STh-01

MODERN ADVANCES IN COMPUTATIONAL IMAGING AT MICROWAVE AND MILLIMETRE-WAVE FREQUENCIES

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General Introduction to Microwave and Millimeter-wave Computational Imaging; Formalisms, Systems and Image Reconstruction

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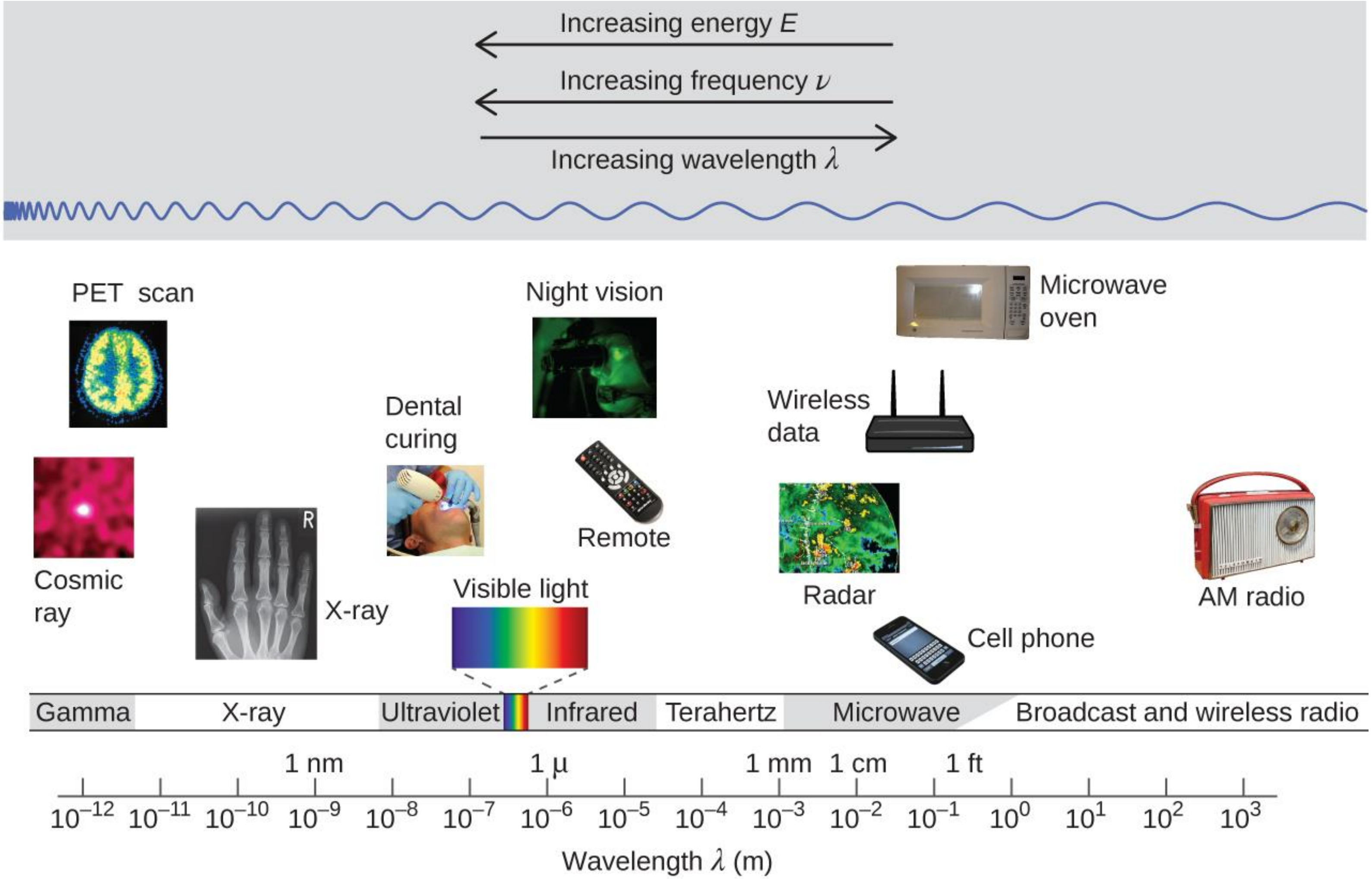
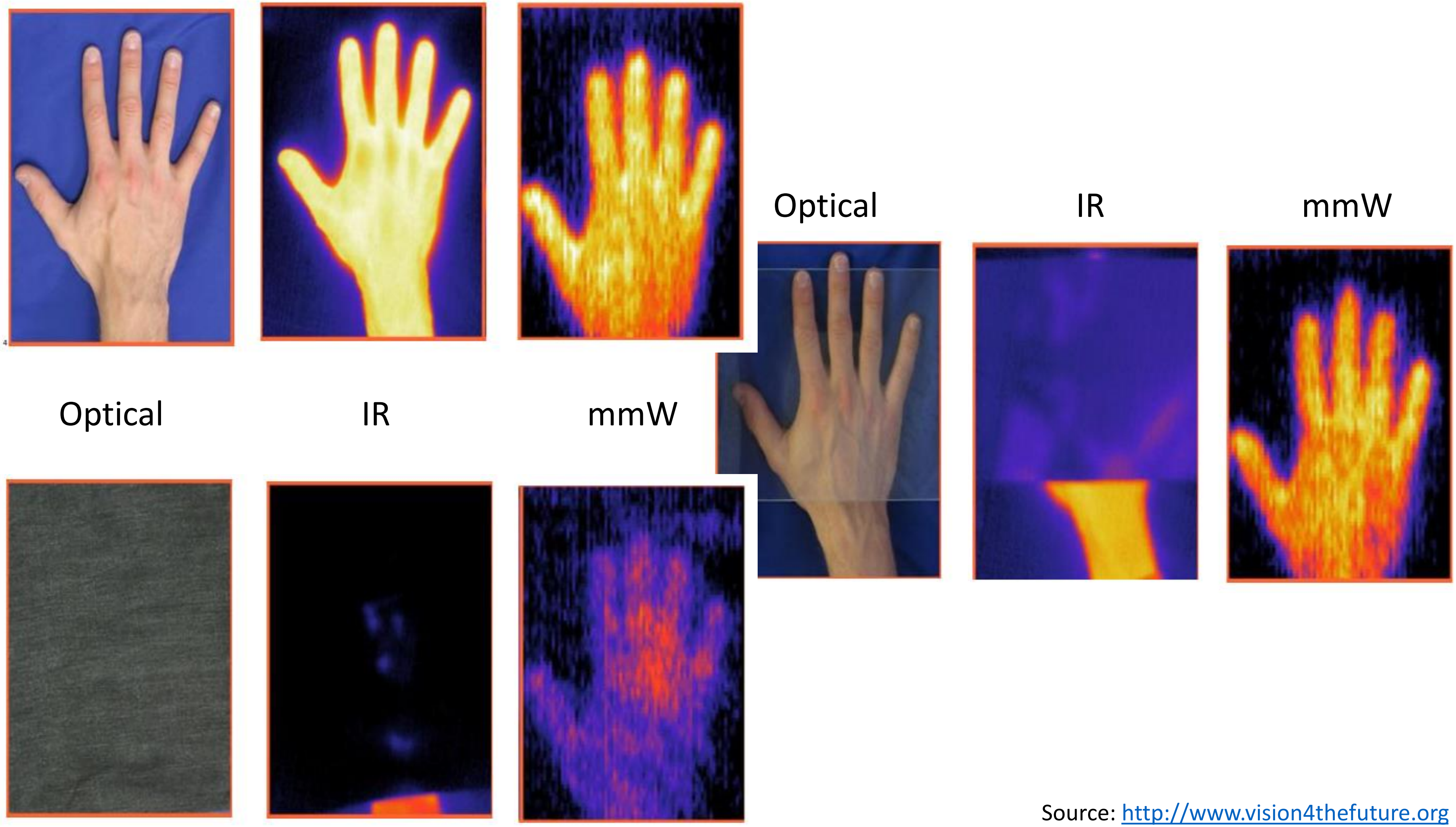
Outline of the First Part

- Introduction
  - Electromagnetic spectrum and imaging
  - Imaging tradeoffs (low frequency, high frequency, wideband, narrowband, active, passive, monostatic, bistatic, multistatic)
  - Resolution and point spread function (PSF)
  - Microwave imaging and conventional imaging modalities
- Computational Imaging
  - Frequency-diverse imaging
  - Image reconstruction algorithms
  - Metasurface antennas for computational imaging
  - Application: Imaging of human-sized objects for security-screening
    - Objects with metal and dielectric threat targets
    - Real-time acquisition and person reconstructions on the move
    - Microwave (computational) and mmW (spotlight) sensor fusion example

Electromagnetic Spectrum and Imaging



Electromagnetic Spectrum and Imaging



Source: http://www.vision4thefuture.org

Low Frequency vs High Frequency

- Low frequency
  - Advantages:
    - Mature and low-cost component technology (off-the-shelf)
    - Better propagation
  - Disadvantages:
    - Low resolution
- High frequency
  - Advantages
    - High resolution
  - Disadvantages
    - High attenuation / short penetration depth in dielectric media
    - High component costs

Wideband vs Narrowband

- Narrowband Imaging
    - Advantages:
        - Simple RF backend
    - Disadvantages:
        - Poor range resolution
    - An extreme case: Single frequency imaging
- Wideband Imaging
    - Advantages:
        - Superior range resolution
    - Disadvantages:
        - Complex RF backend

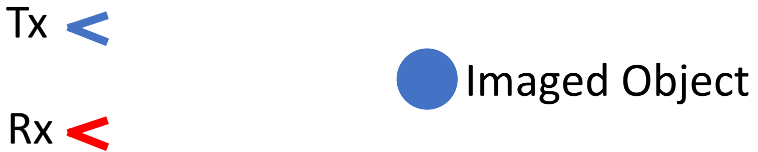
Active vs Passive

- Active Imaging
  - An active radar system relies on illuminating the imaged object and measuring the back-scattered radar signal. It requires transmit and receive antennas.
  - Advantages:
    - Superior signal-to-noise (SNR)
  - Disadvantages:
    - Requires a transmit unit as well as a receive unit
    - Requires higher power and exhibits more complex system architecture
- Passive Imaging
  - Advantages:
    - Only the receiver unit is required. No active illumination is needed.
  - Disadvantages:
    - Low SNR. Extremely sensitive receiving unit is needed at very low signal levels (a common technique is increasing the integration time).

Radar Layout

- For an active radar, depending on the orientation of the transmit and receive antennas and the data acquisition structure, a radar is said to be “monostatic”, “bistatic” or “multi-static”.
- A monostatic radar uses the same antenna aperture to transmit and receive. Alternatively, it can use two antennas that are close to each other in a so-called “quasi-monostatic” layout.

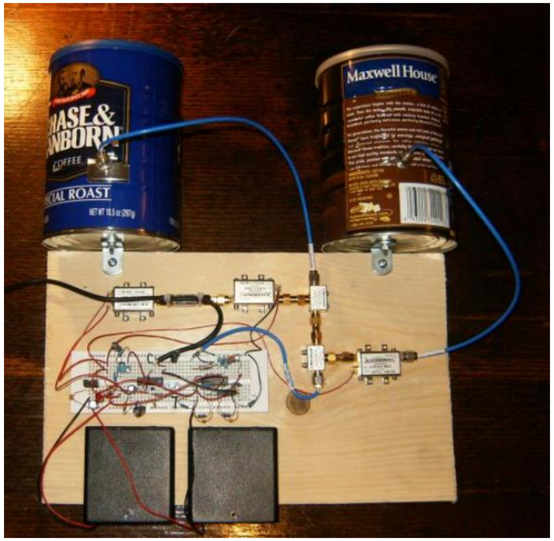
- A bistatic radar uses two antennas; one transmit and one receive to perform imaging.

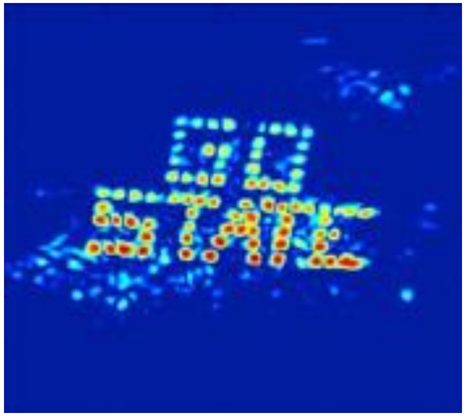


- A multi-static radar uses multiple transmit and receive antennas to perform imaging. They can form a multiple-input-multiple-output (MIMO) layout, which has found numerous applications, not only in imaging but also in 5G recently.

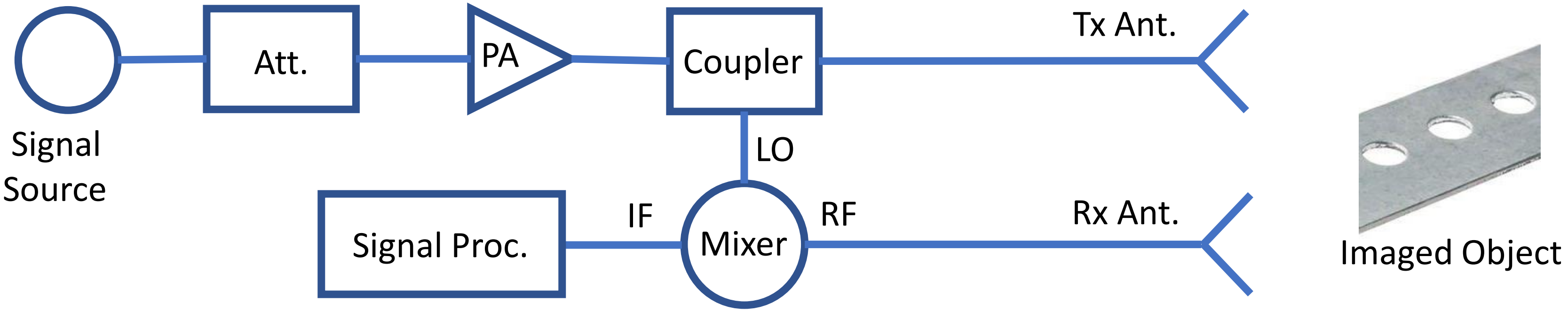
Microwave Radar Architecture

- Anybody can build a radar using off-the-shelf components!
- Below is a picture of a FMCW radar using that operates at 2.4 GHz.





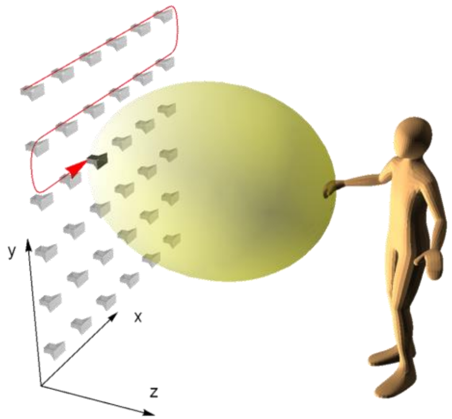
- A typical radar block diagram is seen below.



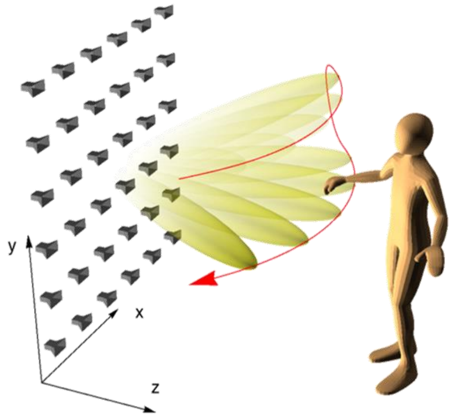
Conventional Imaging Examples

- Synthetic aperture radar (SAR) is a very common way to image a scene. Most commonly, a SAR aperture is synthesized by means of a *mechanical raster scanning* process.
- Alternatively, switching mechanisms and all-electronic beam synthesis can be used.
- Both these techniques have pros and cons.

Synthetic Aperture



Phased Array



OBTAINING MEASUREMENTS

› Steerable antennas can provide direct illumination of regions over a volume, but costly for entire active aperture.

› Synthetic aperture radar techniques avoid phase shifters, use switching or mechanical scanning.

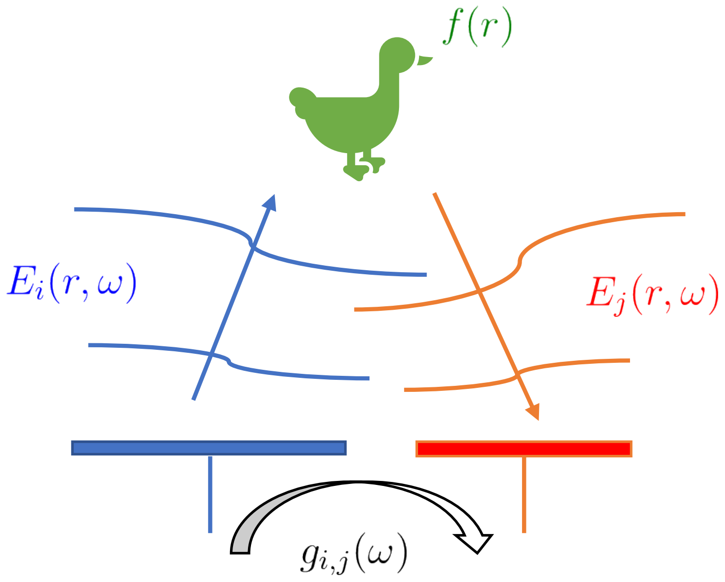
Imaging Problem

General description of the forward model

a measurement corresponds to the interaction between electromagnetic fields and a target characterized by a reflectivity function

$$g_{i,j}(\omega) \propto \int_r [E_i . E_j](r,\omega) f(r)\, d^3 r$$

$g_{i,j}(\omega)$	measured frequency-domain signal
$E_i(r,\omega)$	Tx electric field
$E_j(r,\omega)$	Rx electric field
$f(r)$	reflectivity function ($\Delta\varepsilon(r)$)

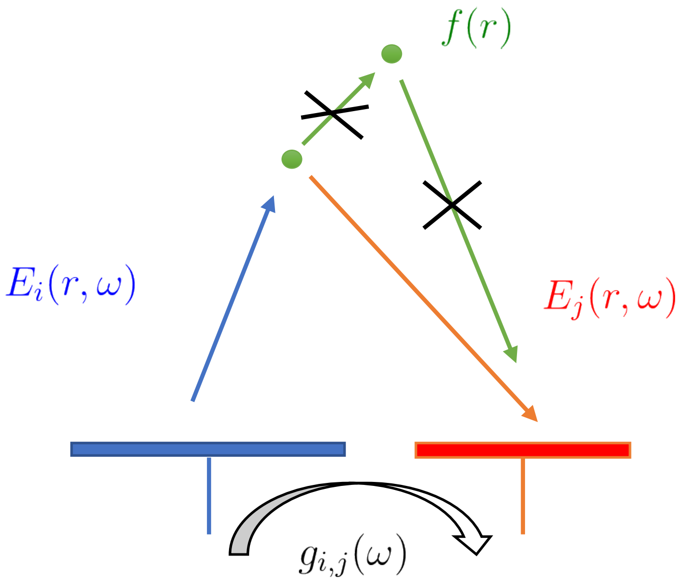


Approximations

- Scalar fields and reflectivity
- No direct coupling effect between Tx and Rx
- Linearization of Maxwell equations (weak scattering)

First-Born Approximation

- The forward model presented below exhibits a fundamental simplification to the imaging problem.
- This simplification is a linearization process known as the first Born approximation.
- First Born approximation assumes that the total field within the region of interest can be modeled as the incident field as opposed to incident field + scattered field (or total field).
- The first Born approximation makes the assumption that the total field is not perturbed by the scattered field.



$$\mathbf{g}_{Mx1} = [\mathbf{E}^{Tx}_{MxN}\mathbf{E}^{Rx}_{MxN}]\mathbf{f}_{Nx1} + n$$

$$\mathbf{E}_{total} = \mathbf{E}_{inc} = \mathbf{E}_{Tx}\mathbf{E}_{Rx}$$

Linearized with First Born approximation

Simulation of a simple 2D imaging system

Single Input Multiple Outputs (SIMO) system

Code available here
https://bit.ly/2Jbfdfn

Starting from the forward model

$$g_{i,j}(\omega) \propto \int_r [E_i . E_j](r,\omega) f(r)\, d^3r$$

the model is simplified considering isotropic sources and a point target:

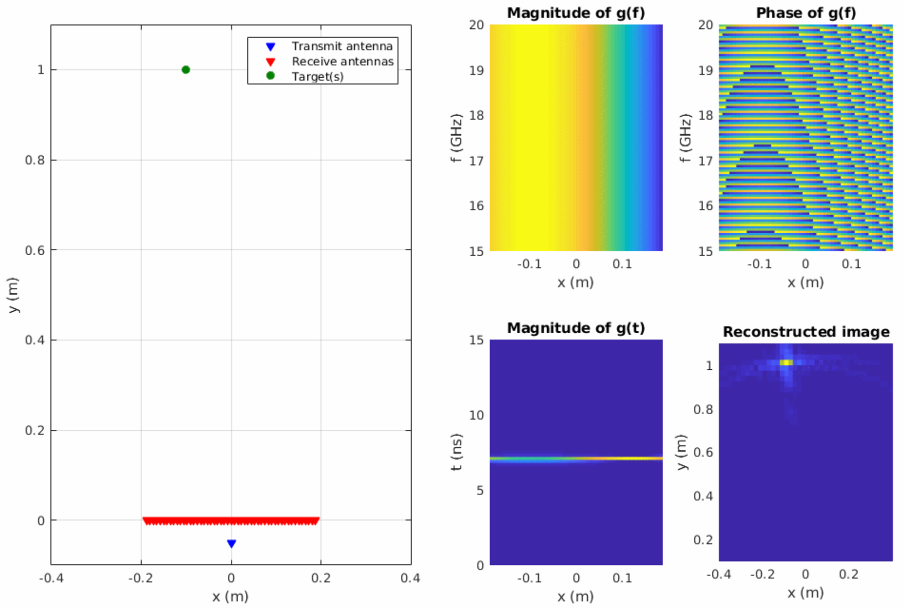
$$E_i = G(r, r_i)$$ for 1 Tx antenna

$$E_j = G(r, r_j)$$ for 101 Rx antennas

$$f(r) = \delta(r - r_C)$$

with the Green's function defined as

$$G(r, r') = \frac{\exp(-j\frac{2\pi f}{c}|r - r'|)}{|r - r'|}$$



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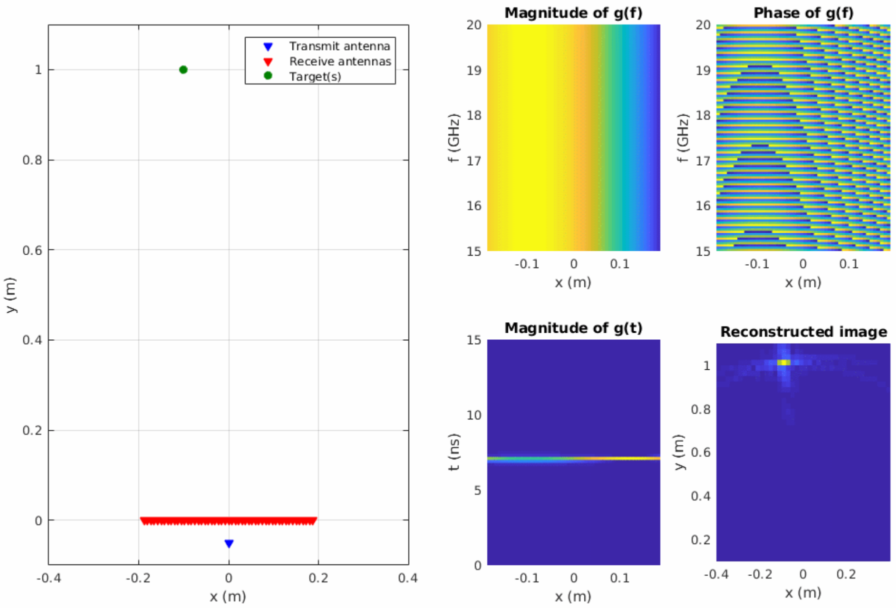
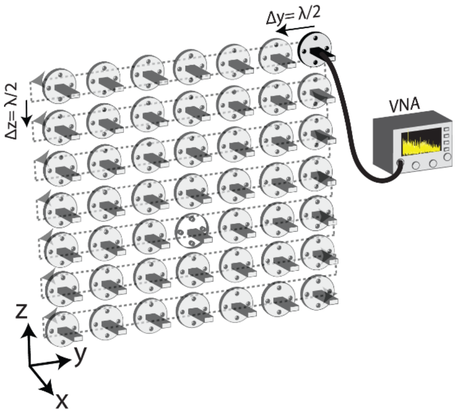
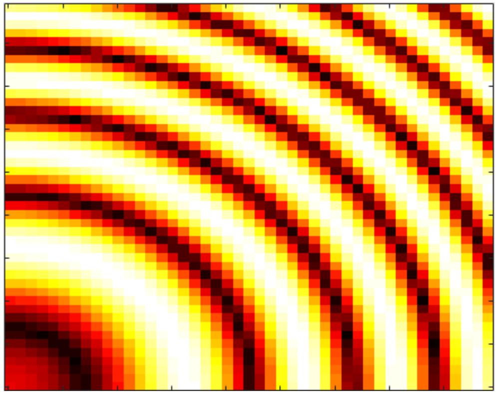


Imaging Problem

- In this example, we consider the mechanical raster scanning scenario.
  A 10 cm x 10 cm aperture is synthesized at the Nyquist limit ($\lambda/2$) and a single waveguide antenna is moved point-by-point.
- The SAR aperture depicted in this example performs a point-by-point scanning of the scene.

*The synthesized aperture consists of 18*18=324 sampling points (or individually switched antennas) .*





- The received signal can be expressed as follows. This is also known as the *forward-model*.

$$g_{i,j}(w) = \int_{\mathbf{r}} E_{Tx}(\mathbf{r_t},\mathbf{r};w)E_{Rx}(\mathbf{r_r},\mathbf{r};w)\, f d^3\mathbf{r}$$

- For this scenario:

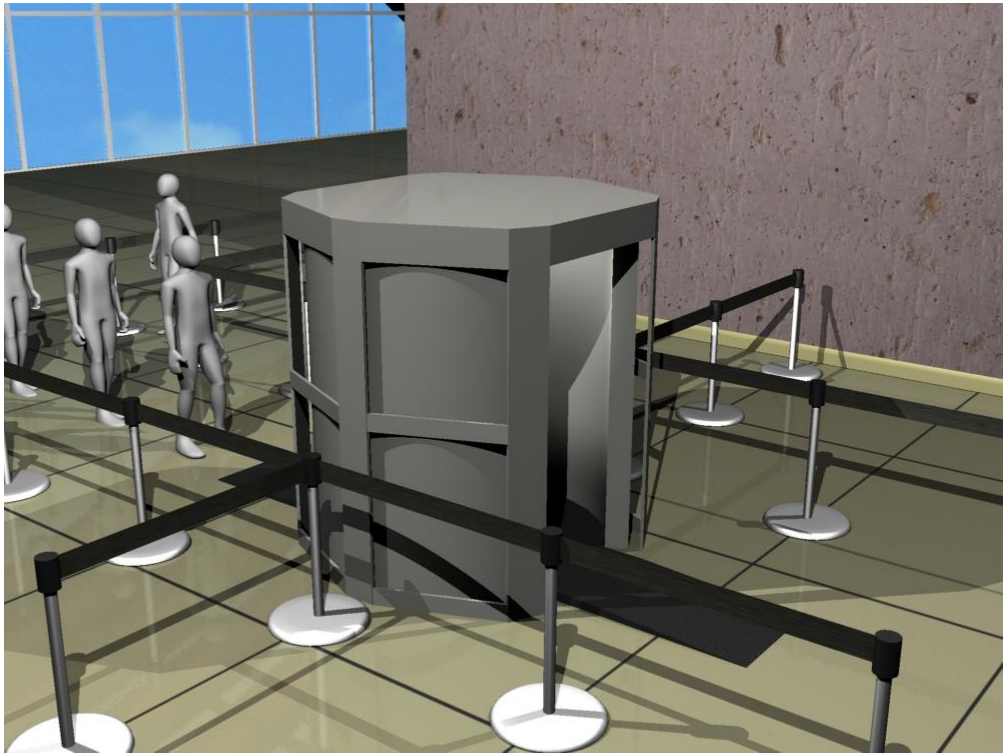
$i=j$

$E_{Tx}=E_{Rx}$

$\mathbf{r}_t$: transmit coordinates
$\mathbf{r}_r$: receive coordinates
r: scene coordinates
f: reflectivity
w: frequency
E: E-field in scene

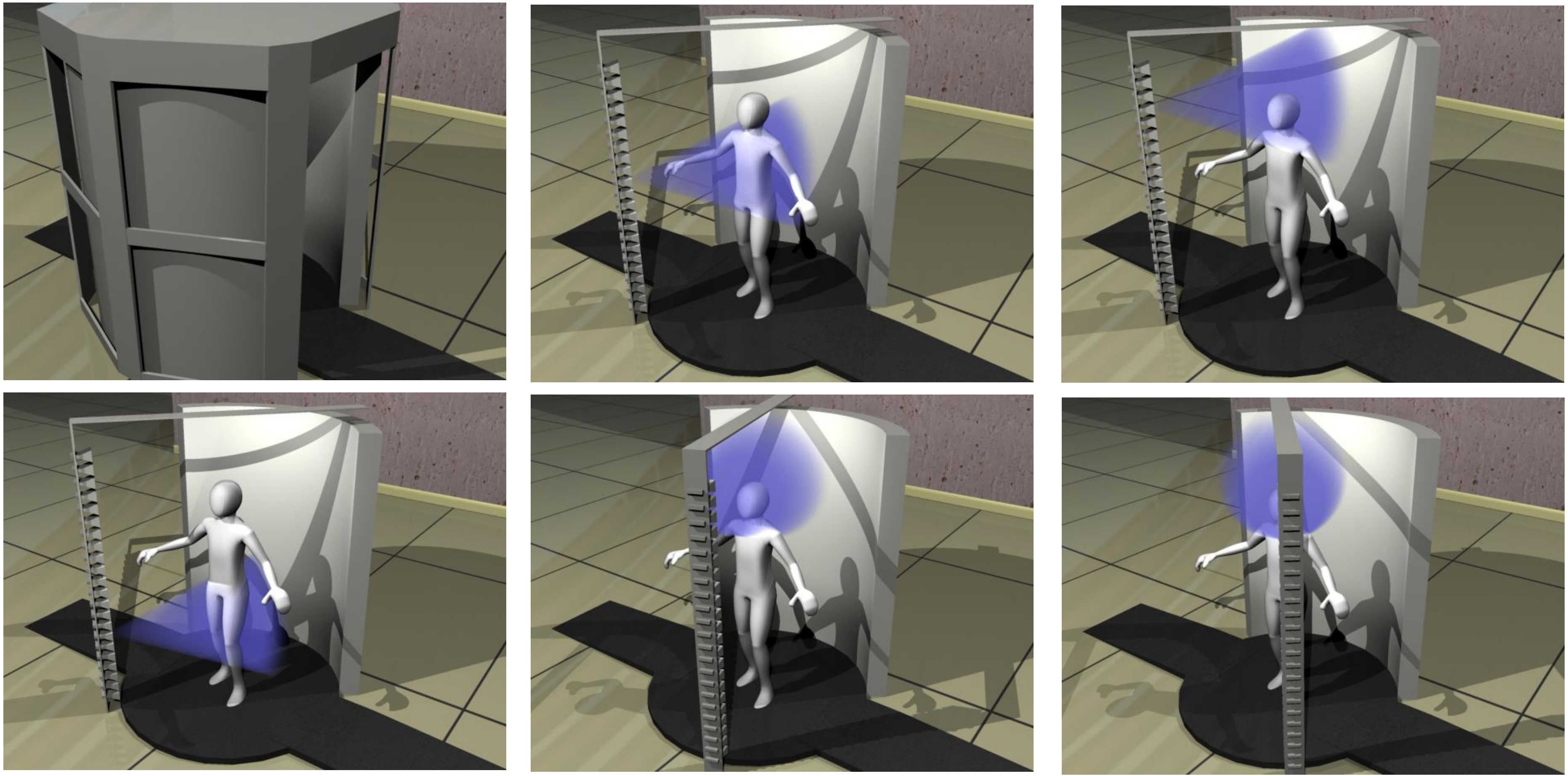
Imaging Problem

- An example imaging problem: Security-screening.
- A cylindrical aperture is synthesized by means of mechanical scanning a vertical antenna array.



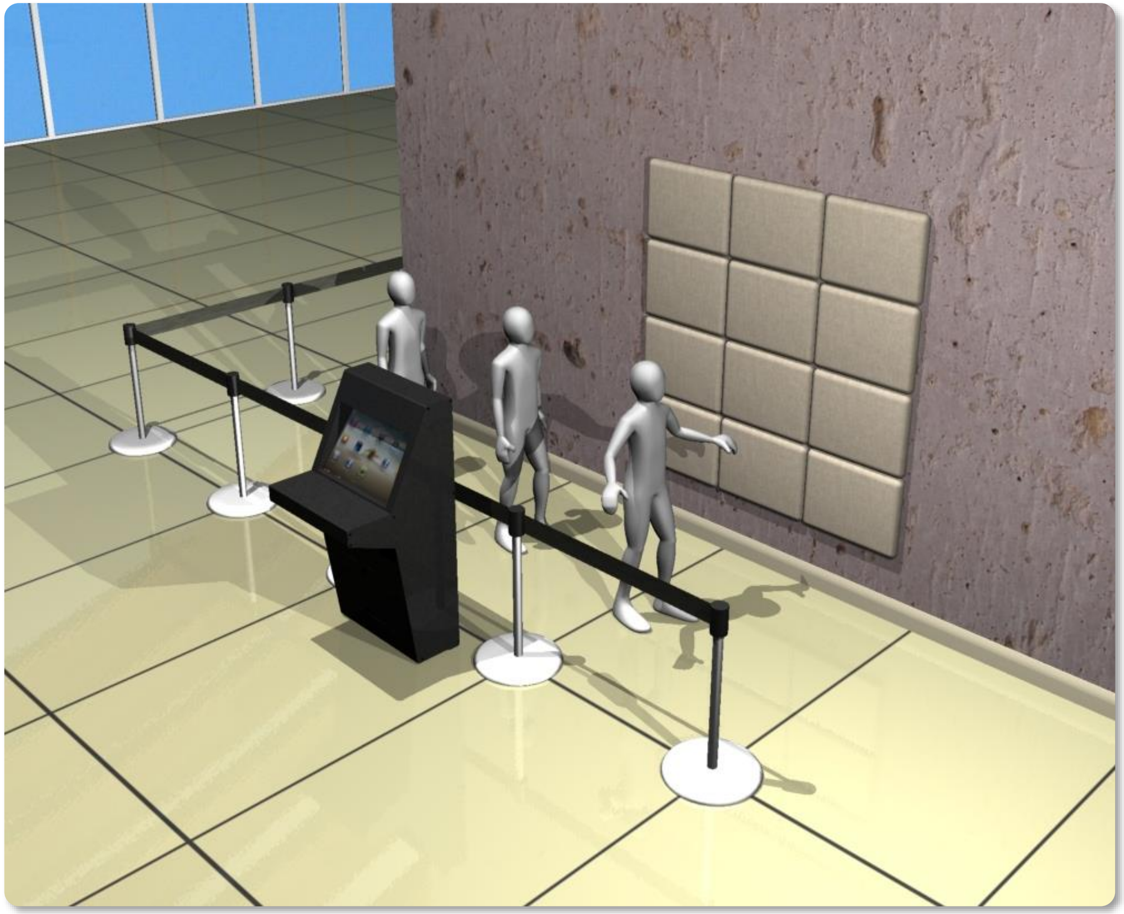
Current Airport Security Screening Checkpoints

- A cylindrical aperture is synthesized by means of mechanical scanning a vertical antenna array.
- This type of data acquisation, albeit being simple, is not real-time.



Motivation for Computational Imaging

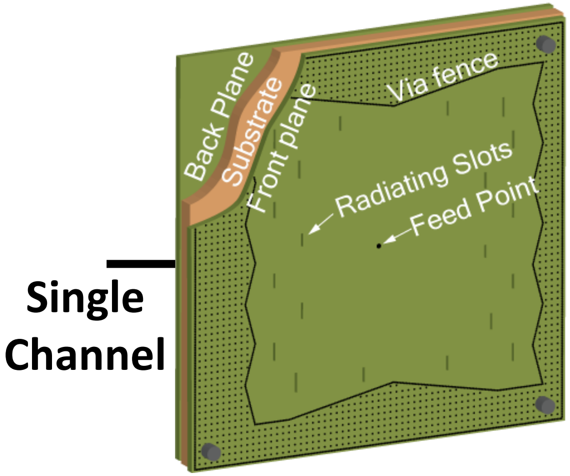
- Data acquisation and image reconstruction in real-time?
- Needs a more clever approach to imaging.



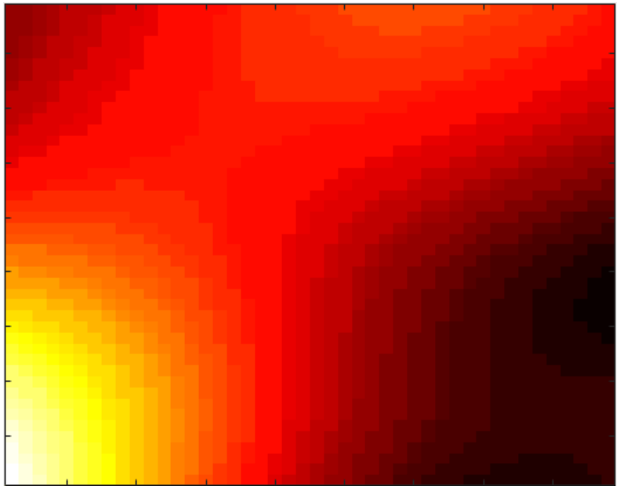
Encoding Scene Information using a Single Channel?

- A significant simplification in the hardware layer can be achieved by radiating coded wave patterns and compressing the back-scattered signal in the physical domain.
- This is as opposed to raster scanning the scene to do point-by-point imaging.

Antenna for Computational Imaging



Antenna Radiated Fields



$$g_{i,j}(w)=\int_{\mathbf{r}} E_{Tx}(\mathbf{r_t},\mathbf{r};w)E_{Rx}(\mathbf{r_r},\mathbf{r};w)\; fd^3\mathbf{r}$$

Imaging Equation

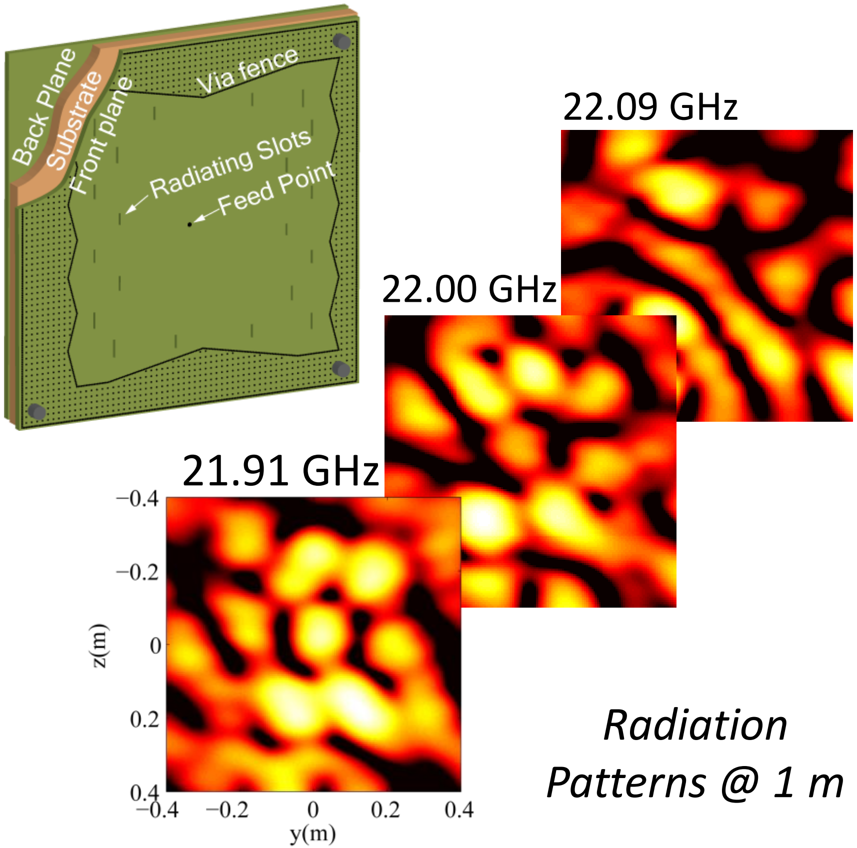
Coded field patterns projected to scene

Frequency Diverse Metasurfaces

- One way to acheieve coded field patterns is to use frequency-diversity. Frequency-diversity is a technique to radiate spatially-incoherent radiation patterns as a function of frequency.

CAVITY BACKED METASURFACE PANEL

- Copper clad circuit board plus via fence boundary form a 2D irregularly shaped dielectric cavity
- Back-fed cylindrical coplanar waveguide mode scatters and mixes in the cavity
- Distribution of irises in the PCB radiate a complex waveform that is a function driving frequency
- *These metasurfaces generates a set of highly frequency diverse field*

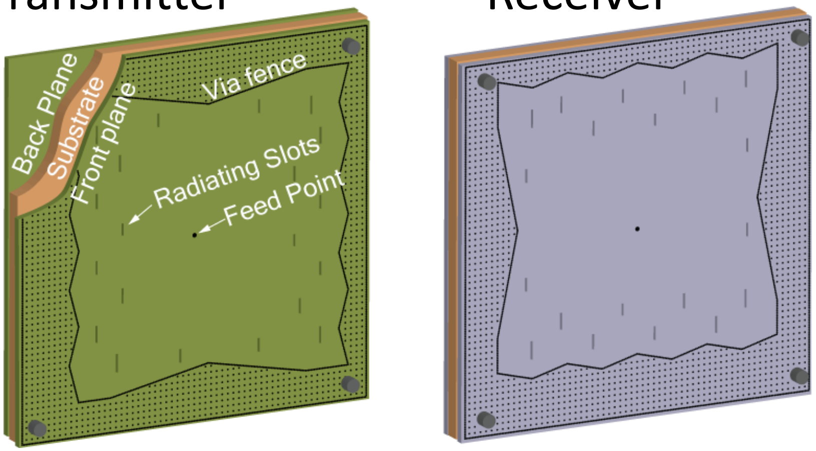


Radiation Patterns @ 1 m

Measurement Masks

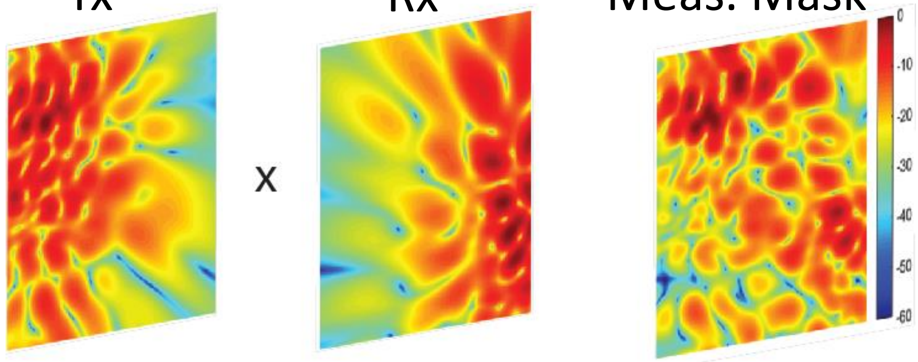
- Let us now consider the forward-model under the context of frequency-diverse antennas.

Transmitter Receiver



- Operation at 100 Frequencies across the K-band (18-26.5 GHz)
- Panel size: 10 cm x 10 cm
- 1 channel per aperture instead of 324.

Tx Rx Meas. Mask



Generated waveform (@ 1 m, 22 GHz)

$$\mathbf{g}_{Mx1} = \underbrace{[\mathbf{E}^{Tx}_{MxN}\mathbf{E}^{Rx}_{MxN}]}_{\text{Measurement Matrix } (\mathbf{H})}\mathbf{f}_{Nx1} + n$$

$$\mathbf{g}_{Mx1} = \mathbf{H}_{MxN}\mathbf{f}_{Nx1}$$

†*M*: Number of measurements
N: Number of voxels

Image Reconstruction

- A number of algorithms (linear and non-linear) can be used for image reconstruction.
- Pseudo-inverse:

$$f_{est} = H^{+} g \xrightarrow{\qquad\qquad} f_{est} = H^{+}(Hf + n)$$

- Matched filter:

$$f_{est} = H^{\dagger} g$$

- Least-Squares: Iterative solution.

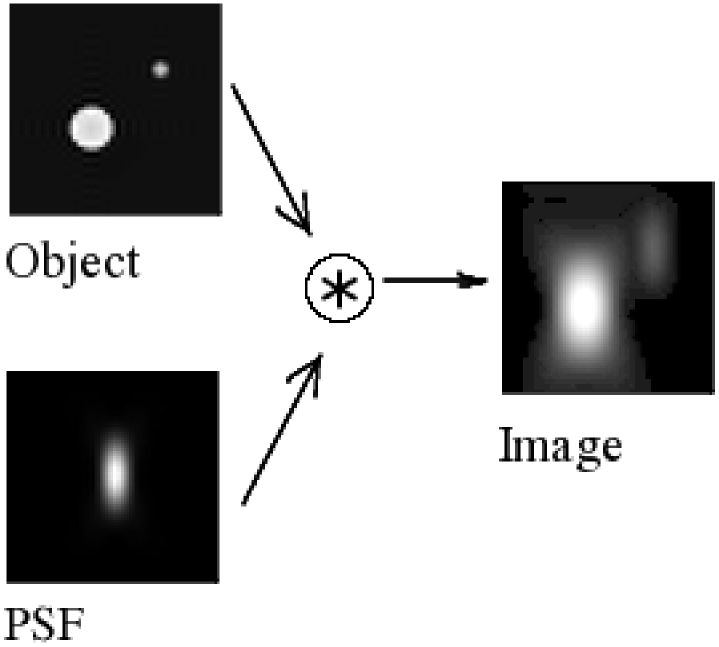
$$\arg\min \left\| g - Hf_{est} \right\|_2^2 \xrightarrow{\text{Regularization}} \left\| H^{\dagger} g - (H^{\dagger} H + \mu I) f \right\|_2^2$$

- TwIST+TV – Iterative solution - requires scene sparsity as prior.

$$0.5\left\| g - Hf \right\|_2^2 + \underset{\substack{\Big\downarrow \\ \text{Sparsity}}}{\lambda R(f)}$$

Point Spread Function

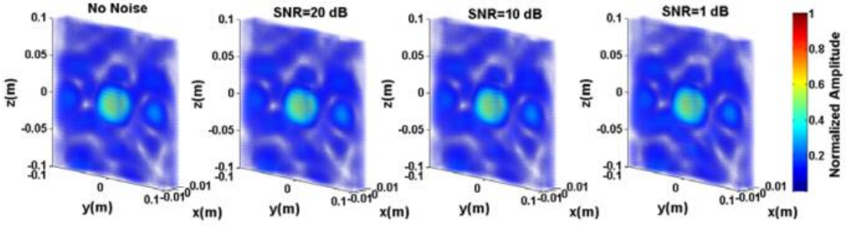
- Point-spread-function (PSF) determines the response of an imaging system to a point source.
- It is an important metric to analyse how much a point source spreads out in reconstructed images and hence the diffraction limited resolution characteristics of the imager.
- Knowing the resolution limit plays a crucial role in knowing the minimum detectable feature size in reconstructed images.



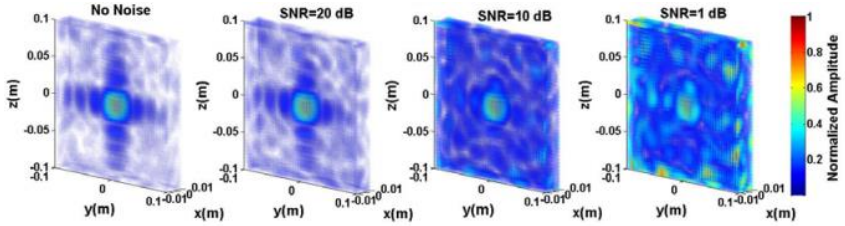
Source: https://en.wikipedia.org/wiki/Point_spread_function

Point Spread Function

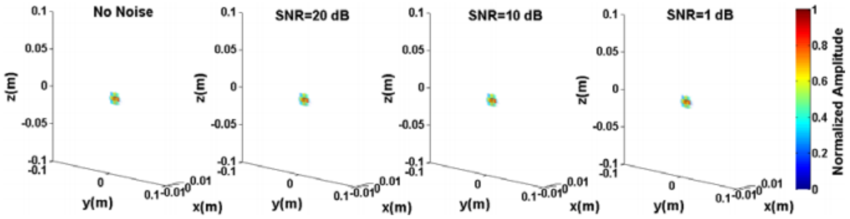
- Matched-filter is a single-shot reconstruction technique and is known to be resistive to noise in measurements. Below is the PSF pattern of a frequency-diverse imaging system reconstructed using the matched filter technique as a function of noise.



- Least-squares can be applied in an iterative manner. Reconstruction is susceptible to system noise.



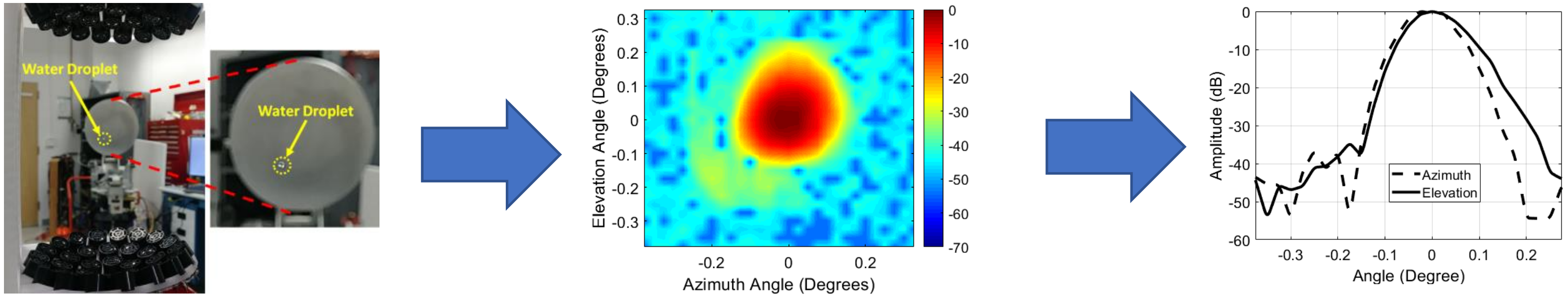
- TwIST+TV is an iterative technique and requires a strong prior, such as sparsity.



Source: Yurduseven, O., Imani, M.F., Odabasi, H., Gollub, J., Lipworth, G., Rose, A. and Smith, D.R., 2015. Resolution of the frequency diverse metamaterial aperture imager. *Progress In Electromagnetics Research*, *150*, pp.97-107.

Resolution

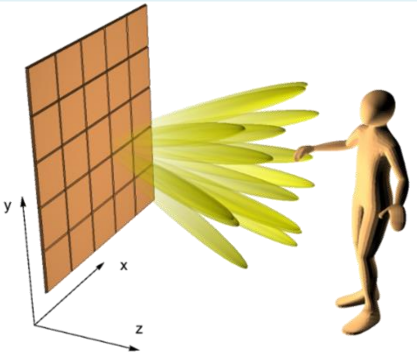
- Resolution limit of an imaging system governs the minimum feature size that we can distinguish in reconstructed images.
- For an imaging scenario, it is desired that this limit is as small as possible.
- There are two different resolution limits we can define:
  - Range resolution: The resolution along the optical axis is defined as the range resolution. Considering a typical imaging scenario, this is in the direction from the imaging aperture to the imaged object.
  - Cross-range resolution: The resolution in the plane parallel to the aperture plane is known as the cross-range resolution.
  - There are other types of terminologies used for resolution definition, such as angular resolution, depth resolution, lateral resolution etc. All these terms can be traced back to the range and cross-range resolution limits.
- Several techniques can be used to improve the imaging resolution:
  - Reducing the imaging distance
  - Increasing the operating frequency band
  - Increasing the operating frequency
- How do we determine resolution?
  - The most common way to determine the resolution limit of an aperture is to analyse the PSF patterns. The full-width-half-maximum (FWHM) of the PSF pattern in range and cross-range planes is a widely used technique in the literature to determine the resolution limit.



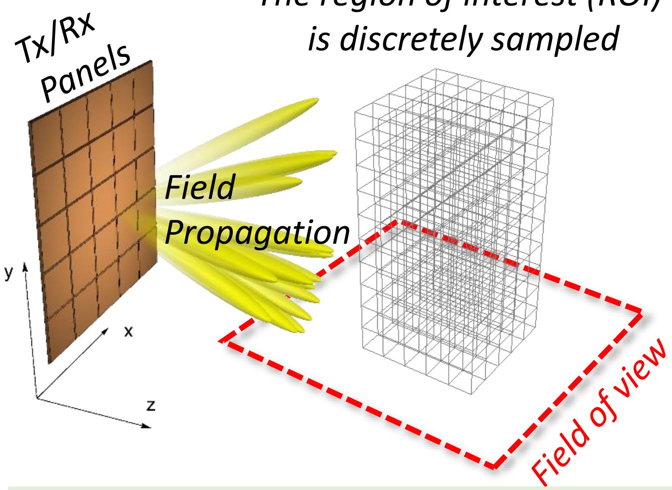
Source: Yurduseven, O., Cooper, K. and Chattopadhyay, G., 2018. Point-Spread-Function (PSF) Characterization of a 340-GHz Imaging Radar Using Acoustic Levitation. *IEEE Transactions on Terahertz Science and Technology*, *9*(1), pp.20-26.

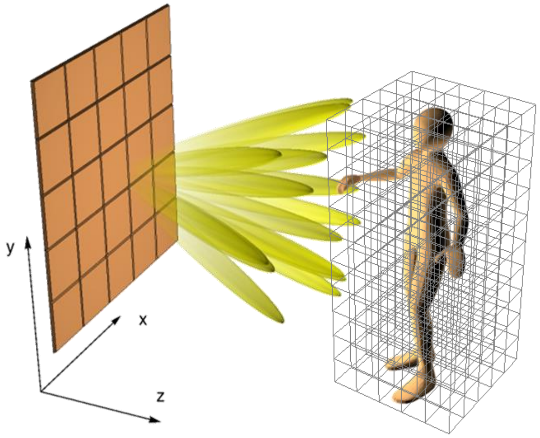
Image Formation within the Computational Approach

The Imaging problem constitutes finding the reflectivity function *f(x, y, z)* of the scene:



The region of interest (ROI) is discretely sampled





Imaging Equation:

Finite resolution allows discrete sampling of the scene (at Nyquist)

$$g = Hf + n$$

g is the measurements vector; *f* is the reflectivity vector (voxels); and, *H is* the measurement matrix

Physical Model:

First Born Approximation:

- Free space propagation of the fields from the panels to each voxel
- Single event scattering

$$h_{ij} \approx \mathbf{E}_i^{TX}\left(\mathbf{r}_j\right)\cdot\mathbf{E}_i^{RX}\left(\mathbf{r}_j\right)$$

Reconstruction:

- Matched Filter (MF)

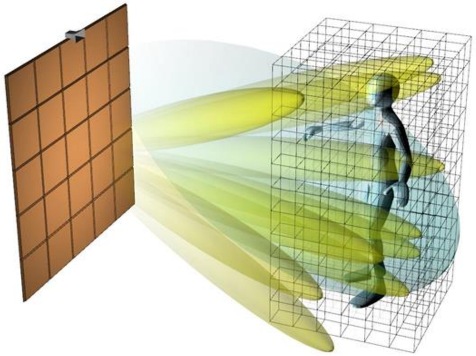
$$f = H^{\dagger} g$$

- Least Squares (LS) – Iterative approach

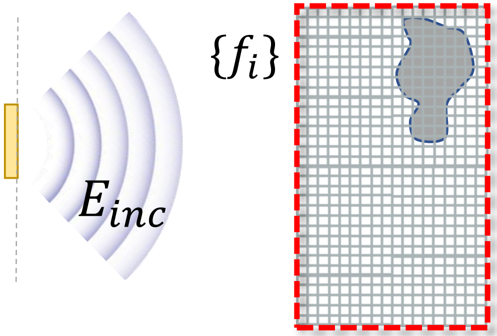
$$\hat{f} = \arg\min \| g - Hf \|_2$$

Image Formation within the Computational Approach

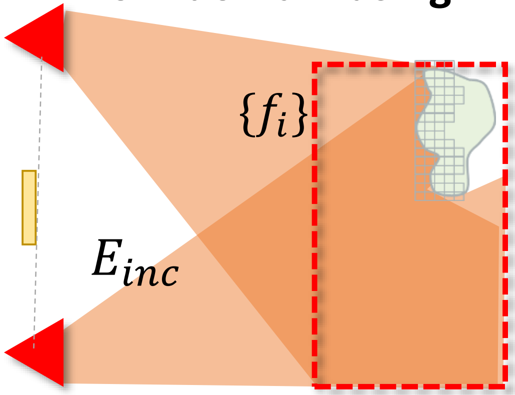
Imaging Scene



Scene domain



Region of interest, extracted from domain using Kinect



SENSOR FUSION:
IR sensor identifies the region of interest for reconstruction

Kinect

Table Parameters:

$x_{\text{range}} = 1\text{ m (Res. 1 cm)}$
$y_{\text{range}} = 2\text{ m (Res. 1 cm)}$
$z_{\text{range}} = 2\text{ m (Res. 1 cm)}$

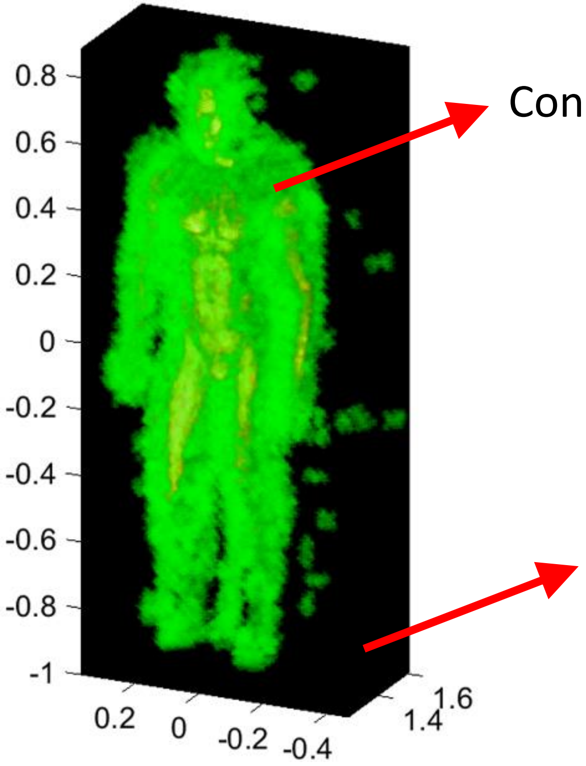
Voxels = 4,000,000

Voxels = 100,000-200,000

Constraining the Region of Interest (RoI) for Imaging

- Below is an example of sensor fusion, leveraging an optical camera to constrain the RoI for image reconstruction.

- For computational imaging, this process has two distinct advantages:
    - Reducing the number of unknowns for image reconstruction.
    - Adding a strong prior to the inverse problem by reducing the solution space.

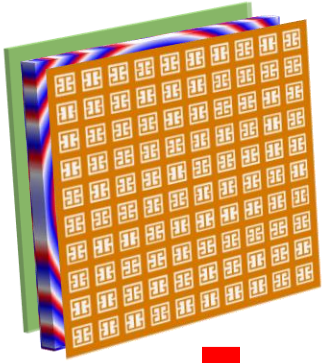


Constrained RoI

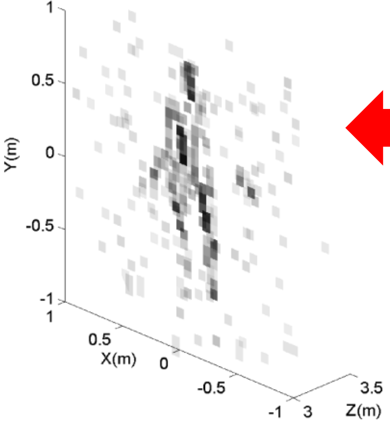
Full RoI

Computational Imaging Steps

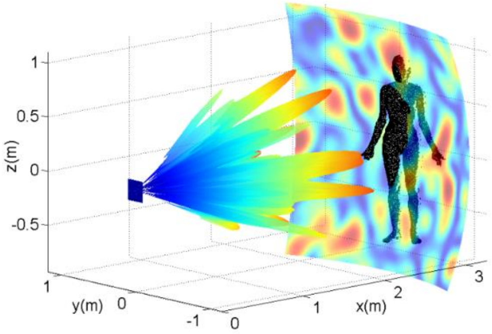
Frequency-Diverse Antenna



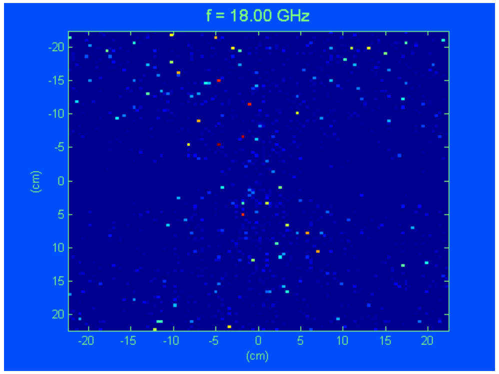
Reconstruct **(f)**



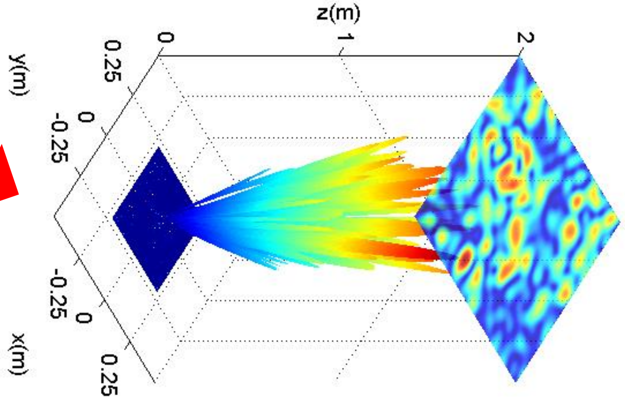
Measurements **(g)**

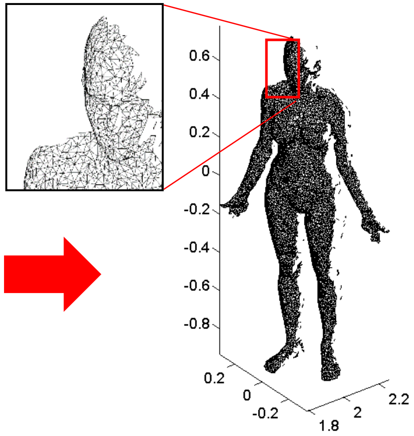


Elements Modeled as Dipoles



Propagate Dipoles to Scene





Imaged Object

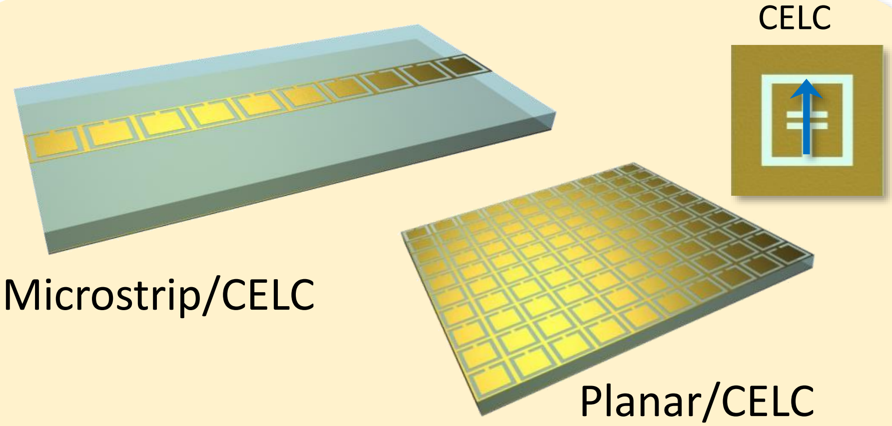
Frequency-Diverse Antennas

Designing a frequency-diverse antenna requires the optimization of certain parameters:

- Quality (Q-) factor
  - A high Q-factor suggests
    - Widened impulse response
    - Minimized correlation between the measurement modes
- Radiation efficiency
  - Governs the imaging signal-to-noise ratio (SNR)
- Antenna volume / antenna size
  - An important for the Q-factor
- Number of radiating irises (QB/f)
  - Increases the radiation efficiency
  - Reduces the Q-factor
- Distribution of irises
  - Effective aperture and sampling redundancy

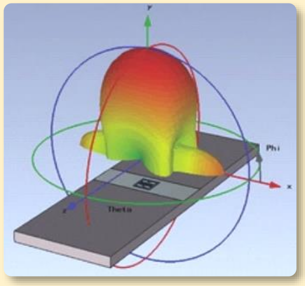
Metasurface Antennas

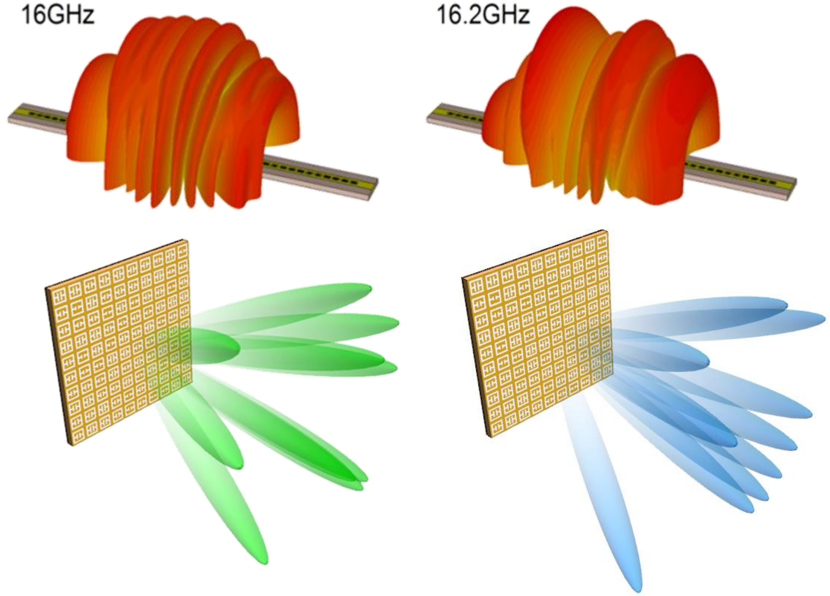
Frequency diversity: An aperture consisting of geometrically varying metamaterial elements will excite different radiation patterns.



Each element radiates as a magnetic dipole, with a geometrically dependent polarizability

$$\alpha_m(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\gamma}$$



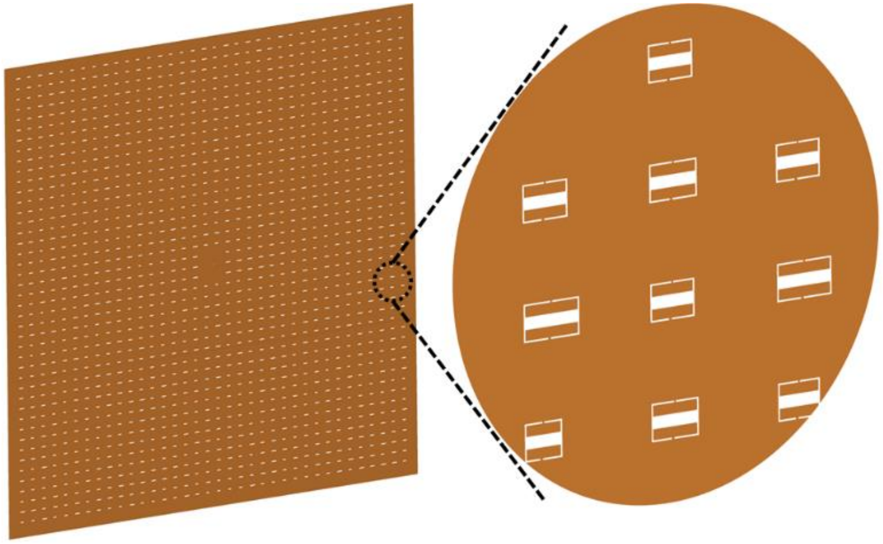


A frequency sweeps will generate a diverse set of waveforms that can be used to encode information in the scene.

Metasurface Antennas

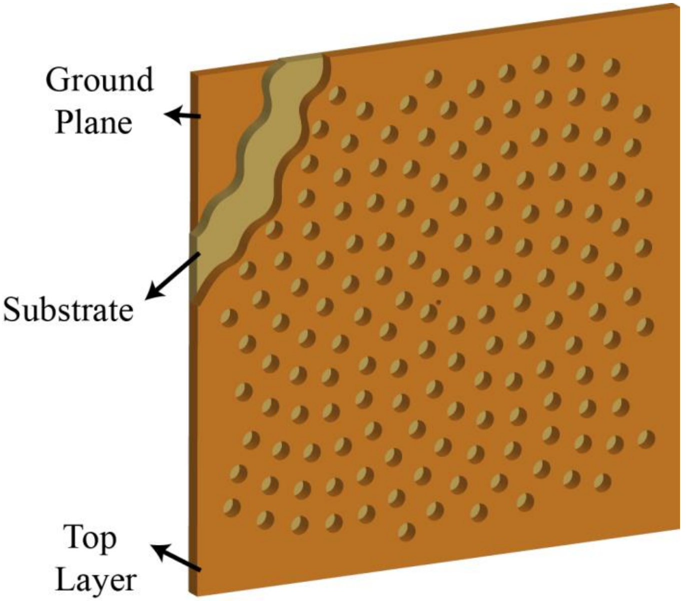
Frequency-Diversity

Method 1: cELC Antennas



- The diversity of the radiated field patterns comes from the randomized distribution of the resonance frequencies of the radiating elements.

Method 2: Cavity Antennas

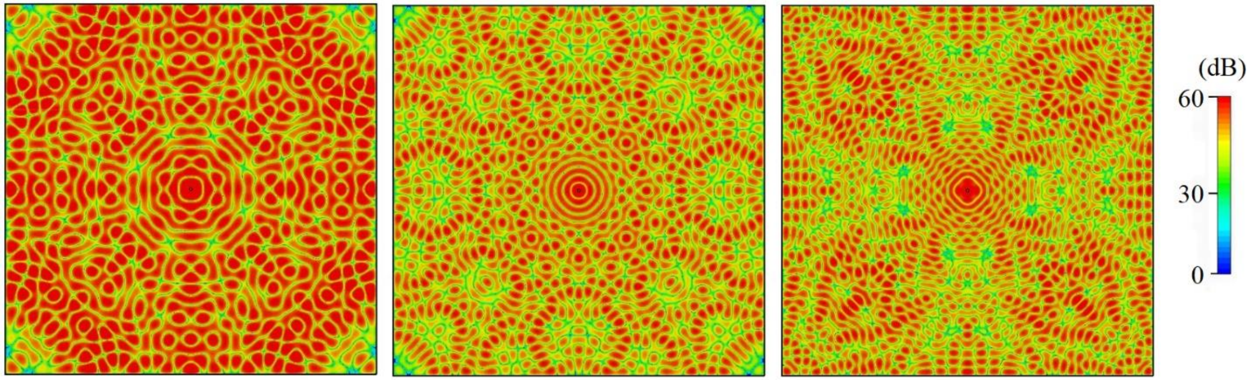


- The diversity of the radiated field patterns comes from the diversity of the guided-mode.

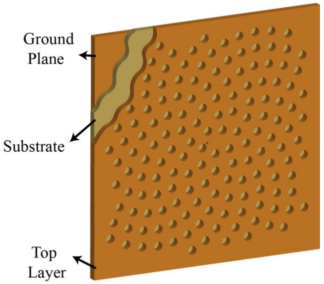
Metasurface Antennas

Method 2: Cavity Antennas

- Below are the guided-mode field patterns launched into the cavity-backed feeding structure as a function of frequency.
- The meta-elements on the metasurface layer sample these guided-mode patterns which vary as a function of operating frequency.

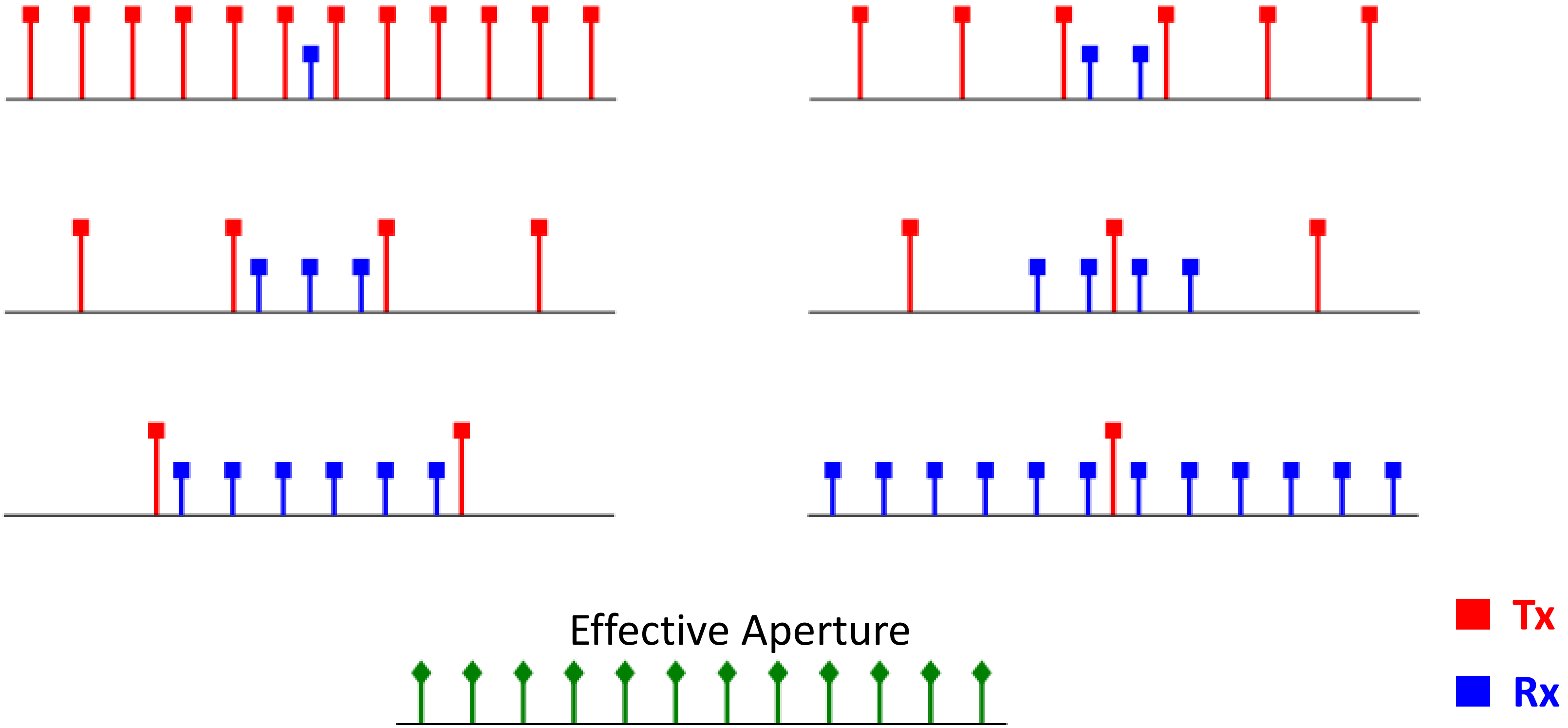


17.5 GHz 22 GHz 26.5 GHz



Effective Aperture Concept

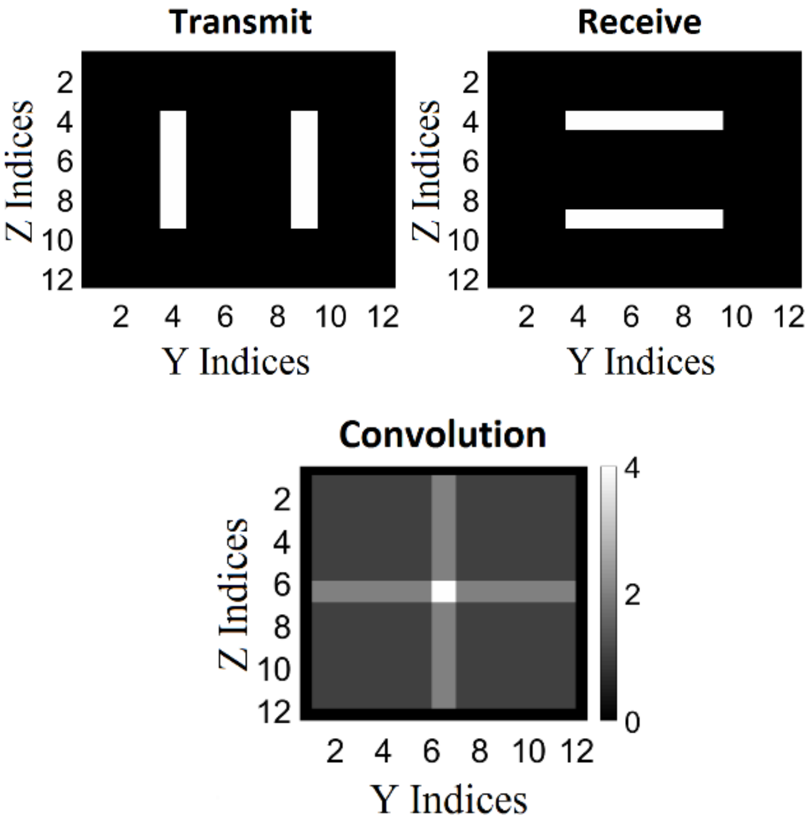
- Effective aperture of a synthesized imaging system is defined as the convolution of the transmit and receive apertures.

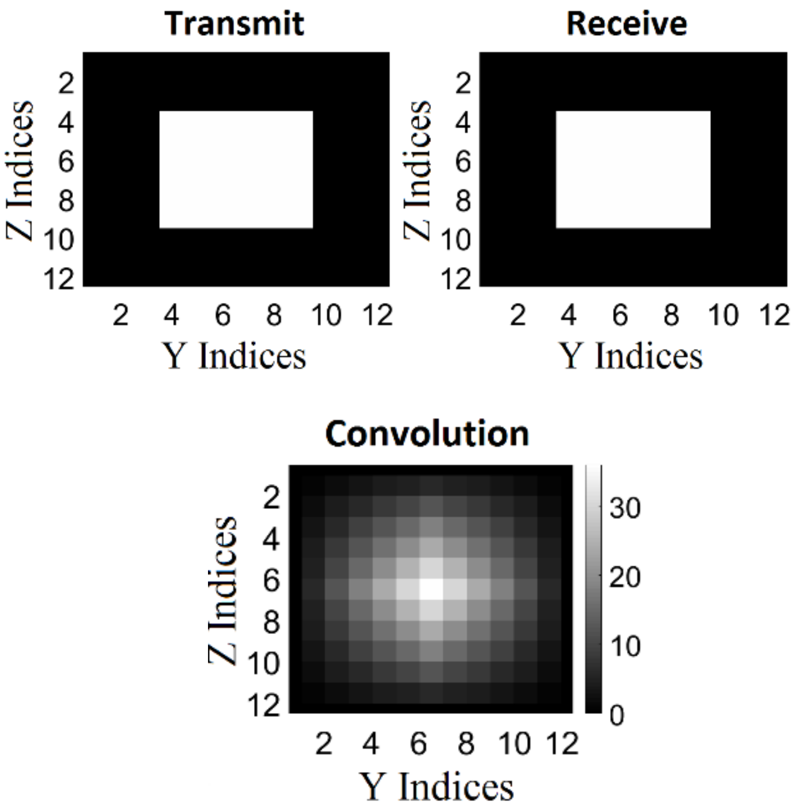


Source: Ahmed, S.S., 2014. *Electronic microwave imaging with planar multistatic arrays*. Logos Verlag Berlin GmbH.

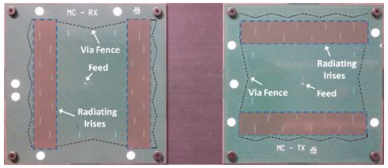
Effective Aperture Concept

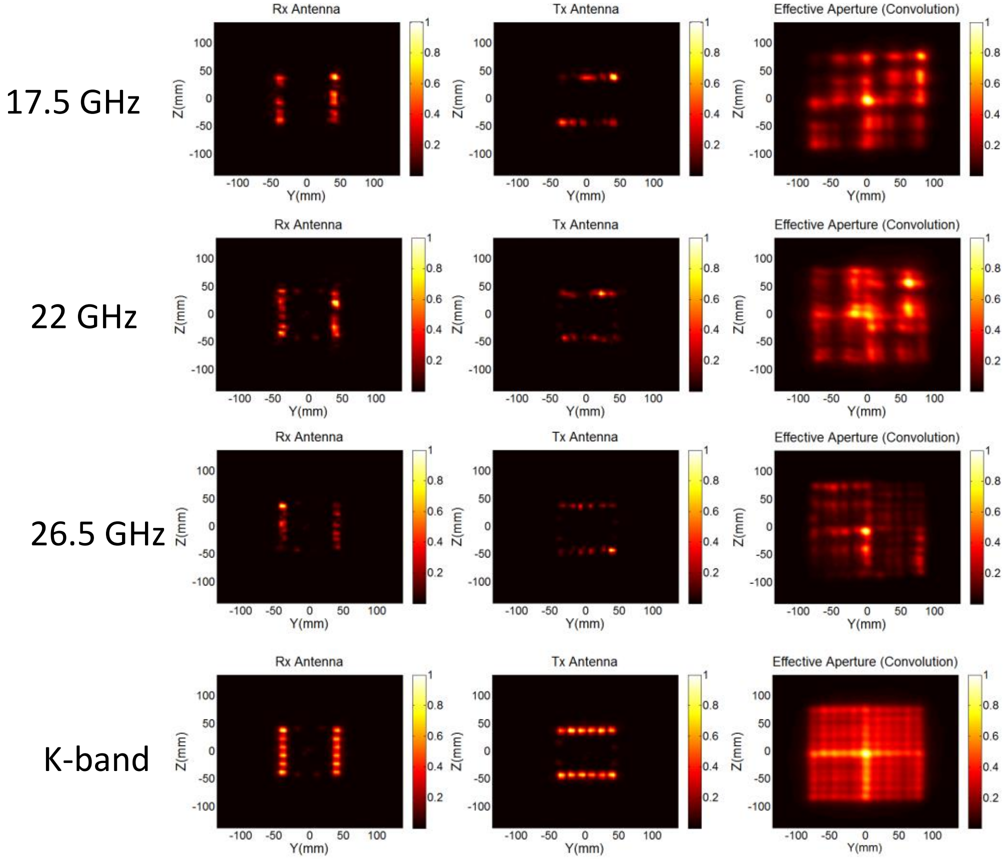
- We can use the effective aperture concept to optimize the distribution of the radiating elements on a frequency-diverse antenna aperture.
- Extent of the effective aperture and sampling redundancy are among the most important design criteria.

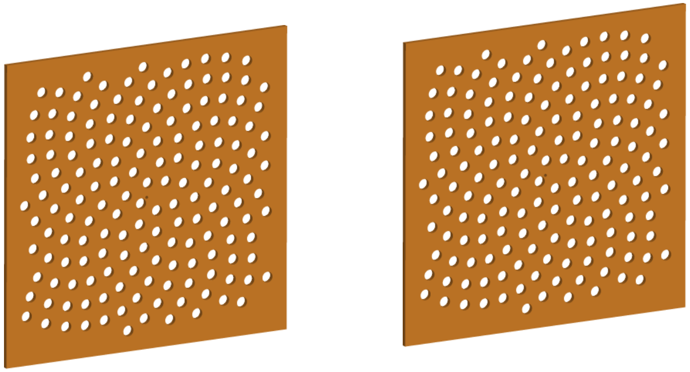


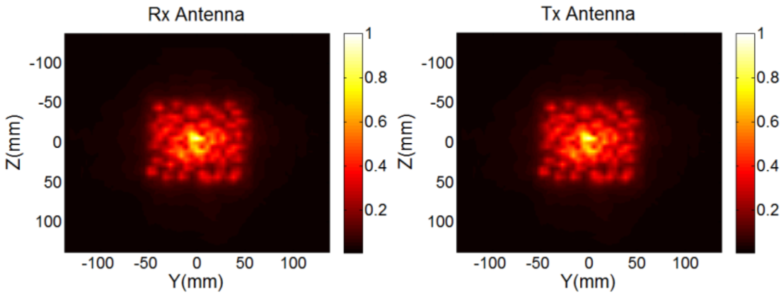


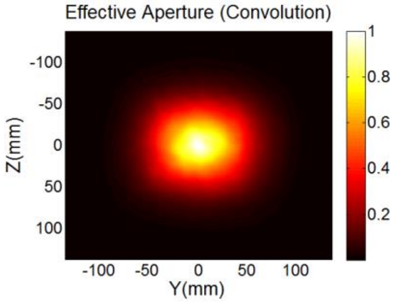
Effective Aperture Concept







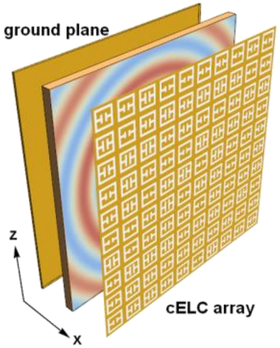


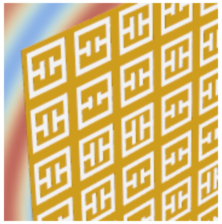


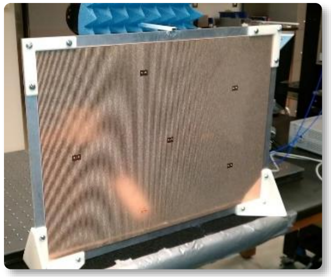
Source: Yurduseven, O., Gollub, J.N., Marks, D.L. and Smith, D.R., 2016. Frequency-diverse microwave imaging using planar Mills-Cross cavity apertures. *Optics express*, *24*(8), pp.8907-8925.

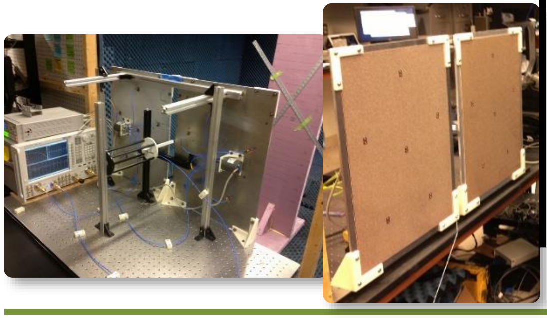
Metasurface Antenna Examples for Computational Imaging

cELC

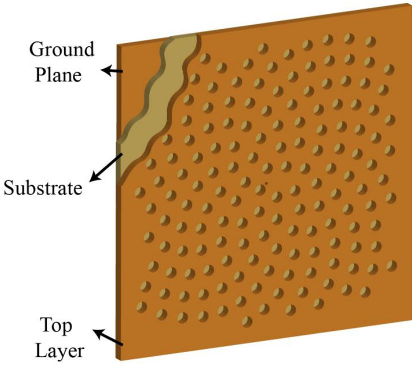


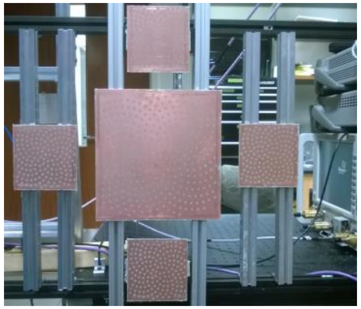




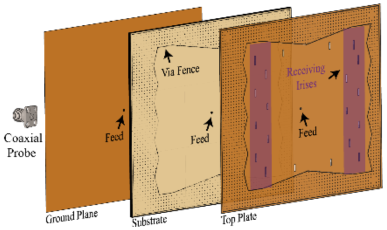


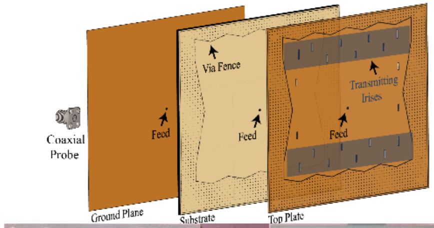
Printed Cavity

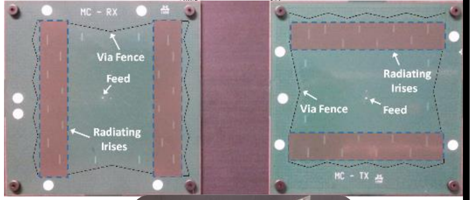


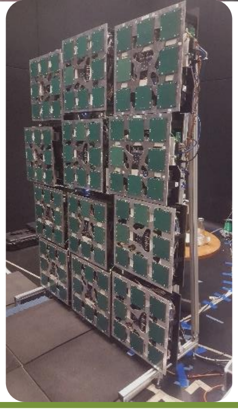


Printed MC Cavity

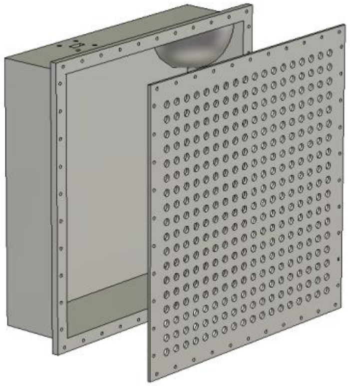


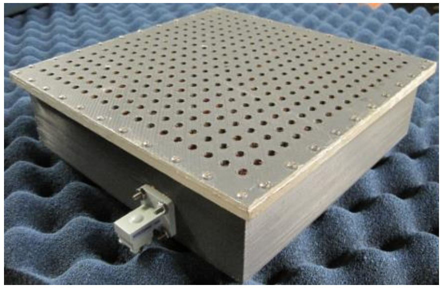


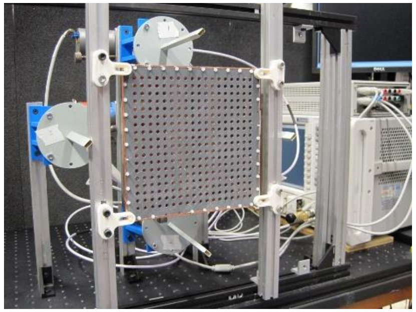




Air-Filled Cavity

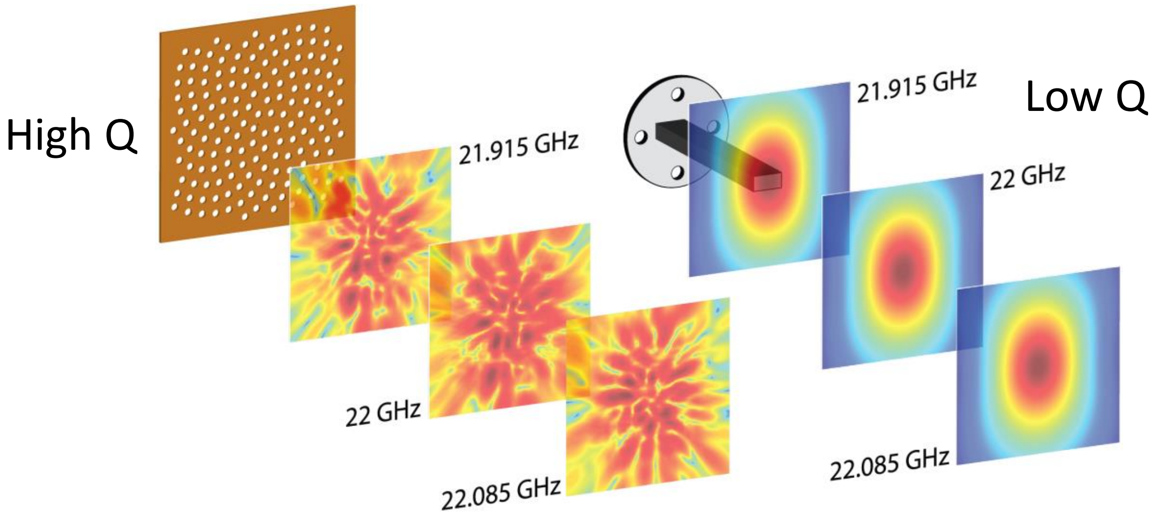






Frequency-Diversity and Q-Factor

- The quality (Q-) factor of a frequency-diverse antenna governs the orthogonality of the measurement modes.
- The Q-factor of a frequency-diverse antenna can be measured using the time-domain impulse response of the antenna. Longer impulse response suggests a higher Q-factor.
- Singular value decomposition (SVD) can be used to analyze the orthogonality of the measurement modes.
- A higher Q-factor suggests a slowly decaying singular value pattern – better conditioned measurement matrix.



Sensing Matrix and SVD

- From previous slides, we know that the sensing matrix is the element-wise product of the E-field patterns radiated by the frequency-diverse antennas and propagated to the imaged scene.

$$\mathbf{g}_{Mx1} = [\underbrace{\mathbf{E}^{Tx}_{MxN}\mathbf{E}^{Rx}_{MxN}}_{\text{Measurement Matrix }(\mathbf{H})}]\mathbf{f}_{Nx1} + n$$

- Inverse problems are conventionally ill-posed (high condition number). To analyze the conditioning of the sensing matrix, we perform an SVD analysis. Using SVD on H:

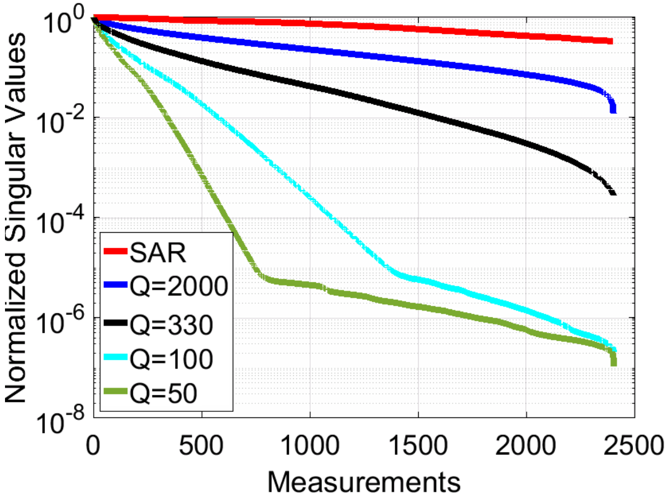
$$\mathbf{U}\underset{\substack{\Big\downarrow \\ \text{Diagonal matrix consisting of singular values}}}{\boldsymbol{\sigma}}\mathbf{V}^* = \mathrm{SVD}(\mathbf{H})$$

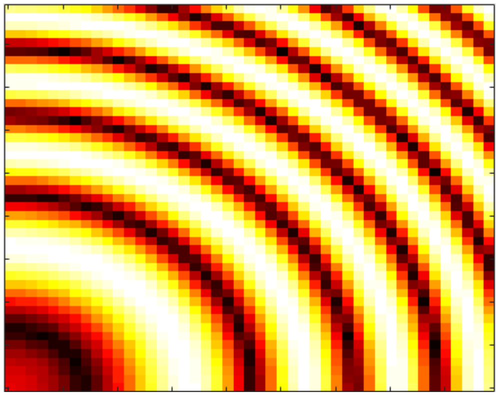
Sensing Matrix and SVD

$$\mathbf{U}\boldsymbol{\sigma}\mathbf{V}^* = \mathrm{SVD}(\mathbf{H})$$

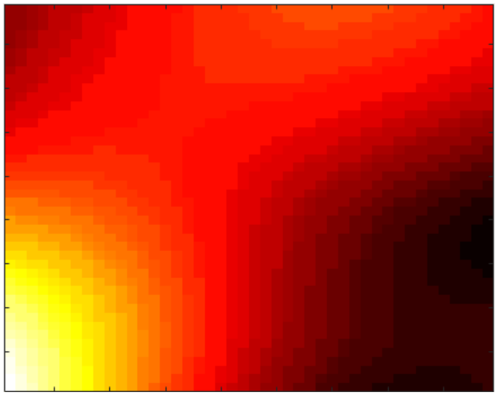
Diagonal matrix consisting of singular values

- Below is an example of singular value pattern as a function of Q-factor.





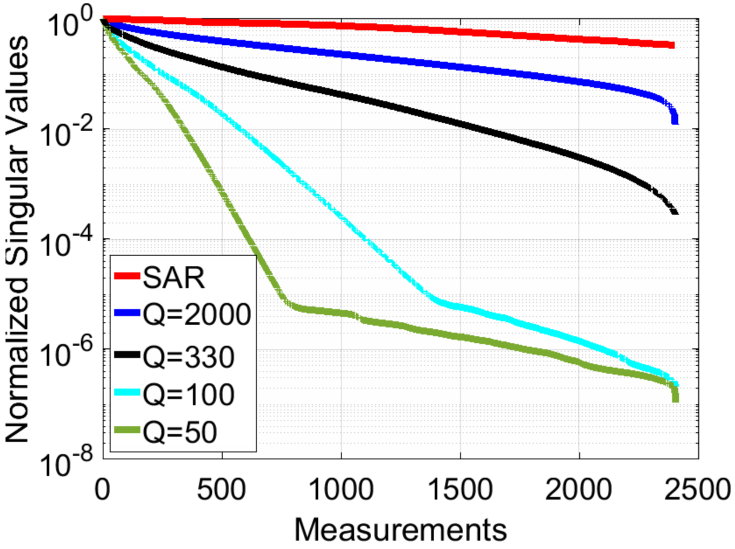
SAR



Frequency-Diverse (*Q*=330)

Sensing Matrix and SVD

- A fast decaying SVD pattern suggests a high correlation between the field patterns radiated by the frequency-diverse antenna as a function of frequency.



- Condition number of the sensing matrix is defined as the ratio between the highest singular value and the smallest singular value:

$$CN = \sigma_{max}/\sigma_{min}$$

Best Case Scenario: 1

Worst Case Scenario: Inf.

Simulation of a 2D computational imaging system

Starting from the forward model

$$g_{i,j}(\omega) \propto \int_r [E_i.E_j](r,\omega) f(r)\, d^3r$$

Code available here
https://bit.ly/308DnNi

the model is simplified considering isotropic sources and a point target:

$$E_i = G(r, r_i)$$ for 1 Tx antenna

$$Ej = \sum_k C(r_k) G(r, r_k)$$

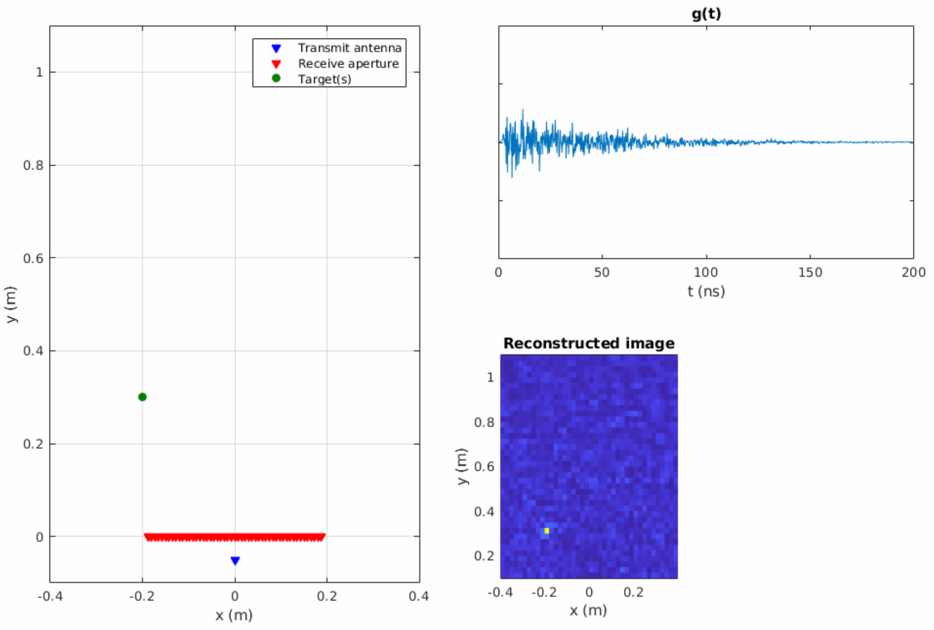
$$f(r) = \delta(r - r_C)$$

Where $C(r_k)$ is the set of transfer functions of the metasurface

$$C(r_k) = \mathfrak{F}^{-1}\left(n(t)\exp\left(\frac{-t}{2\tau}\right)\right)$$

$$n(t) \sim \mathcal{N}(\mu = 0,\ \sigma^2 = 1)$$

$$Q = 2\pi f_c \tau$$



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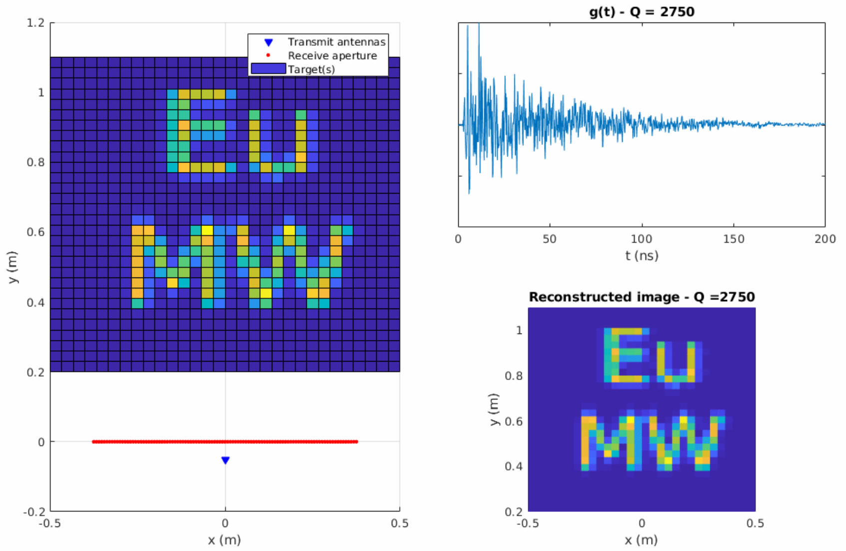
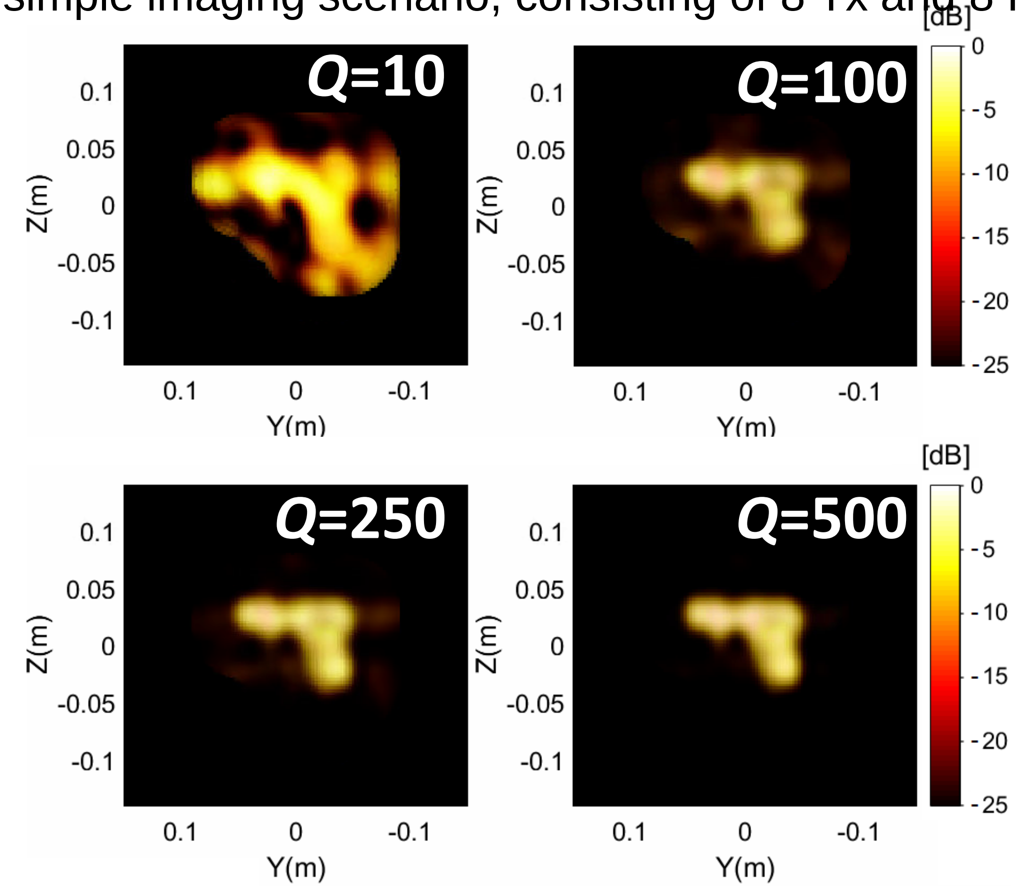
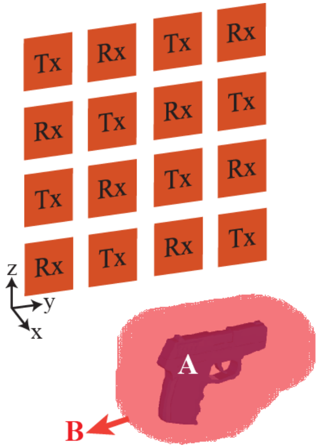


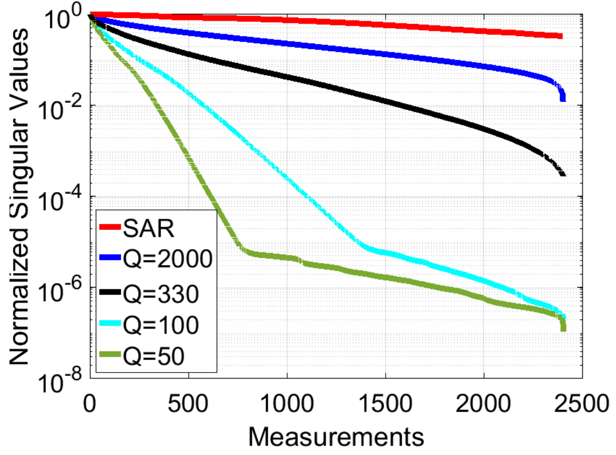
Frequency-Diversity and Q-Factor

Q-Factor

- In order to analyze the effect of Q-factor (hence mode diversity) on imaging, we study a simple imaging scenario, consisting of 8 Tx and 8 Rx antennas.





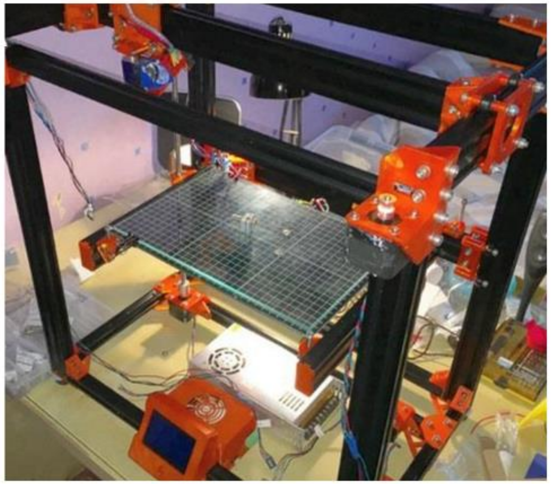


Source: Yurduseven, O., Gollub, J.N., Rose, A., Marks, D.L. and Smith, D.R., 2016. Design and simulation of a frequency-diverse aperture for imaging of human-scale targets. *IEEE Access*, *4*, pp.5436-5451.

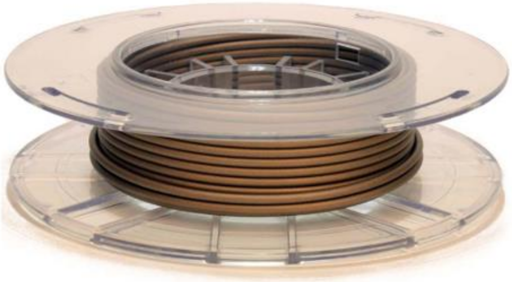
3D Printed Cavity-Backed Antenna

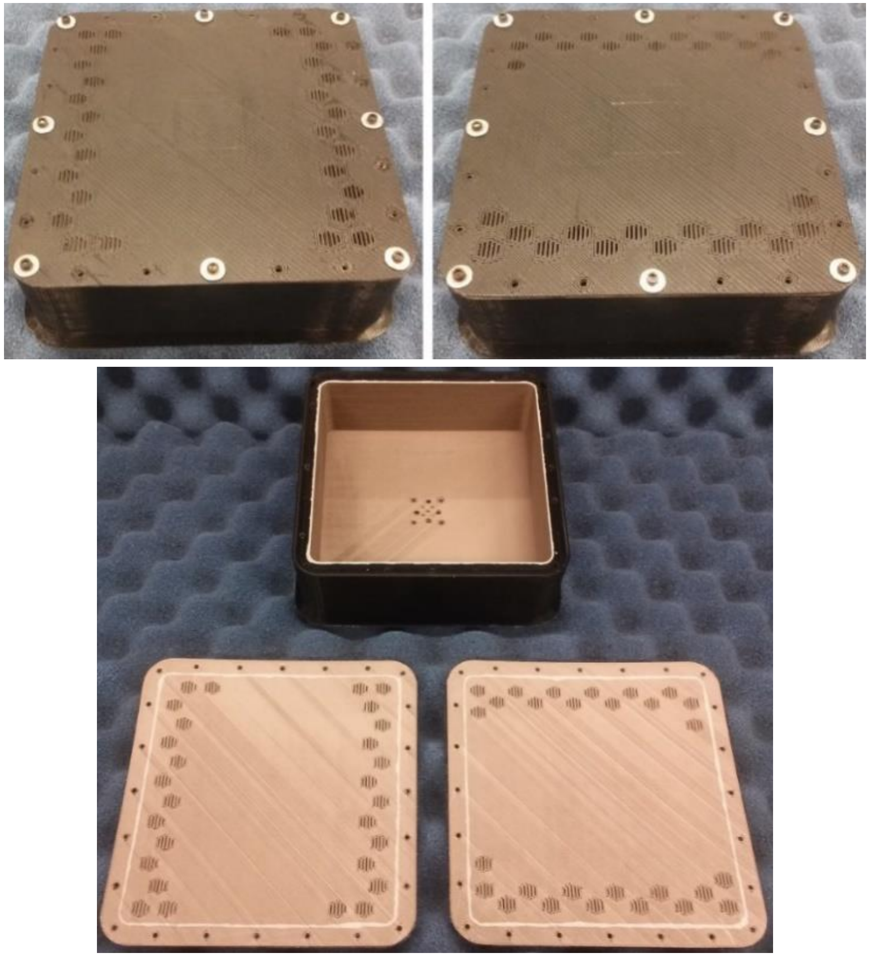
- Antennas for computational imaging, such as frequency-diverse antennas, exhibit unusual aperture architectures. As well as PCB prototyping, such antennas can also be fabricated using 3D printing techniques.

Dual-Mode FDM Printer



Electrifi Filament

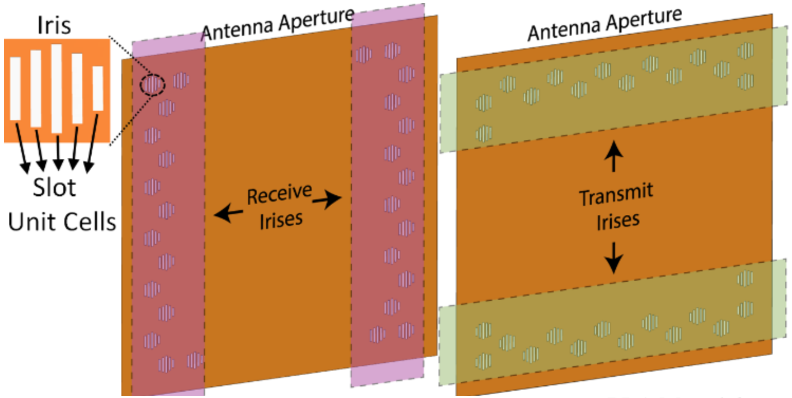


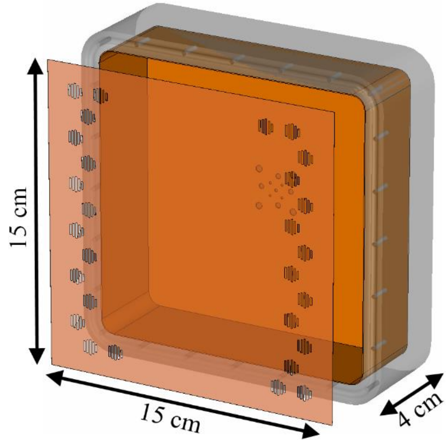


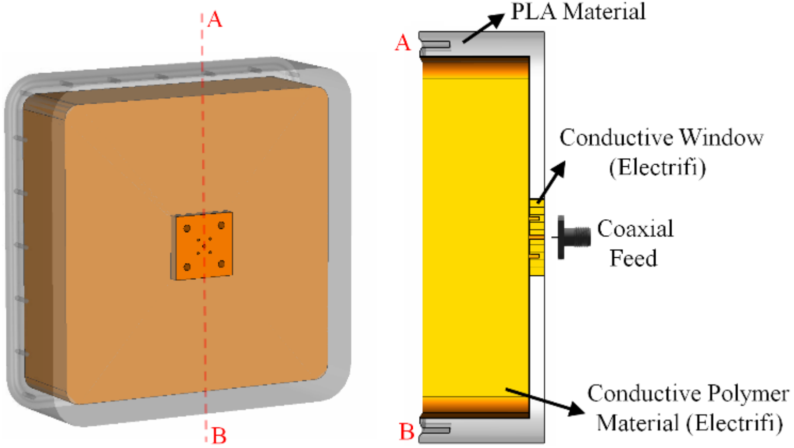
Source: Yurduseven, O., Flowers, P., Ye, S., Marks, D.L., Gollub, J.N., Fromenteze, T., Wiley, B.J. and Smith, D.R., 2017. Computational microwave imaging using 3D printed conductive polymer frequency-diverse metasurface antennas. *IET Microwaves, Antennas & Propagation*, *11*(14), pp.1962-1969.

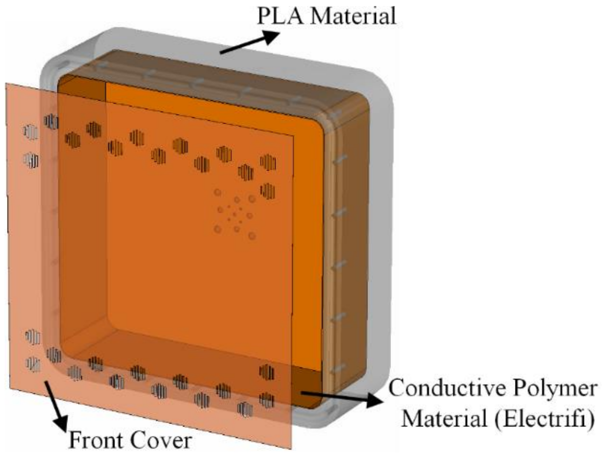
3D Printed Cavity-Backed Antenna

- The 3D cavity-backed metasurface antenna presented in this example was printed using a conductive filament as the 3D printing material.
- Each meta-element iris across the Mills-Cross metasurface consists of subwavelength slots of varying lengths to ensure that the overall radiation response of the antenna remains flat across the frequency band of interest.

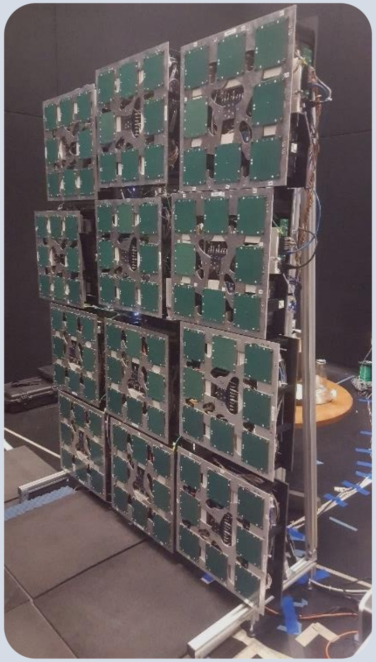




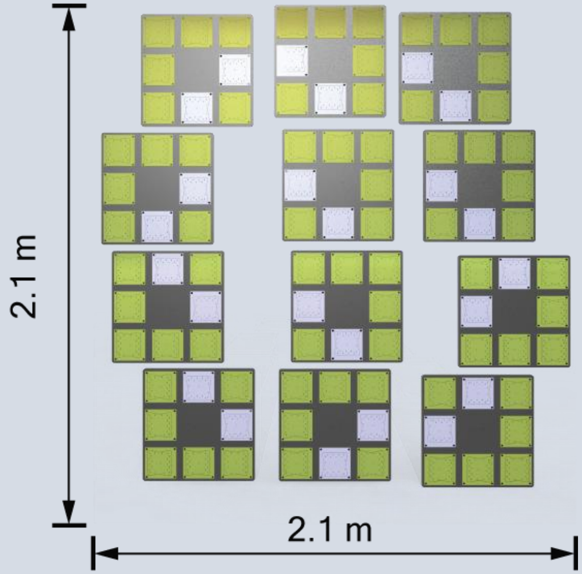


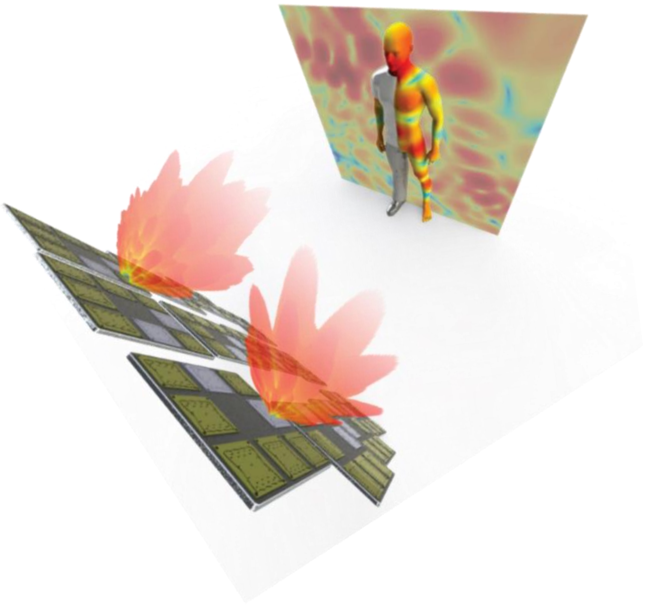


An Example Computational Imaging System



System Layout





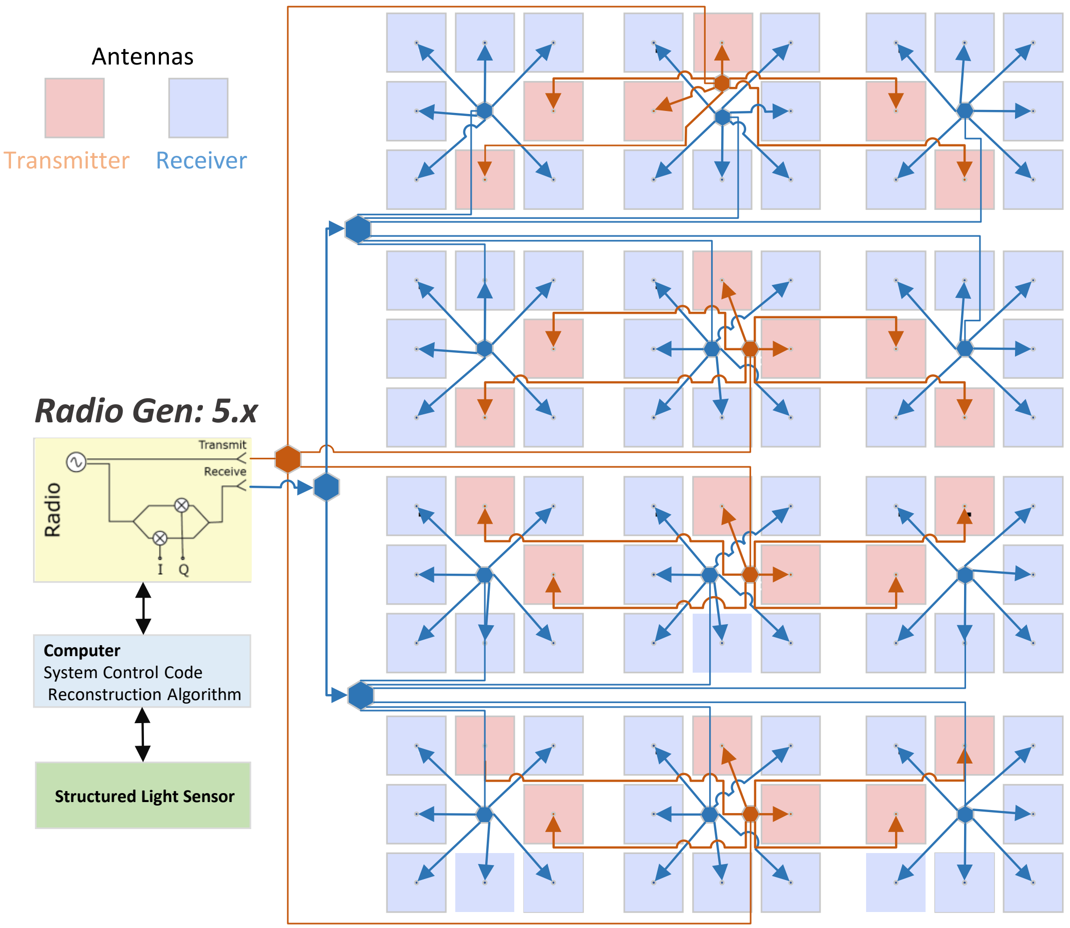
The system consists of 72 receive and 24 transmit cavity-backed metasurface antennas. Each antenna is 10 cm x 10 cm. In total, the system has only 96 antennas.

Synthesizing the same aperture at the Nyquist limit, we would need more than 137,000 antennas!

- *MEASUREMENT MODES: (24 Tx panels) x (72 Rx panels) x (100 freqs.) =* ***172,800***

Source: Gollub, J.N., Yurduseven, O., Trofatter, K.P., Arnitz, D., Imani, M.F., Sleasman, T., Boyarsky, M., Rose, A., Pedross-Engel, A., Odabasi, H. and Zvolensky, T., 2017. Large metasurface aperture for millimeter wave computational imaging at the human-scale. *Scientific reports*, *7*, p.42650.

Multiple-Input-Multiple-Output (MIMO) Computational Imaging System Example



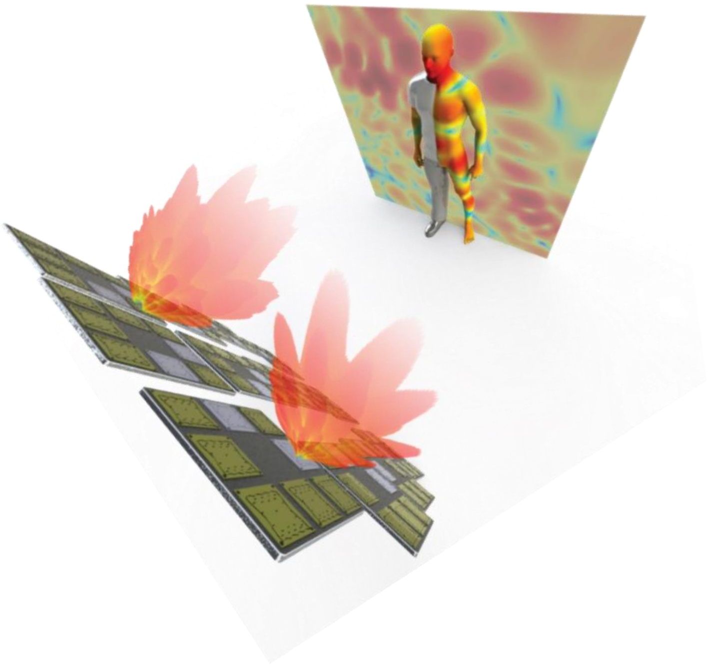
Antennas

🟥 Transmitter 🟦 Receiver

Radio Gen: 5.x

Computer
System Control Code
Reconstruction Algorithm

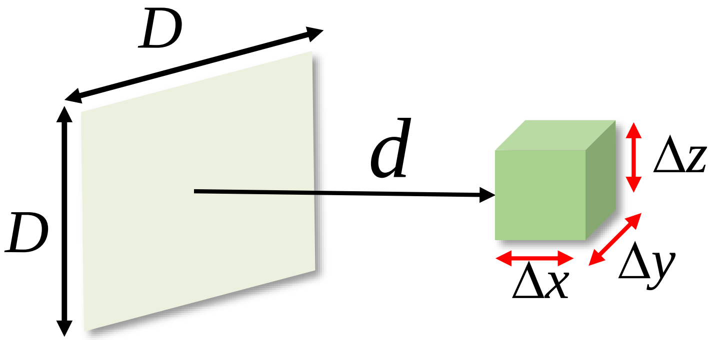
Structured Light Sensor



System Resolution

Questions to be asked:

- How does the resolution compare to the resolution of a conventional SAR system?
- In other words, are we still diffraction limited?
- To answer these questions, we need to analyze the resolution limit. That is the PSF!



Range Resolution

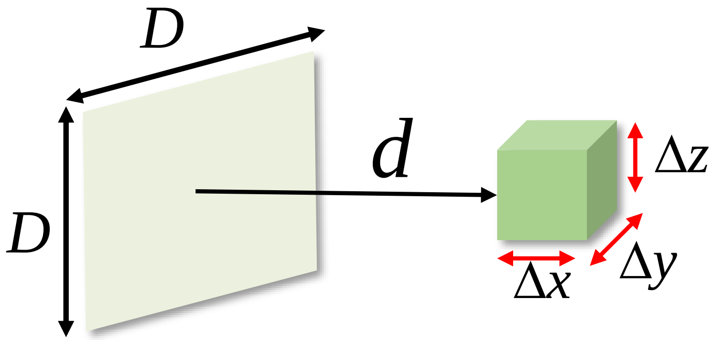
$$\Delta x = \frac{c}{2B} = 17 \text{ mm}$$

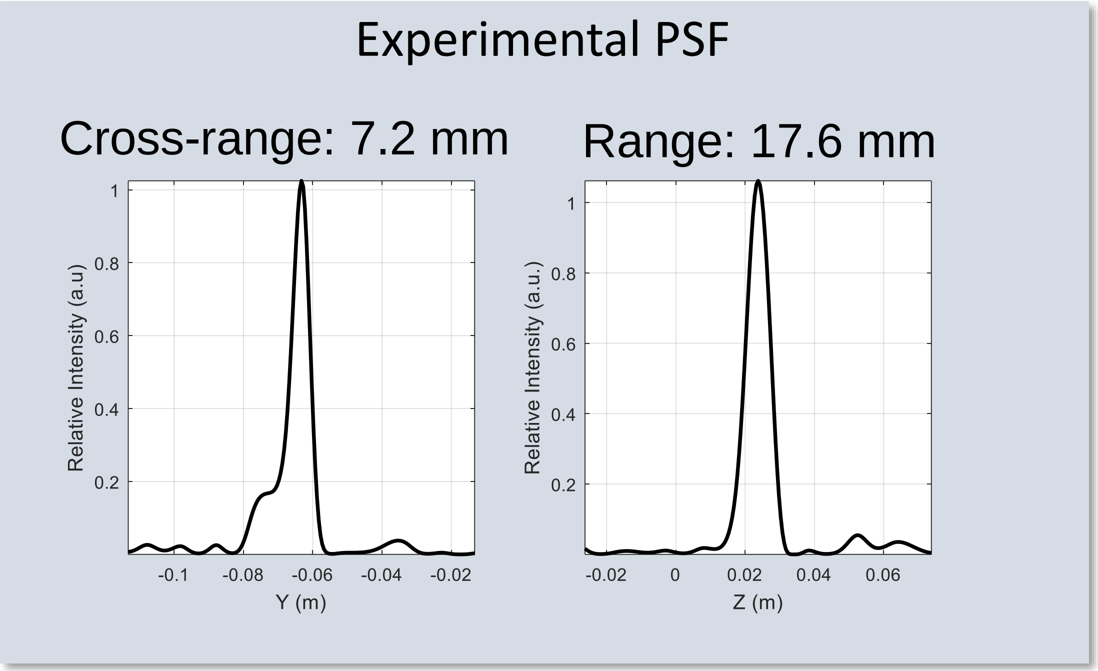
Cross-Range Resolution

$$\Delta y, \Delta z = \frac{\lambda d}{D} = 7 \text{ mm}$$

System Resolution

- To retrieve the PSF pattern of the computational imaging system, we image a metal bead placed at *d*=1 m in from of the aperture.
- The reconstructed 3D PSF patterns are then analyzed to calculate the FWHM values in range and cross-range to determine the resolution limits.
- The observed values are in good agreement with the theoretical values.





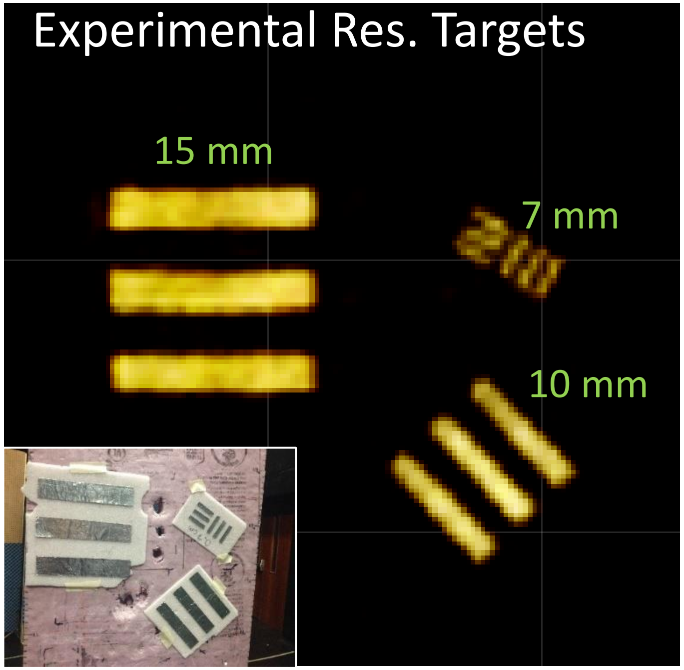
Experimental PSF

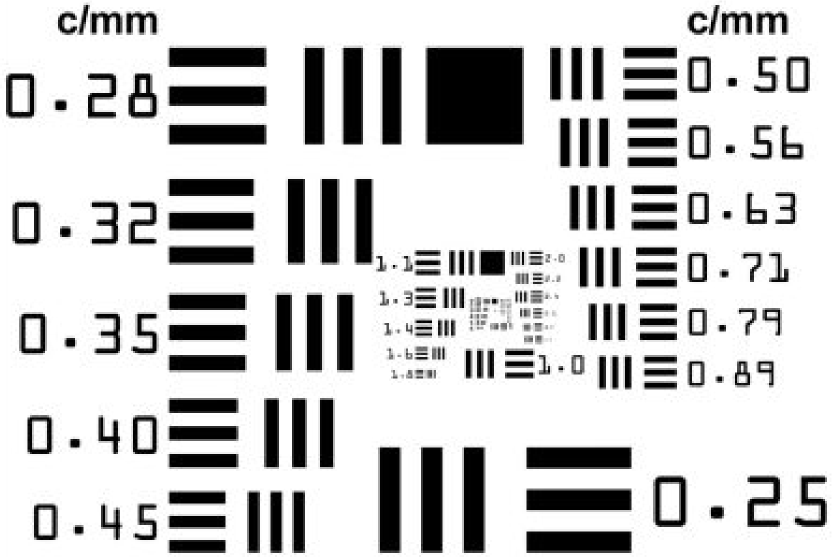
Cross-range: 7.2 mm

Range: 17.6 mm

System Resolution

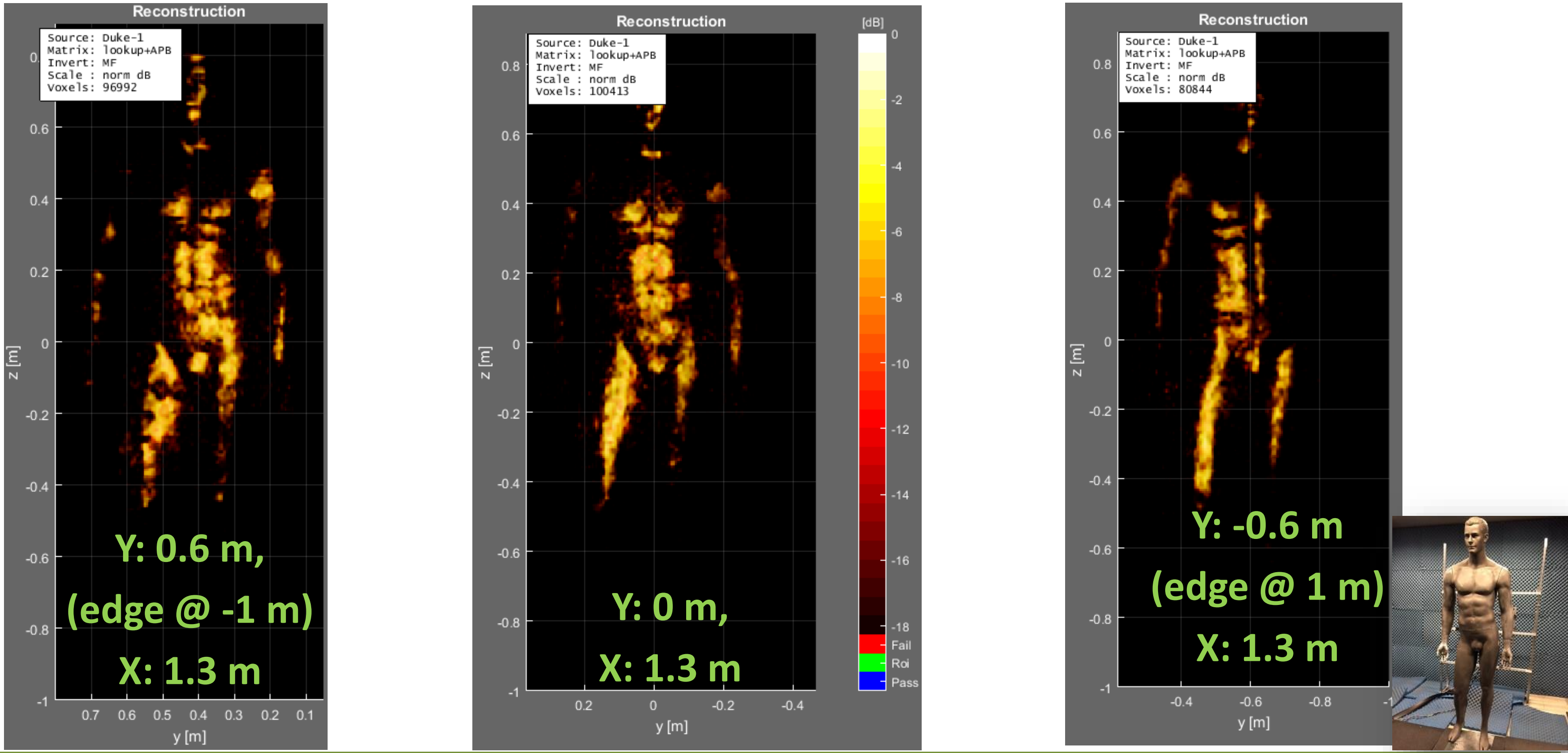
- Once the resolution limits are analyzed, we can use standard target bases to validate these results.
- A very common target example is the USAF resolution target.
- We place the resolution target at *d*=1 m (the distance where the PSF analysis was carried out).



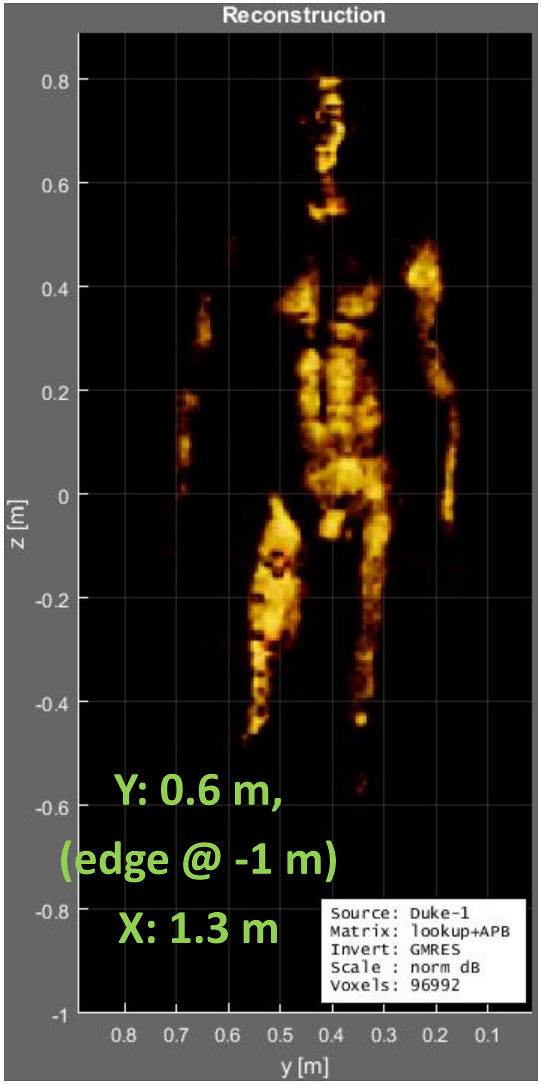


Experimental Reconstruction – Matched Filter

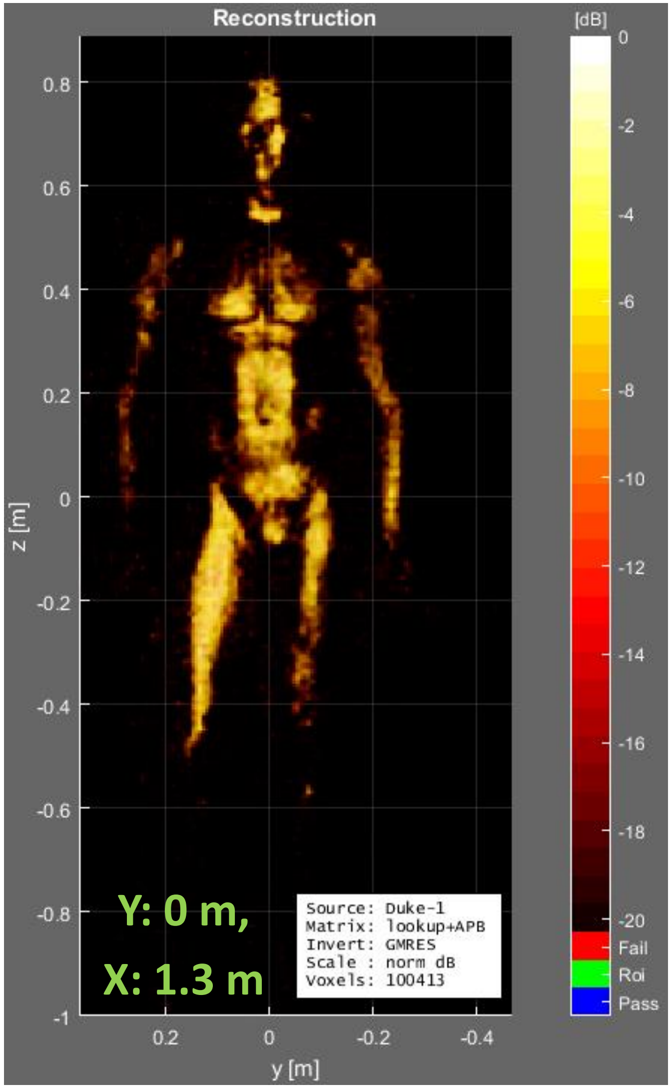
- Imaging a human sized object requires that an electrically large aperture is synthesized.
- To test the computational imaging concept for this application, we first need to eliminate challenges related to data acquisition speed. The best test scenario for this is a static scene.
- For this example, we image a mannequin target painted in conductive material to replicate the reflectivity response of the human skin at microwave frequencies.



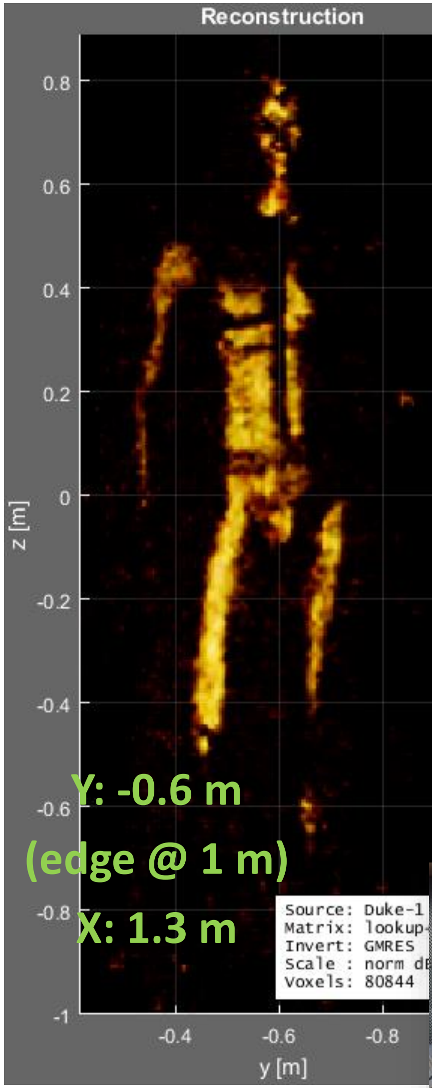
Experimental Reconstruction – Least Squares



Y: 0.6 m,
(edge @ -1 m)
X: 1.3 m



Y: 0 m,
X: 1.3 m



Y: -0.6 m
(edge @ 1 m)
X: 1.3 m

Threat Detection

- A significant advantage of microwave imaging is that we can see what is behind optically opaque materials.
- This has a particular application in security screening: Imaging and detection of threat objects behind clothing.
- Microwave imaging is a qualitative method; i.e. in this case, we are retrieving the susceptibility (reflectivity distribution) of the scene.
- The biggest challenge is that the human skin is a very good reflector at microwave frequencies!

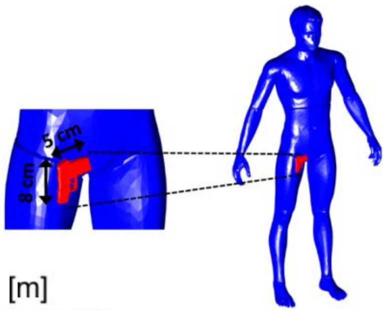
Photo

Microwave Image

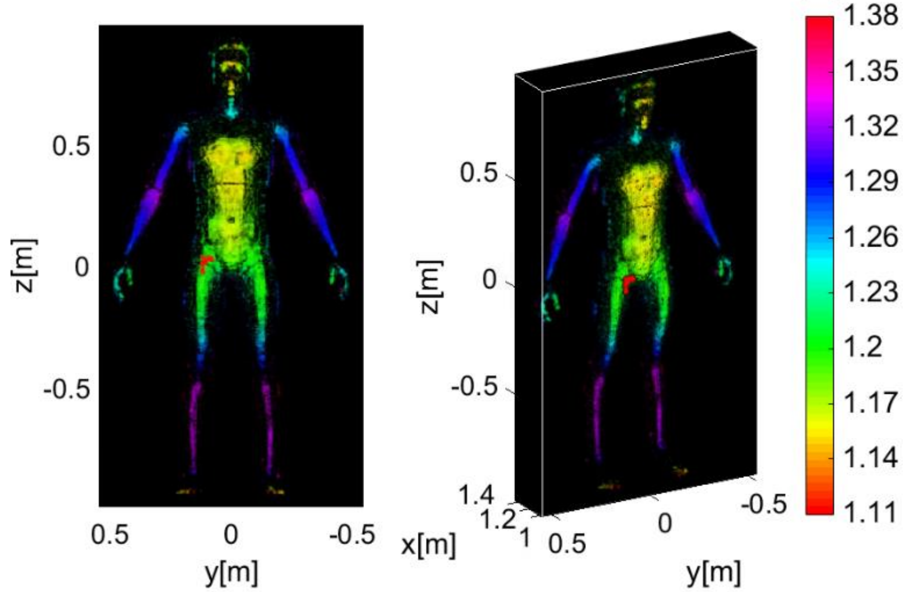
Source: Ahmed, S.S., 2014. *Electronic microwave imaging with planar multistatic arrays*. Logos Verlag Berlin GmbH.

Color-Coding in Reconstructions

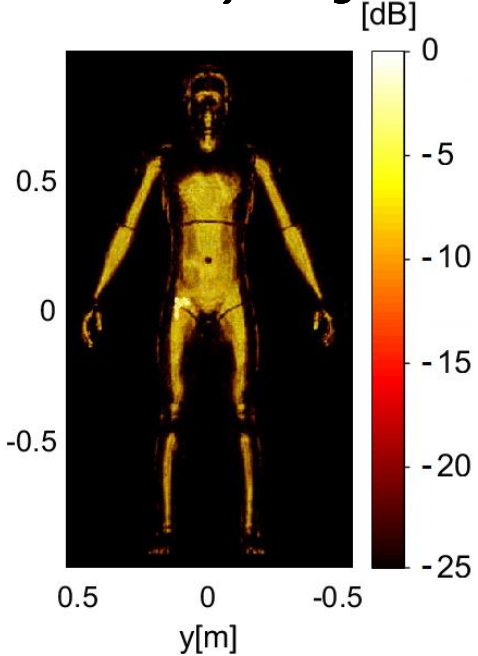
- To achieve threat detection from reconstructed microwave images, typically, complex signal processing techniques are used.
- A very primitive, simple technique could be the color-coding the reconstructed images as a function of depth.



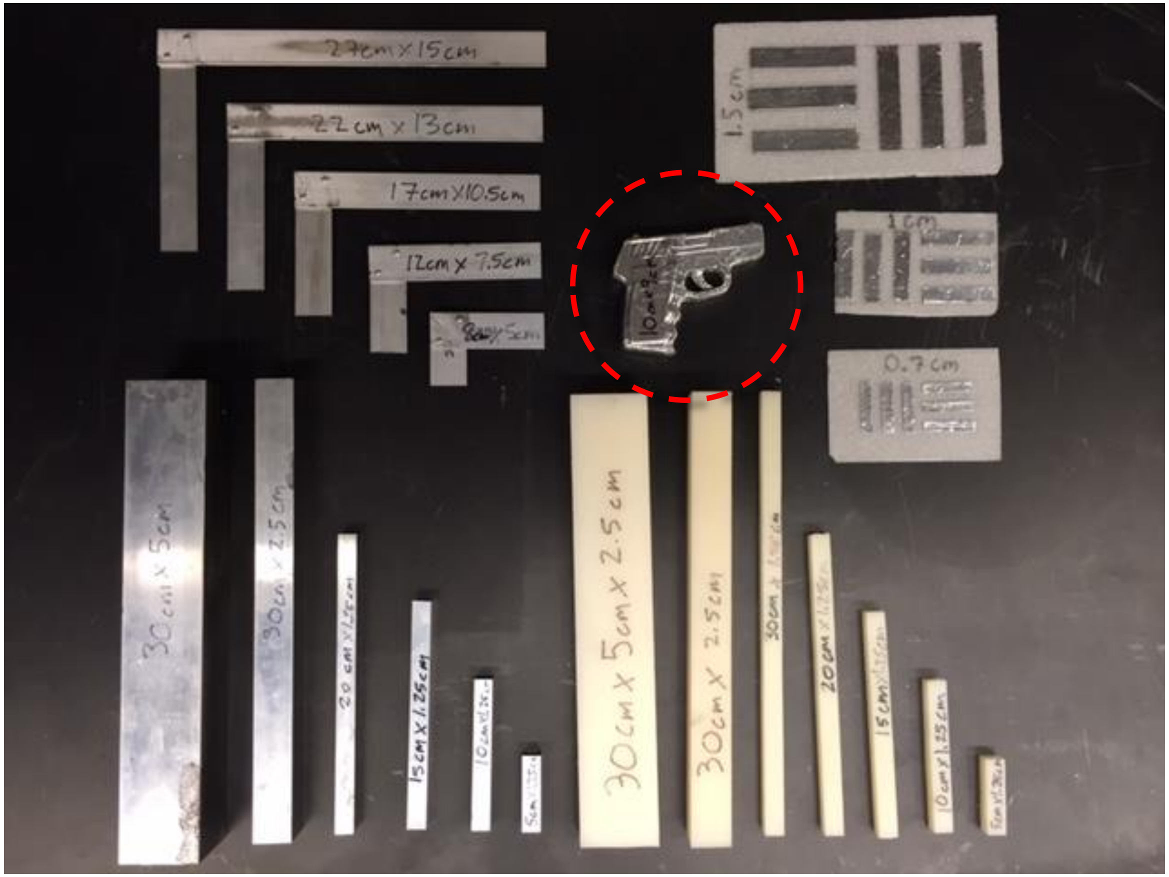
Color-Coded Intensity Image



Intensity Image



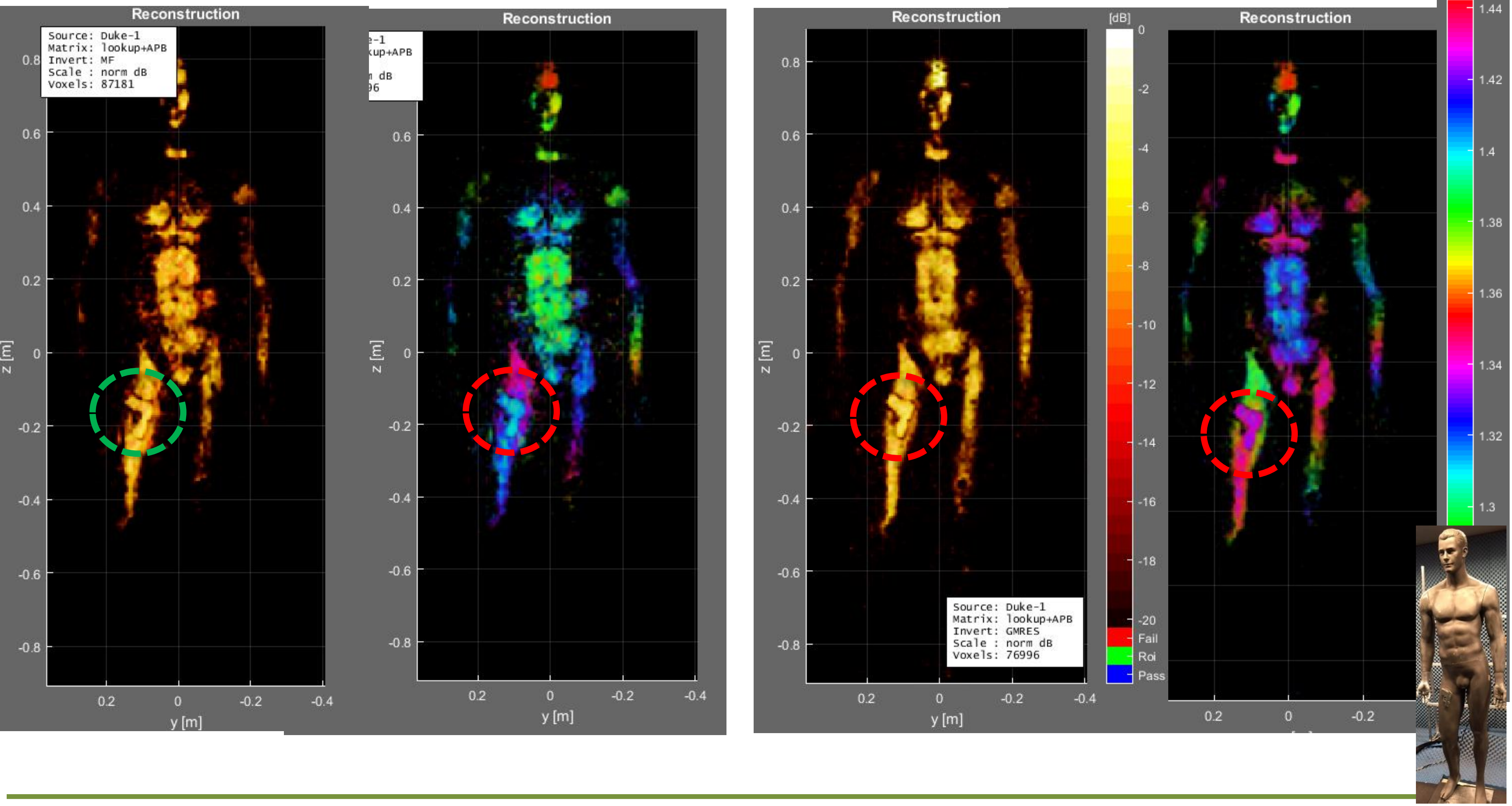
Experimental Reconstruction – Threat Objects



Threat object: Gun phantom

Experimental Reconstruction – Threat Objects

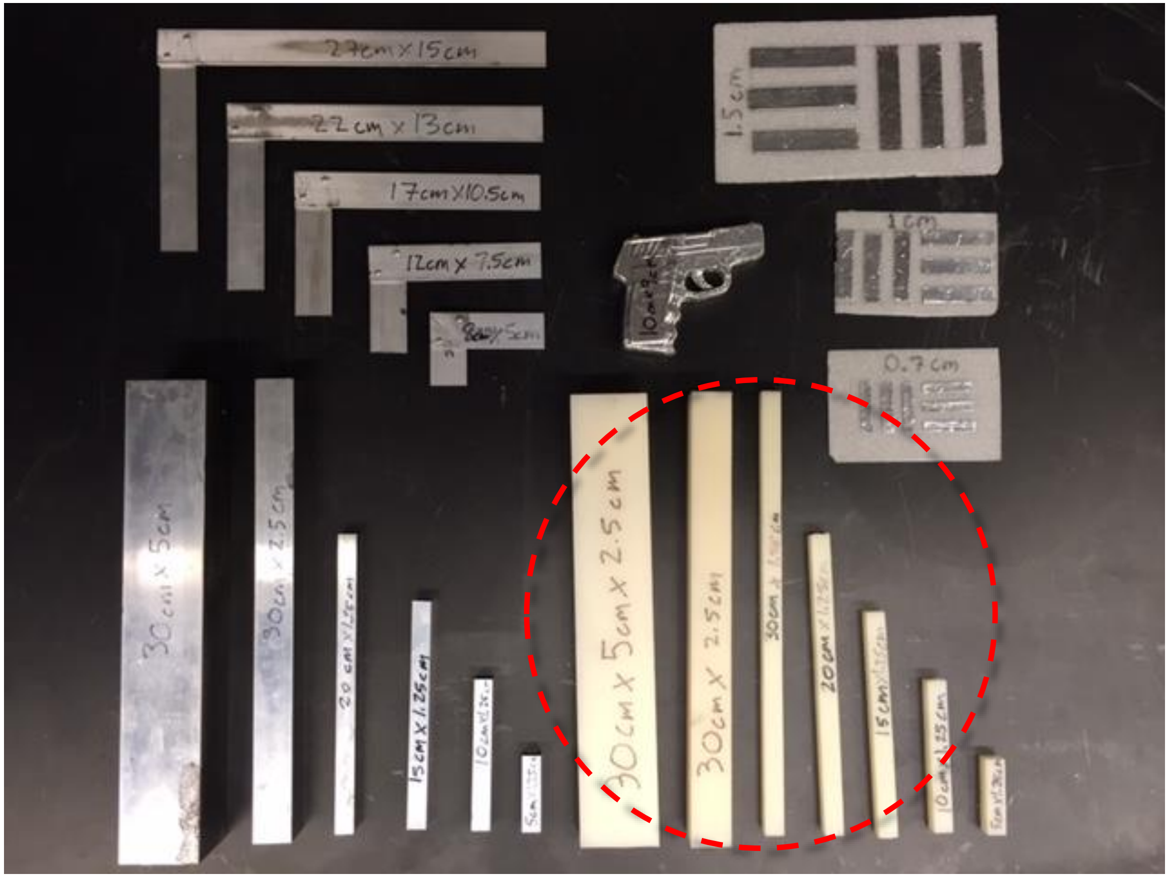
MF **MF – Color Coded** **LS** **LS – Color Coded**



Source: Duke-1
Matrix: lookup+APB
Invert: MF
Scale : norm dB
Voxels: 87181

Source: Duke-1
Matrix: lookup+APB
Invert: GMRES
Scale : norm dB
Voxels: 76996

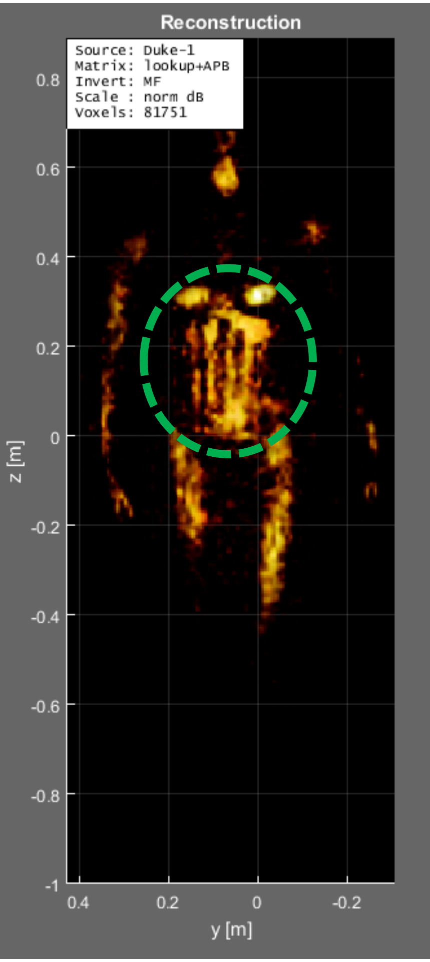
Experimental Reconstruction – Threat Objects



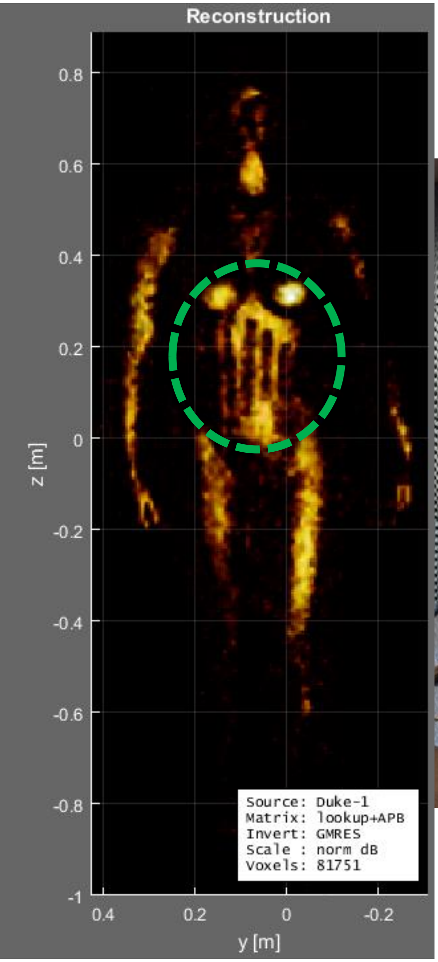
Threat Object: Dielectric

Experimental Reconstruction – Dielectric Threat Objects

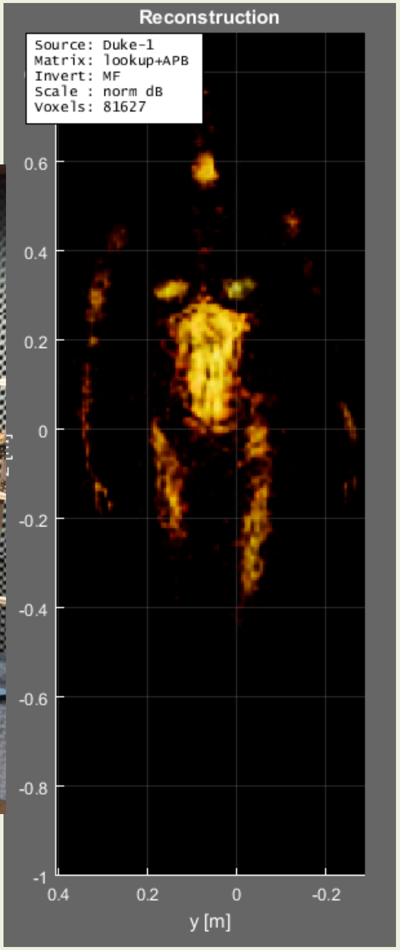
MF



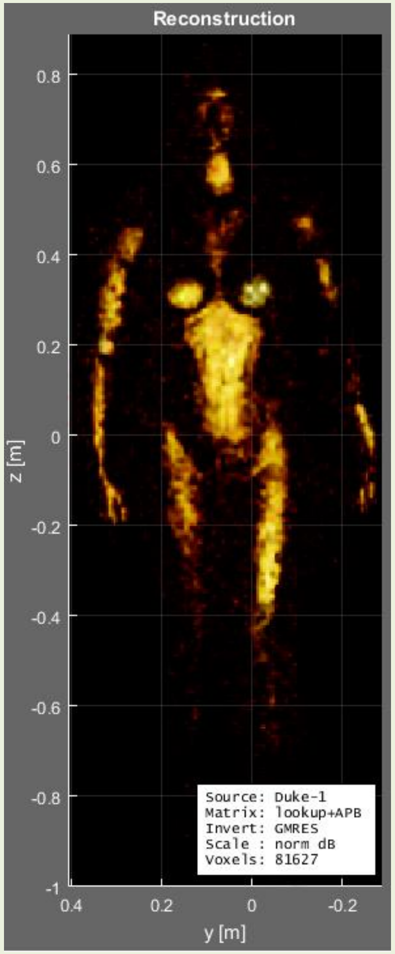
LS



Clean - MF

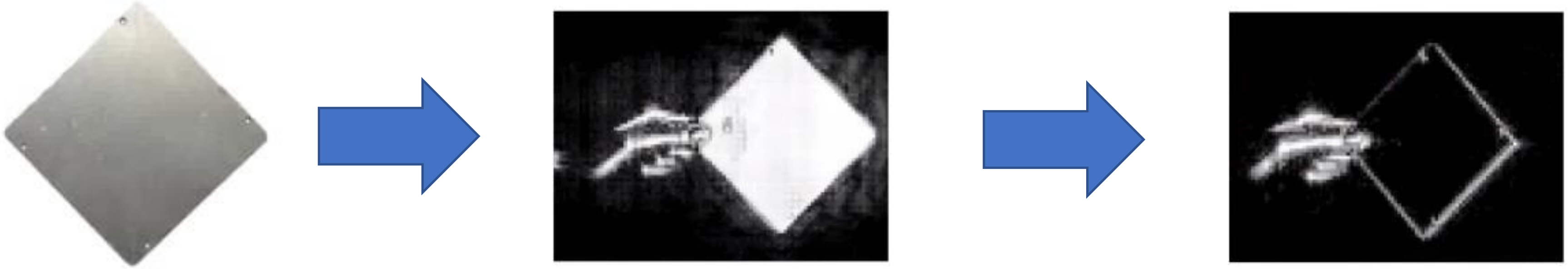


Clean - LS

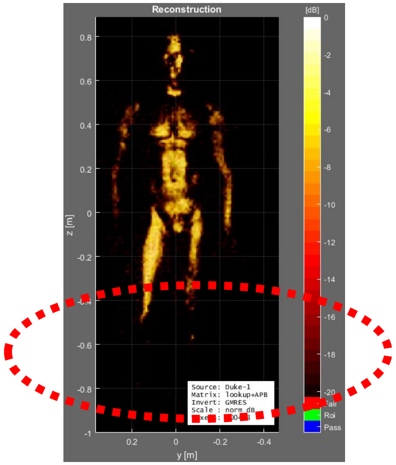


Specularity

- Imaging at microwave and mmW frequencies exhibits specularity: An object reflects the incoming illumination in a specific direction (or directions). If the receiver is not positioned in the reflection direction, no information is received.
- This phenomenon shows itself as missing parts in reconstructed images.



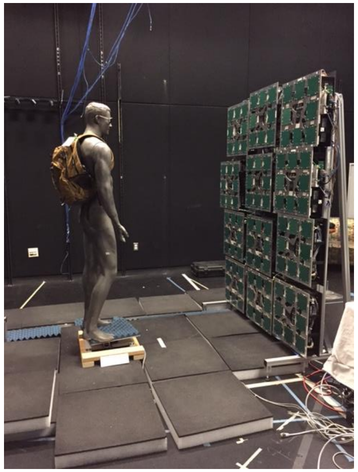
Source: Ahmed, S.S., 2014. *Electronic microwave imaging with planar multistatic arrays*. Logos Verlag Berlin GmbH.



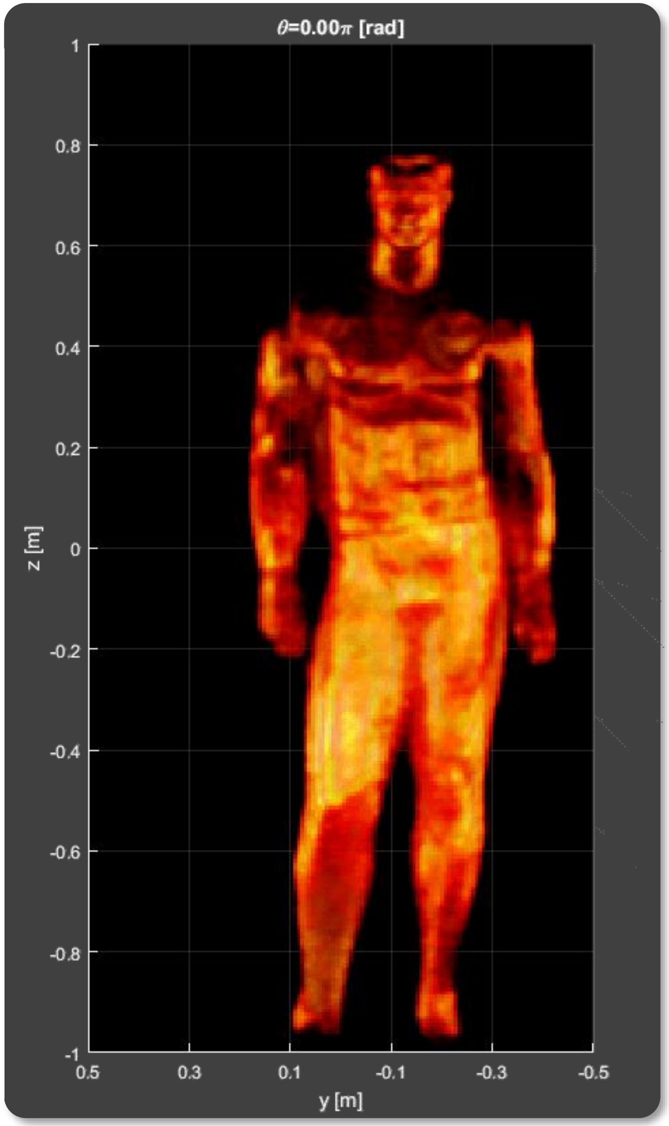
Source: Yurduseven, O., Gollub, J.N., Rose, A., Marks, D.L. and Smith, D.R., 2016. Design and simulation of a frequency-diverse aperture for imaging of human-scale targets. *IEEE Access*, *4*, pp.5436-5451.

Specularity

- How to address specularity?
- One way to address it is that we can look at the imaged object from multiple angles.
- We can then stitch those images together.
- Here, we look at an example with a mannequin object carrying a backpack with a cooker in it.

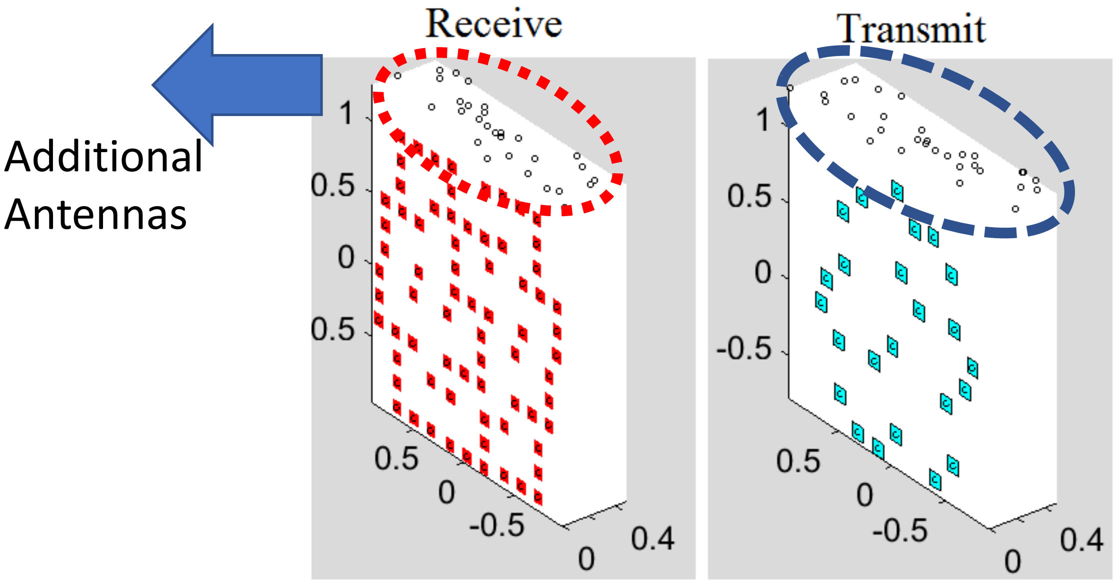


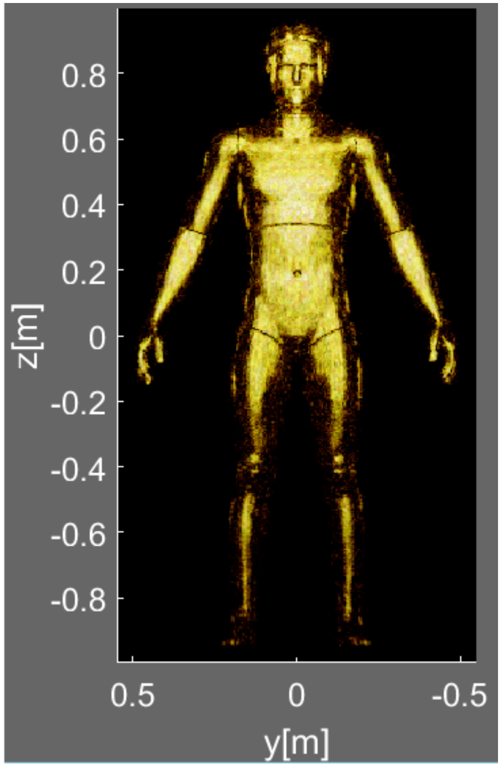
- Looking at the stitched image, previously invisible parts are visible!



Specularity

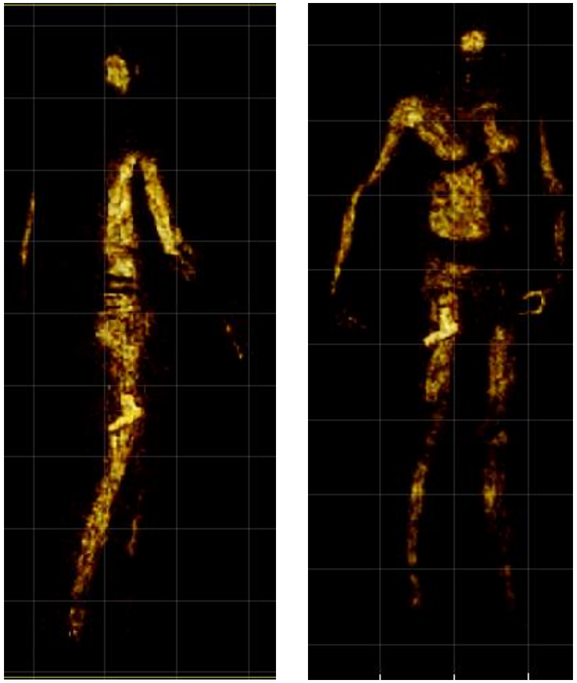
- How to address specularity?
- Another way is to address specularity is that we can place antennas in directions where we cannot capture the return signal.
- Therefore, the system layout must be optimized for the imaging problem at hand.

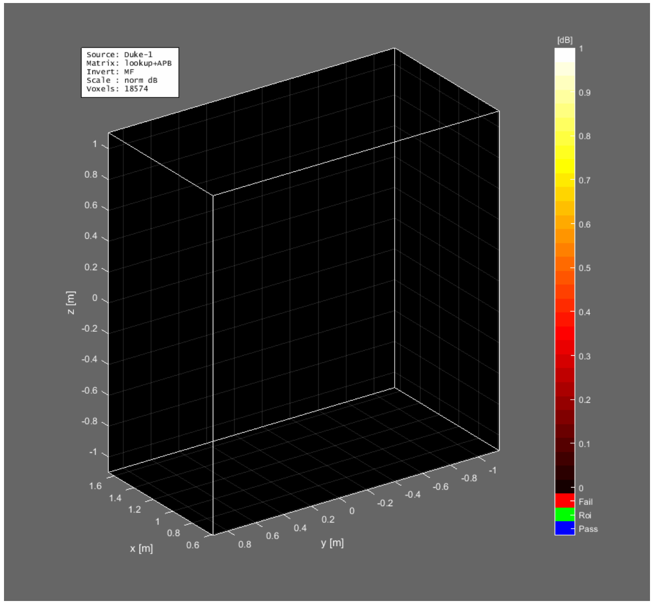


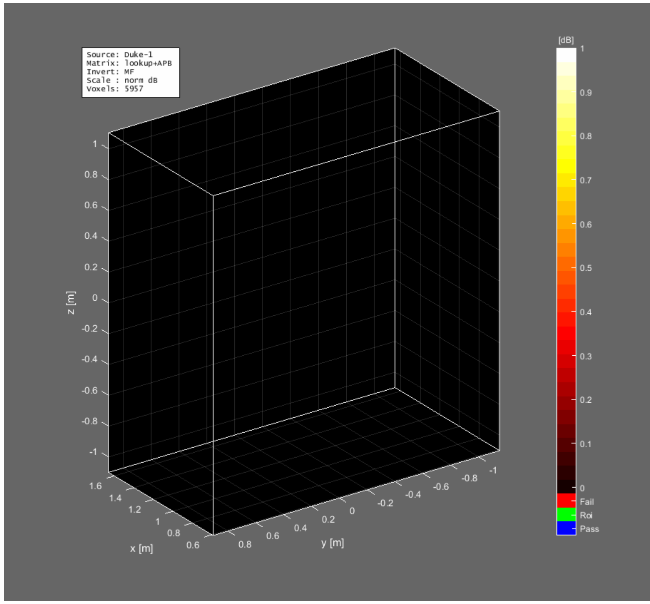


Experimental Imaging – Person Reconstructions

- Microwave imaging of people requires that data acquisition is done in-real time. This is because periodic movements, such as breathing etc displaces the surface of the human body. This results in blurring in reconstructed images if not corrected.
- For conventional imaging systems, this is an extremely challenging problem. Consider the 2.1 m x 2.1 m aperture that was presented for the frequency-diverse imaging system. Conventionally, this aperture would require over 137,000 channels, each sweeping over operating frequency band.
- Through computational imaging, the recued number of channels, 96, enables 7 frames per second data acquisition. As a result, it is possible to acquire date in real-time.



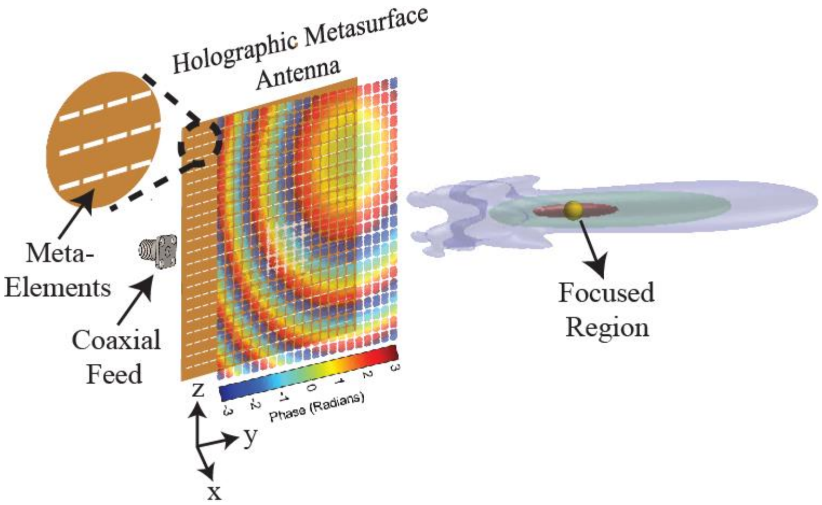


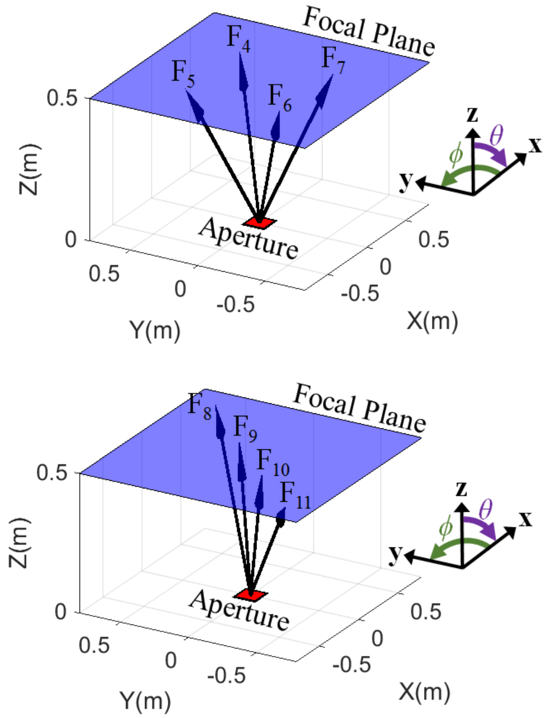


Sensor Fusion and Spotlight Imaging

Reconfigurable Metasurface Antennas

- We have previously presented an example of sensor fusion which involved the integration of an optical camera with a mmW imaging system to constrain the RoI for imaging.
- Another example could be the integration of two imaging systems operating at different frequencies.
- As well as creating quasi-random radiation patterns, metasurface antennas can be used to radiate specific beam patterns, such as focusing a focal spot to generate spotlight modes.

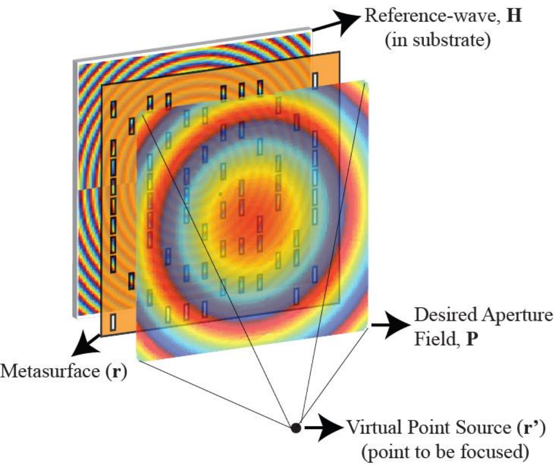


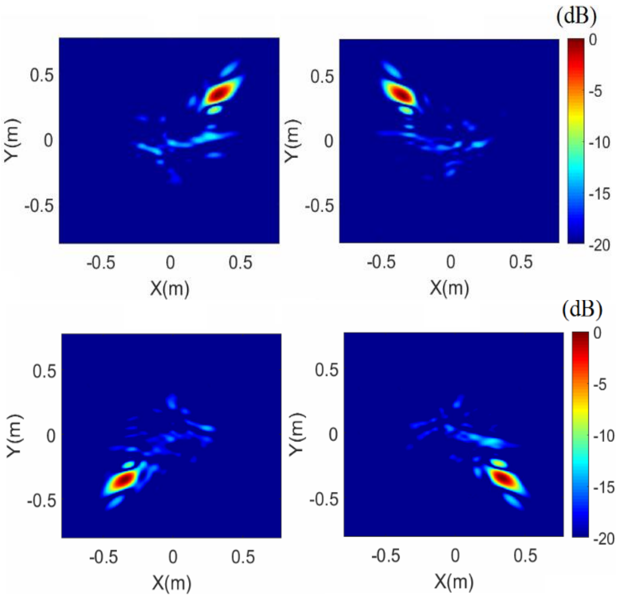


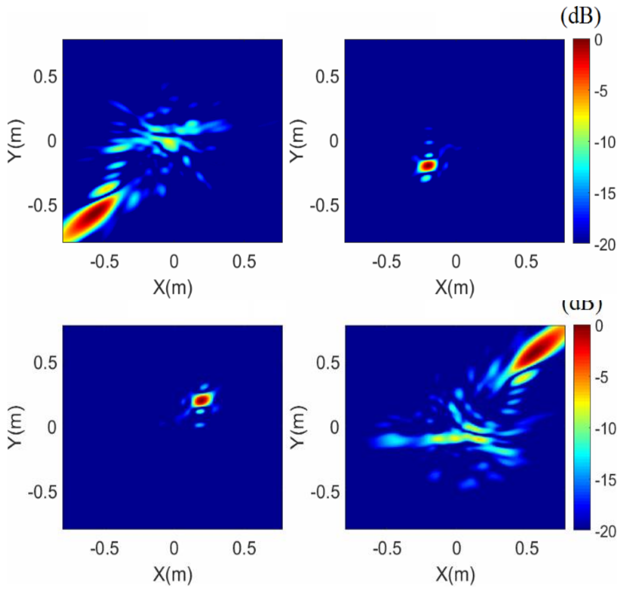
Sensor Fusion and Spotlight Imaging

Reconfigurable Metasurface Antennas

- In the below example, a metasurface antenna that focuses its radiation at *d*=1 m distance is presented.
- This focusing pattern can be changed dynamically
- The metasurface radiates at 75 GHz, within the W-band frequency regime.

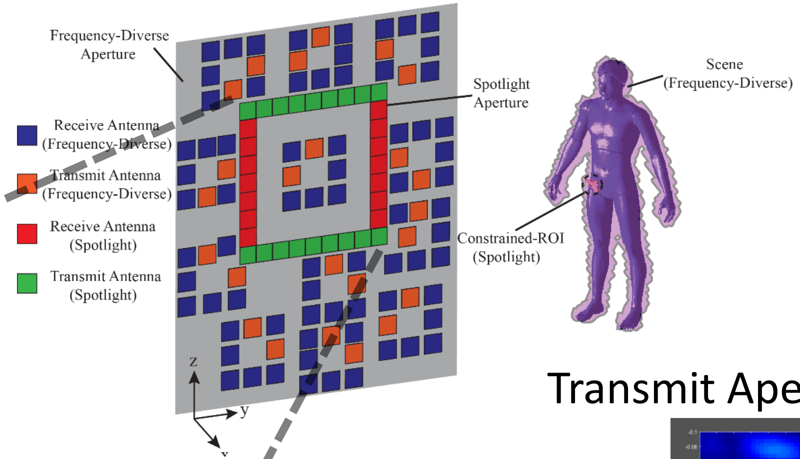


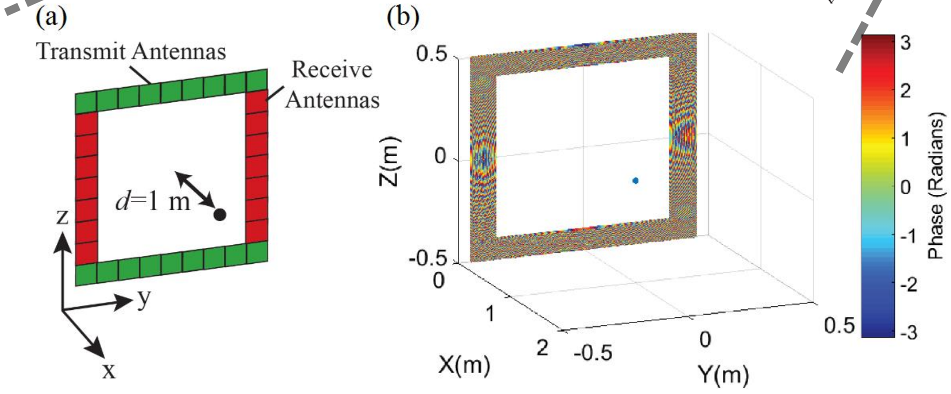


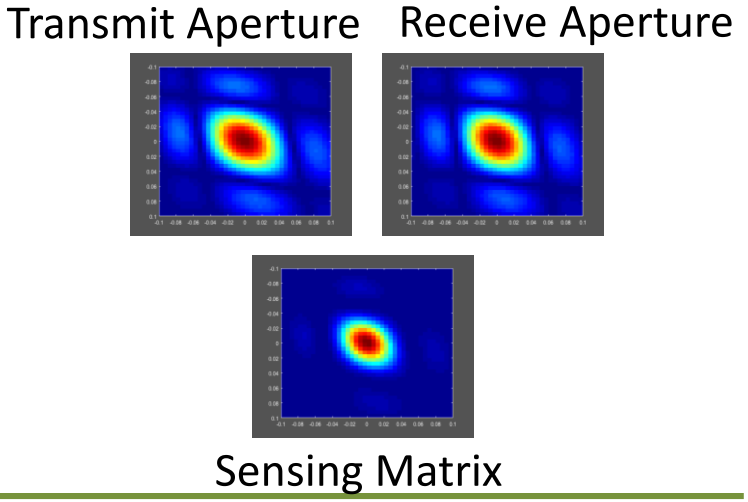


Sensor Fusion and Spotlight Imaging

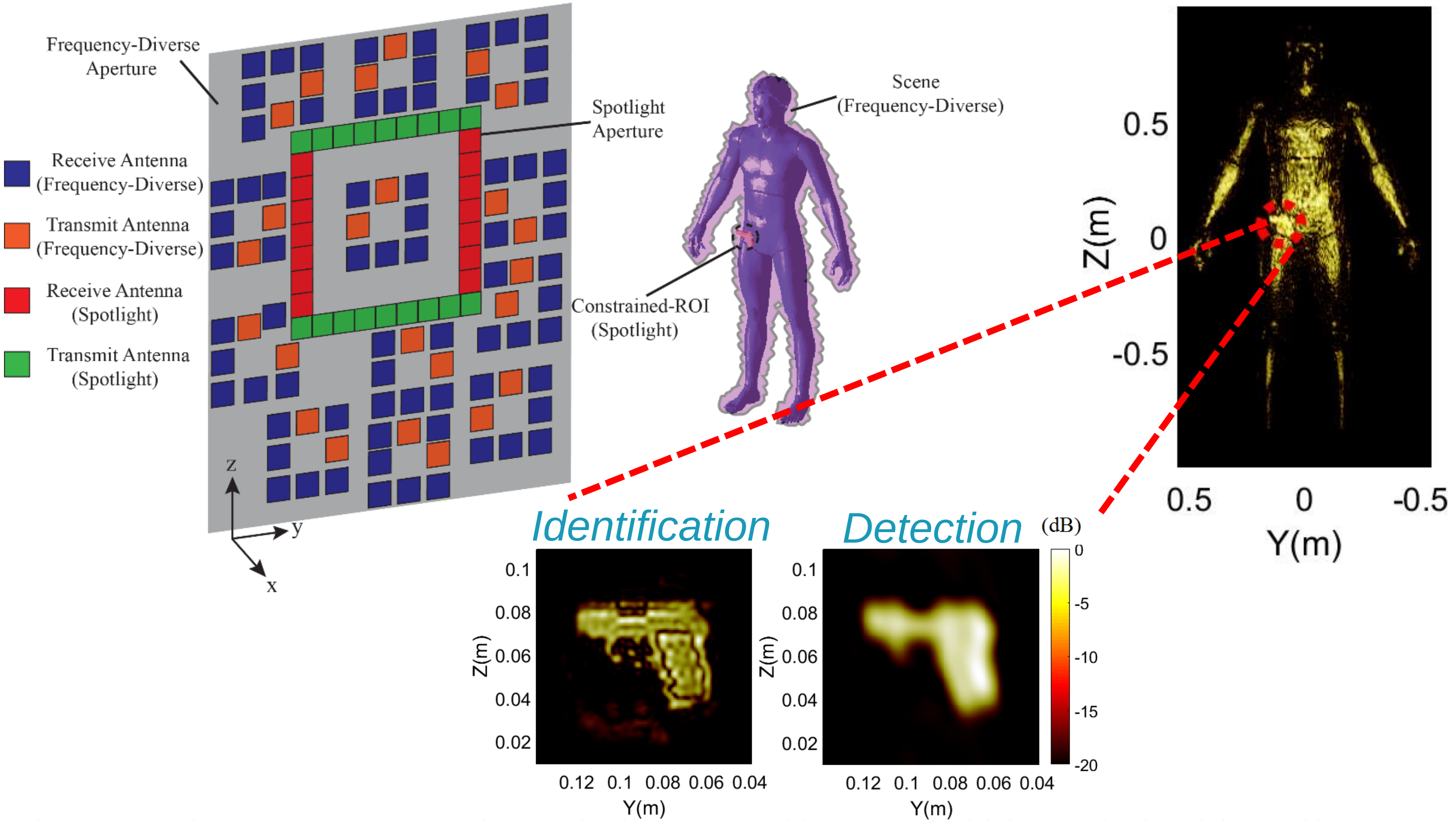
- As a second type sensor fusion example, we K-band frequency-diverse computational imaging system with a W-band spotlight aperture.
- K-band system, because of its lower frequency, can be used to do fast low resolution imaging for detection. W-band spotlight system can be activated to do high resolution identification.







Sensor Fusion and Spotlight Imaging



Yurduseven, O., Marks, D.L., Fromenteze, T., Gollub, J.N. and Smith, D.R., 2017. Millimeter-wave spotlight imager using dynamic holographic metasurface antennas. *Optics express*, *25*(15), pp.18230-18249.

STh-01

MODERN ADVANCES IN COMPUTATIONAL IMAGING AT MICROWAVE AND MILLIMETRE-WAVE FREQUENCIES

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