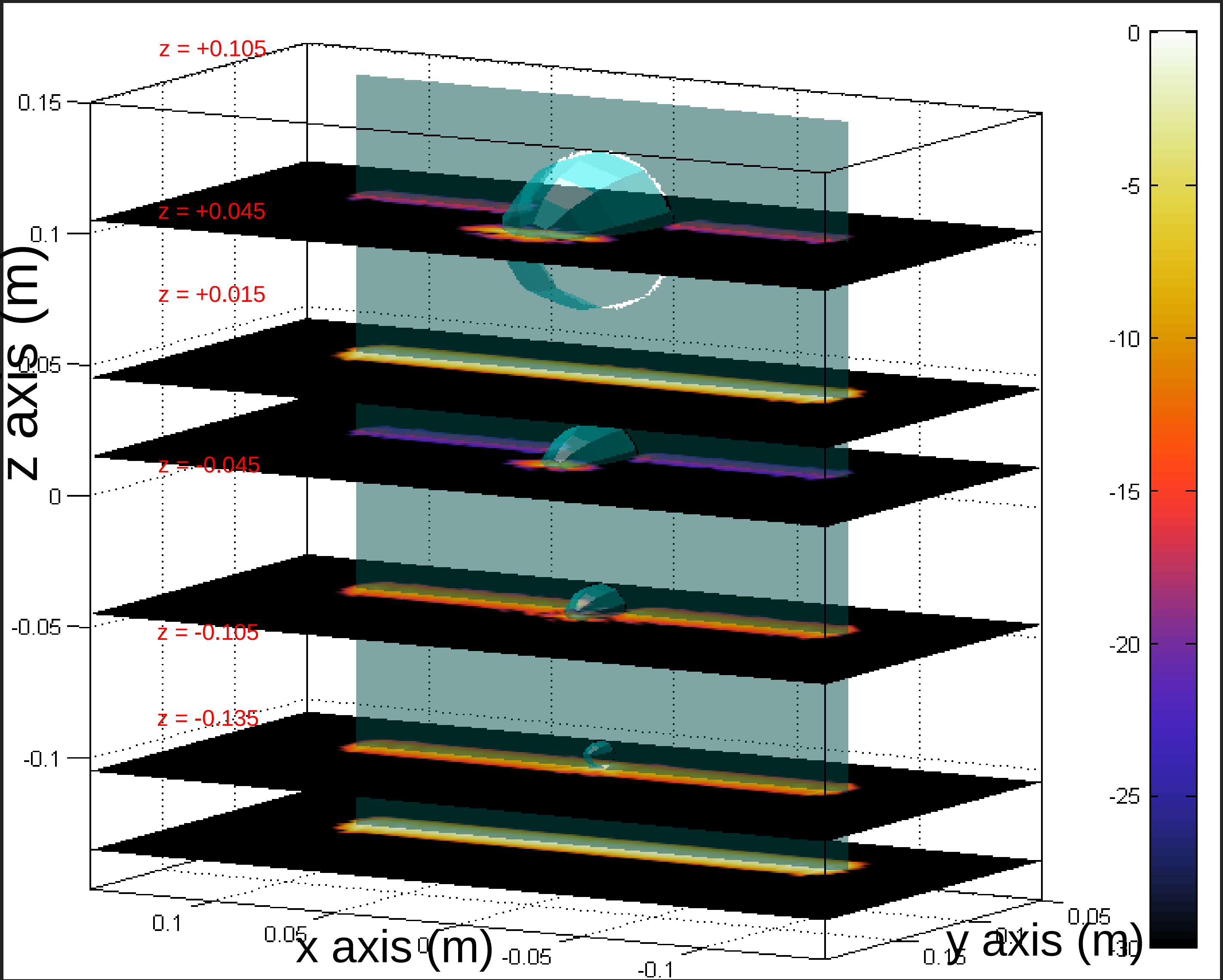




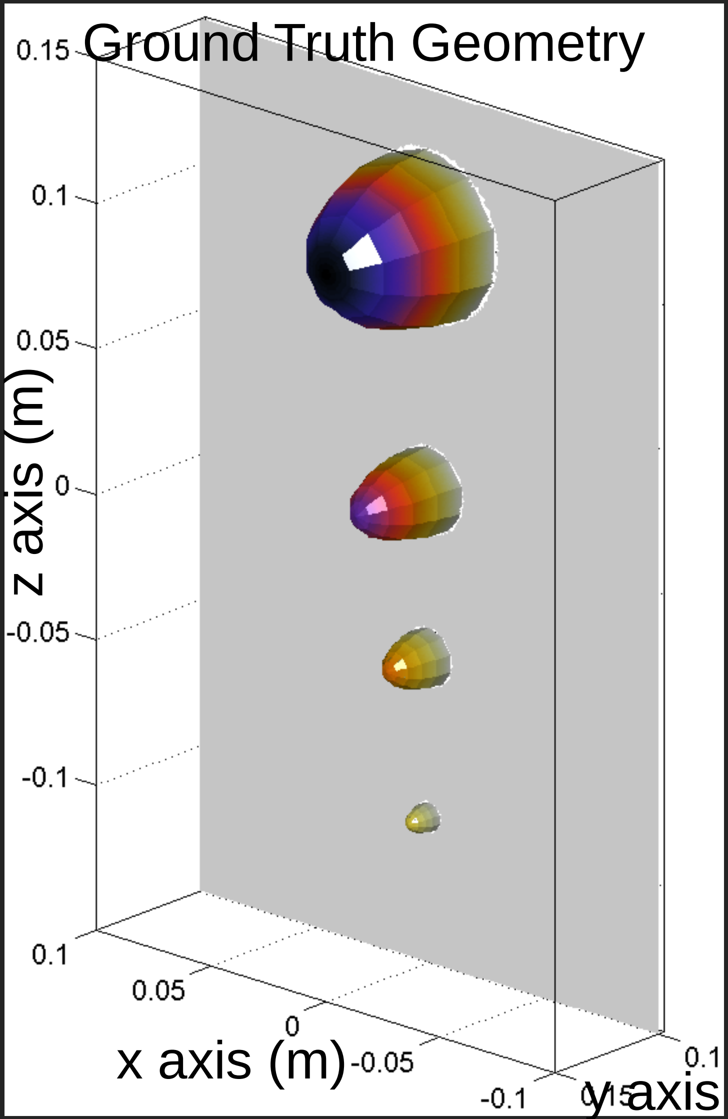


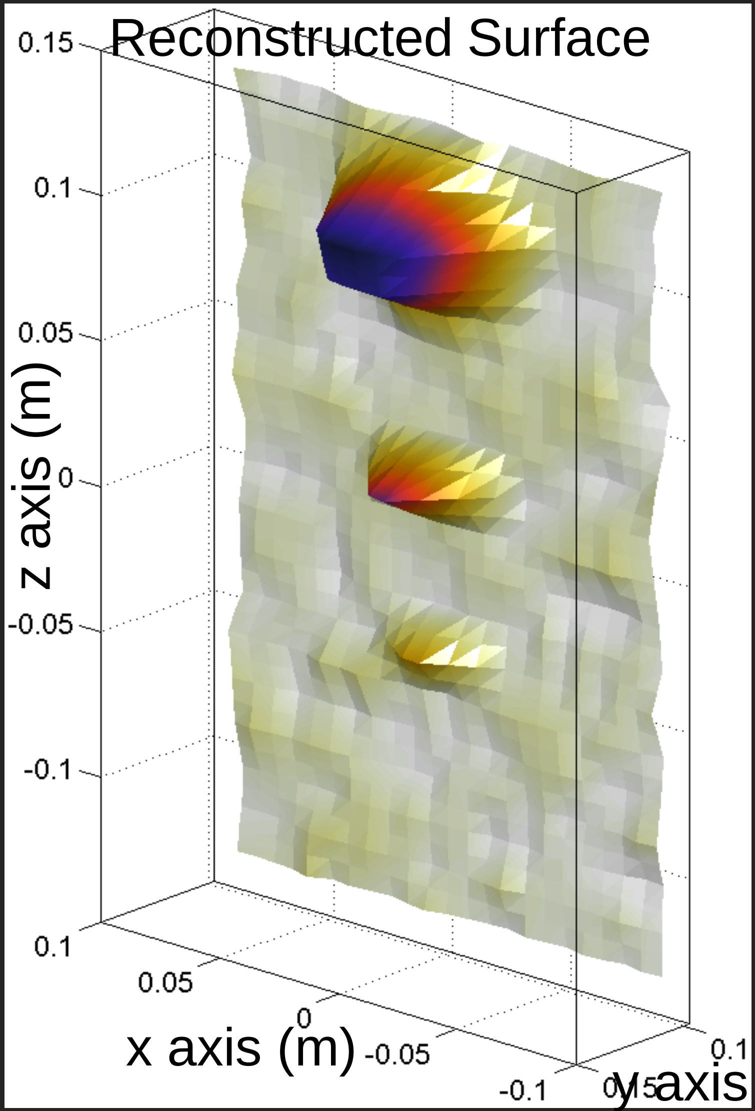


Stacked slices – 4 Protrusions

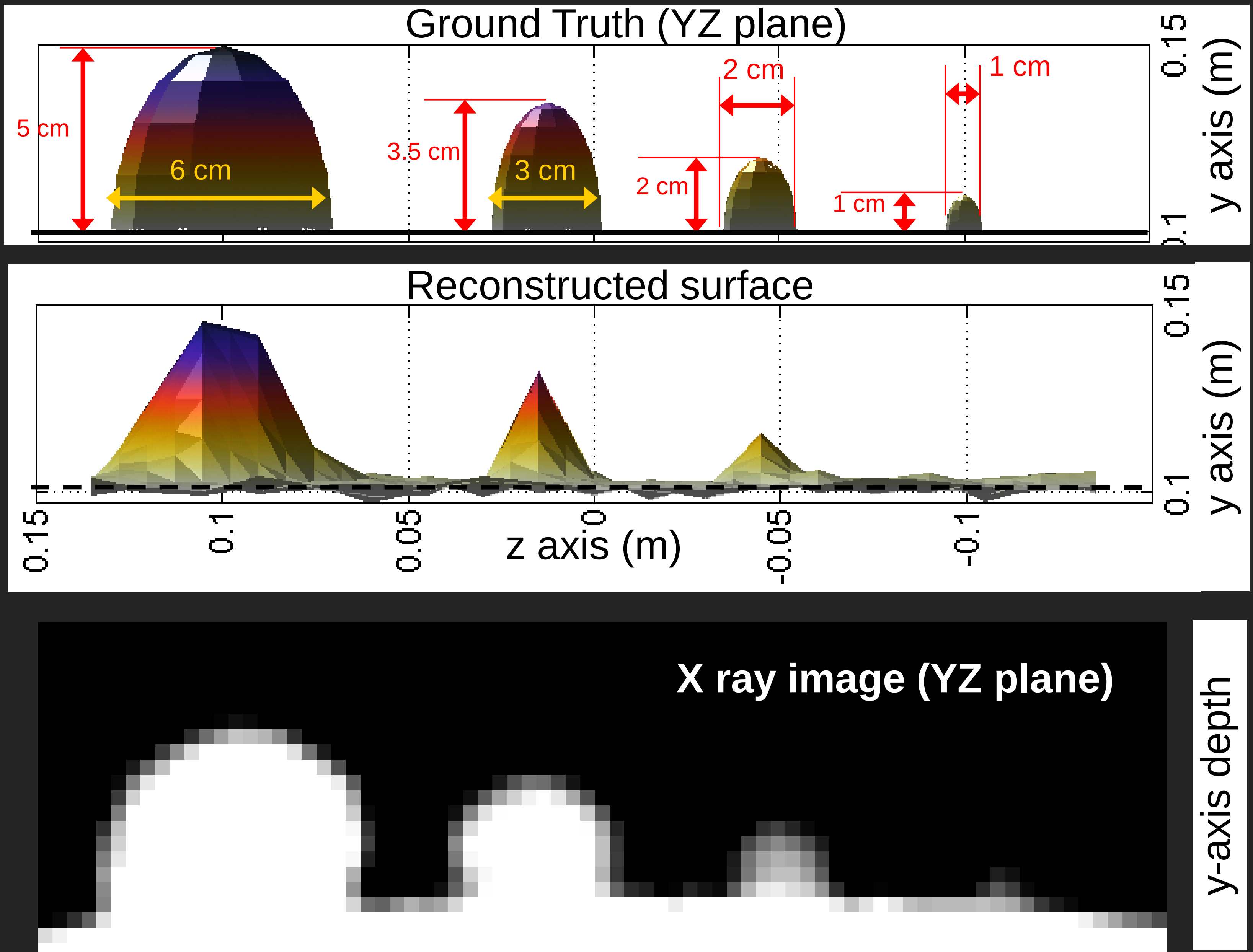


3D Surface Reconstruction:
4 Protrusions of Water from Water Plane

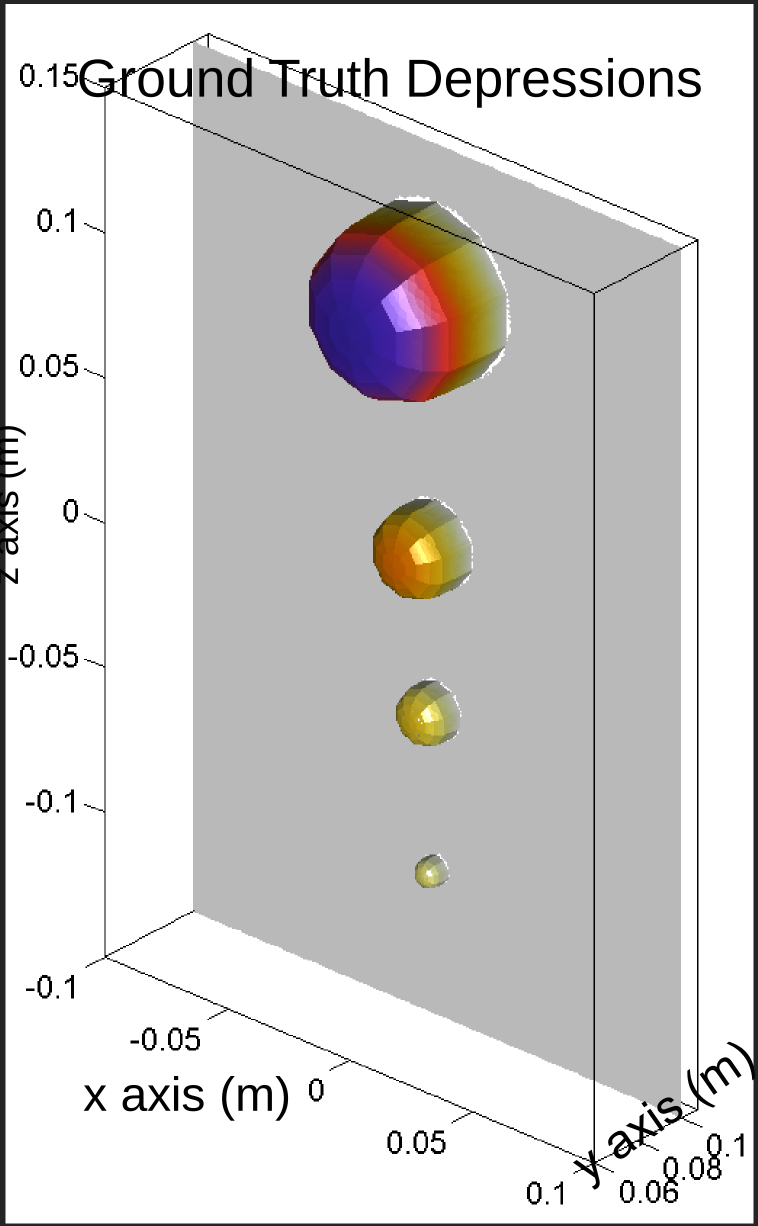


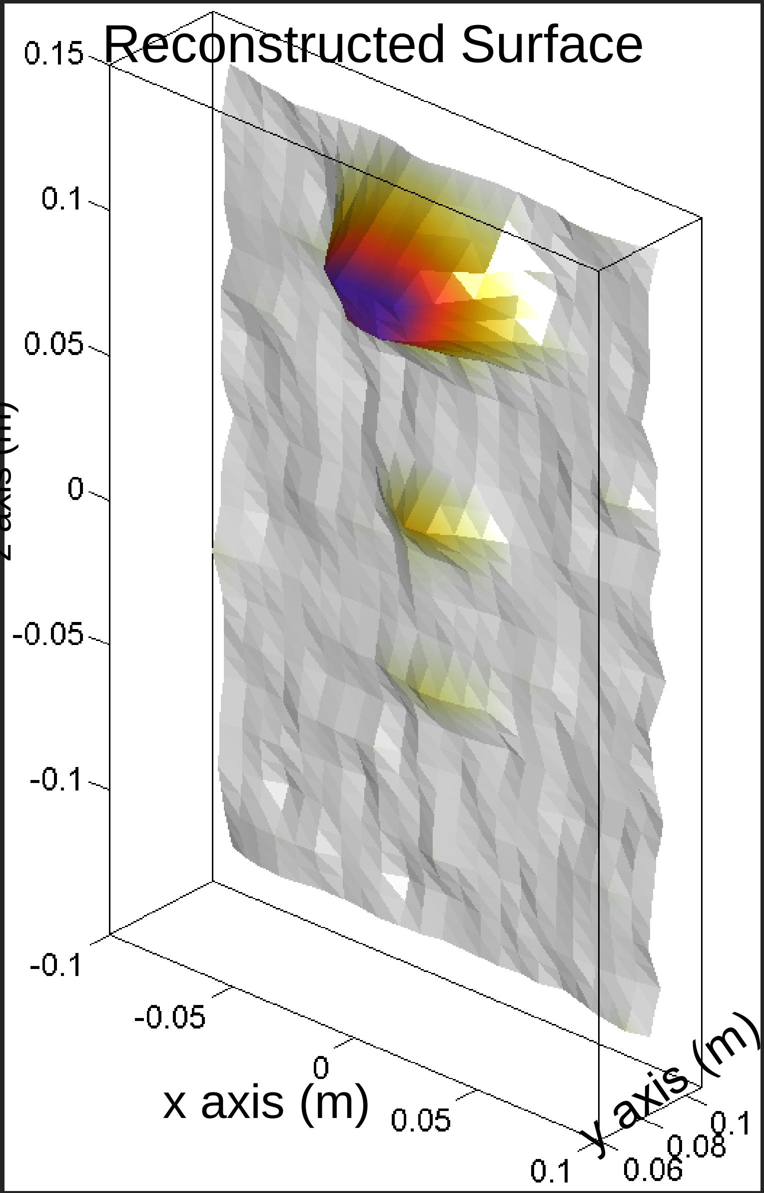


3D Height Reconstruction: 4 Protrusions

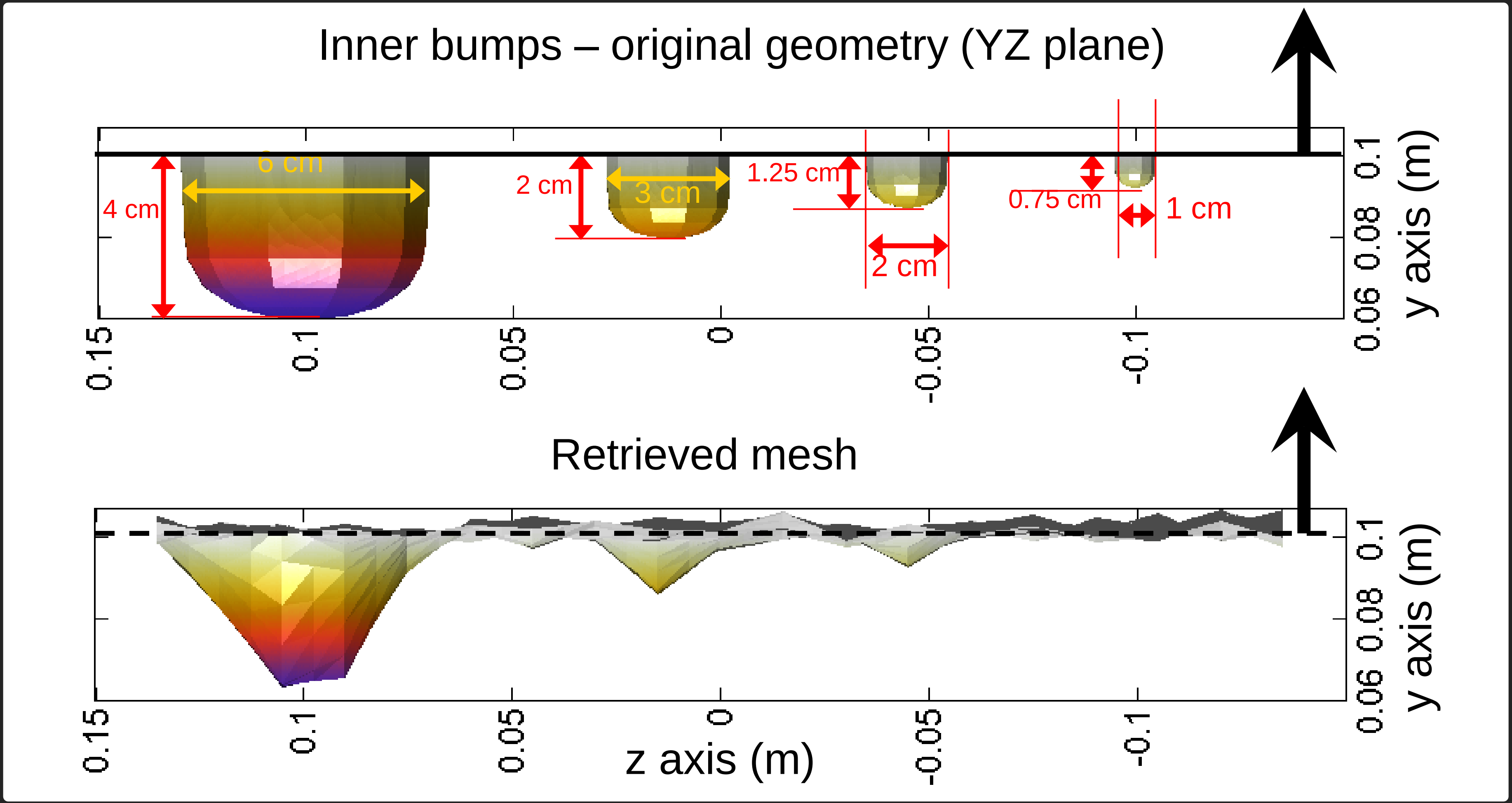


3D Height Reconstruction: 4 Depressions in Water Wall (Inside View)





Quantitative comparison of Reconstruction – 4 Depressions



Note: No X-ray image available for depressions

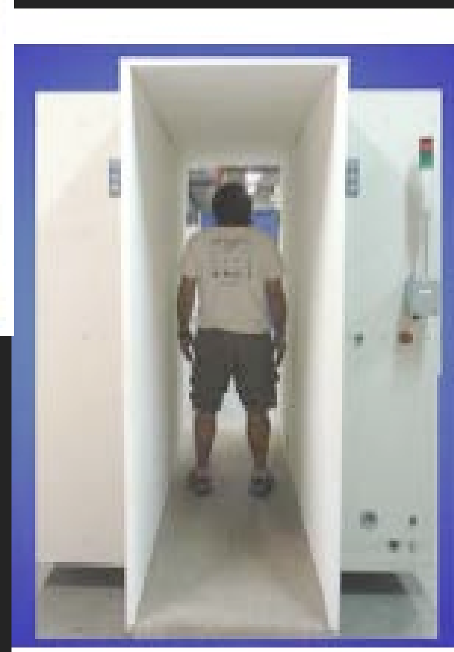
Intimately Near Detection: Advanced Imaging Technologies (AIT) for Whole Body Imaging

- NEU Testbed: Unbiased academic-oriented testbed for development and evaluation of multi-modal sensors and algorithms for whole body imaging
  - Enable experimentation with new sensing modalities
    - Optimize sensor configurations
    - Optimize scanning modes
  - Explore new algorithm concepts
    - Model based vs. Fourier inversion
    - High resolution fused imaging
    - Automated anomaly detection
  - Develop approaches to information fusion and adaptive multisensor processing

Whole Body Imaging Sensors to Fuse with Mm-Wave

- X-ray Backscatter
  - Penetrates all concealing layers
  - Dual energy distinguishes foreign materials
  - Ionizing radiation but very low dosage
- IR Thermography
- NQR
- THz

Nuclear Quadrupole Resonance (NQR)



- Detect local nuclear fields of nuclei with spin > 1 (^{14}N)
- Detect presence of ^{14}N

- Very specific to material ID
- Penetrates throughout body
- Close sensor proximity
- Must be solid phase
- Temperature dependent

http://www.morphodetection.com/technologies/quadrupole-resonance/

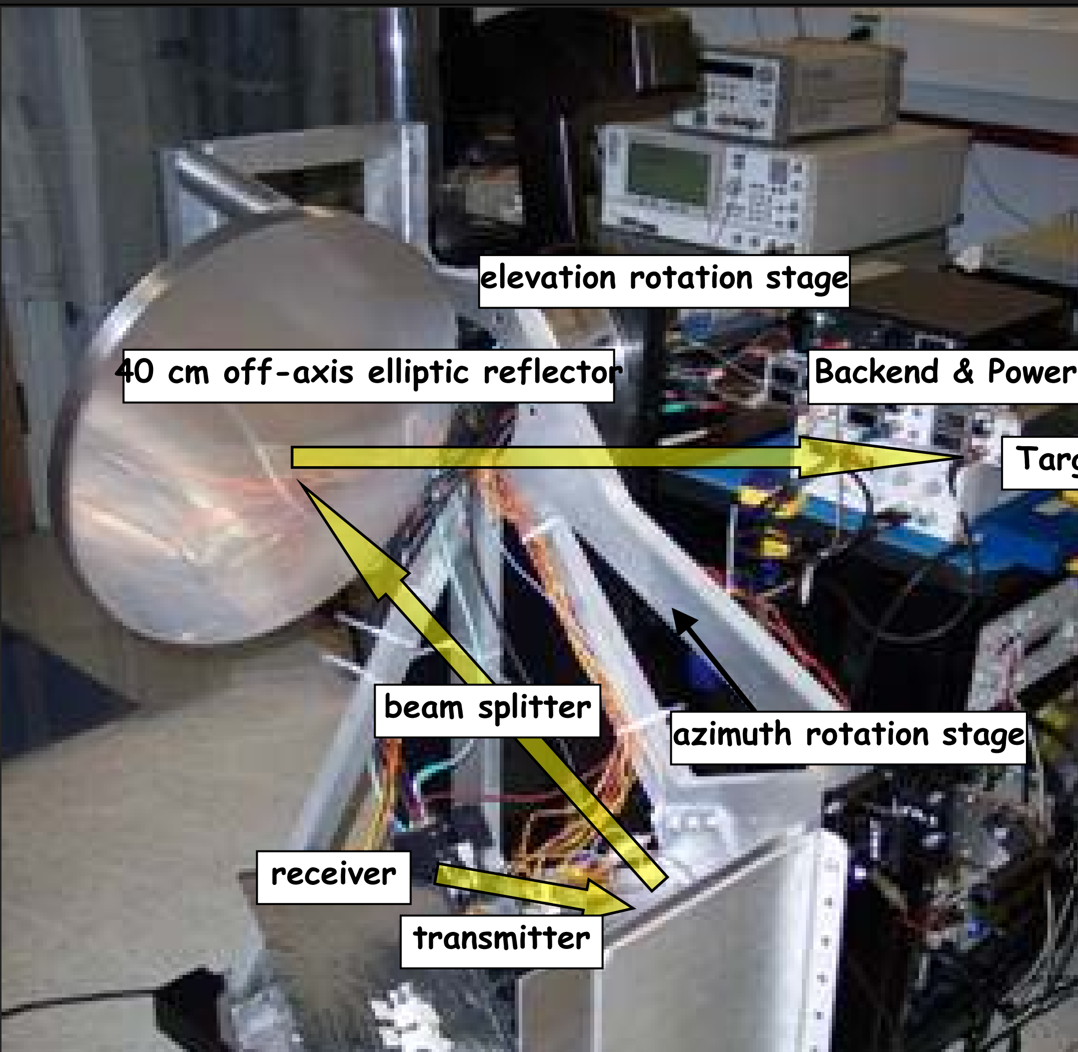
Passive Thermography

- IR absorption is a function of molecular vibrations and rotations
- Variable absorption / emittance of IR by materials between body and detector
- Signal can be enhanced with environmental pre-cooling

- Non-ionizing
- Fast
- Low-resolution
- Low penetration through clothing

http://www.nec-avio.co.jp/en/products/ir-thermo/lineup/tvs200is_tvs500is/index.html

THz Imaging



Siegel, JPL: 654-686 GHz Heterodyne T/R System with 32 GHz Chirp (1cm range bin)

- Passive/active – similar to mm-wave
- Must be scanned mechanically

- Non-ionizing
- High spatial & depth resolution
- Clutter from clothing scatter
- No skin penetration
- Surface texture affects scatter
- Time domain systems can be slow

Conclusions

- Established detection regime and parameters
- Described why fusion necessary
- Showed potential challenges and considerations with fusion with mm-waves
- Described the ALERT AIT Testbed (ScanBED)
- Explained how advanced simulation and modeling saves lots of time and money
- Presented a specific example of the potential of fusing x-ray backscatter with mm-wave sensing
- Described the plans for ScanBED multi-modal fusion

People Who Actually Did the Work…

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Kathryn Williams
Galia Ghazi
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Dan Busioc
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