Millimeter Wave Imaging using Metamaterial Transceivers

Jonah Gollub

Duke University

CENTER FOR METAMATERIALS AND INTEGRATED PLASMONICS

metaImager Team and Funding

David R. Smith
Dr. Jonah Gollub
Dr. Hayrettin Odabasi
Dr. Mohammadreza Imani
Dr. Okan Yurduseven
Dr. Tomas Slovensky
Michael Boyarsky (grad)
Nick Caira (grad)
Vinah Gowda (grad)
Guy Lipworth (grad)
Tim Sleasman (grad)
Parker Trofatter

David Brady
Dr. Daniel Marks
Ruoyu Zhu (grad)

Larry Carin
Dr. Xuejun Liao

Guillermo Sapiro
Dr. Mauricio DelBracio

Nan Jokerst
Dr. Talmage Tyler

Matt Reynolds
Dr. Daniel Arnitz
Andreas Pedross-Engel (grad)

EVOLV Technology
Mike Ellenbogen (CEO)
Anil
Mike LitchfiChitkaraeld
Peter Conway
Scott Macintosh
Alec Rose

University of Utah
David Schurig
(grad)
(grad)

Teledyne
Bobby Briare
Adam Young

This work was supported by the Department of Homeland Security, Science & Technology Directorate (Contract No. HSHQDC-12-C-00049). The published material represents the position of the author(s) and not necessarily that of the DHS.

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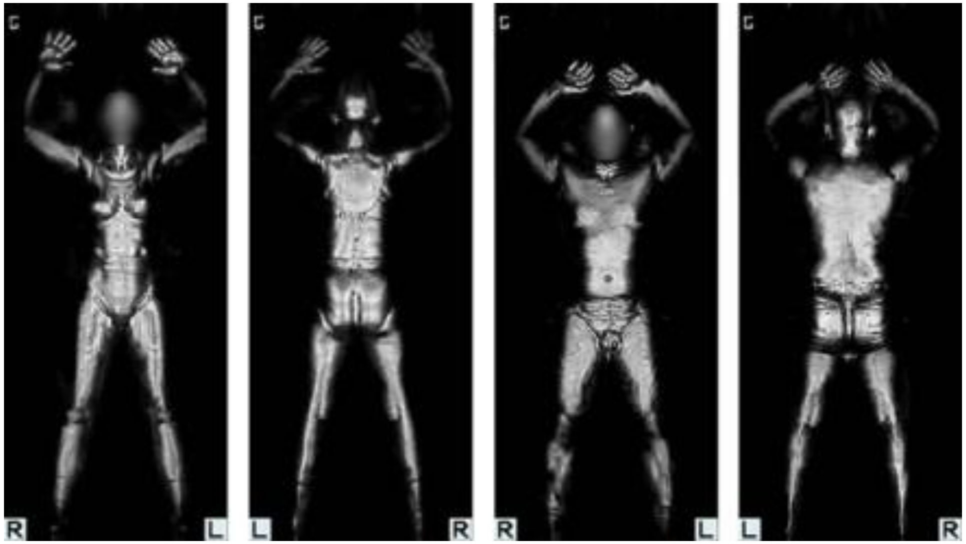
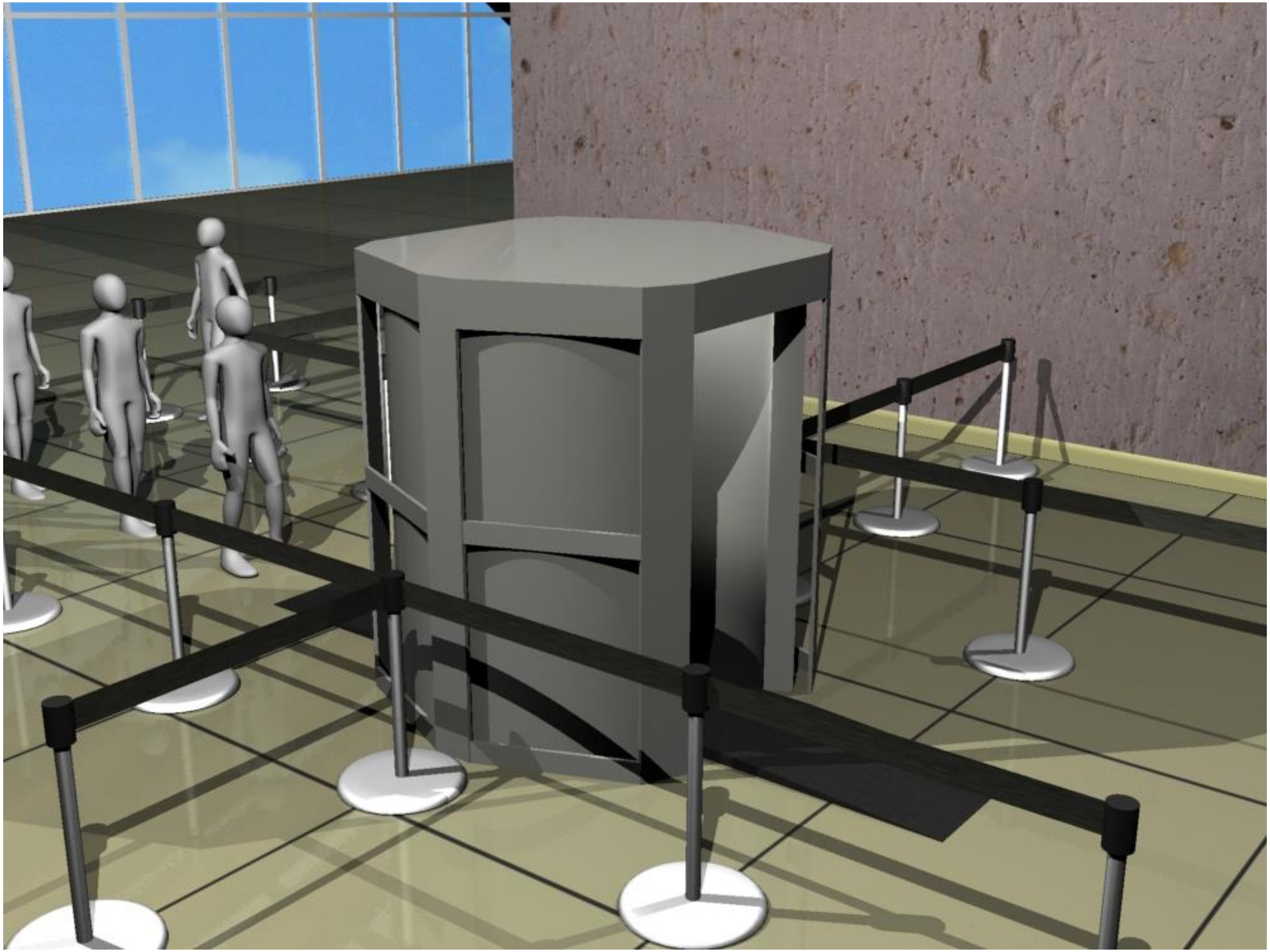
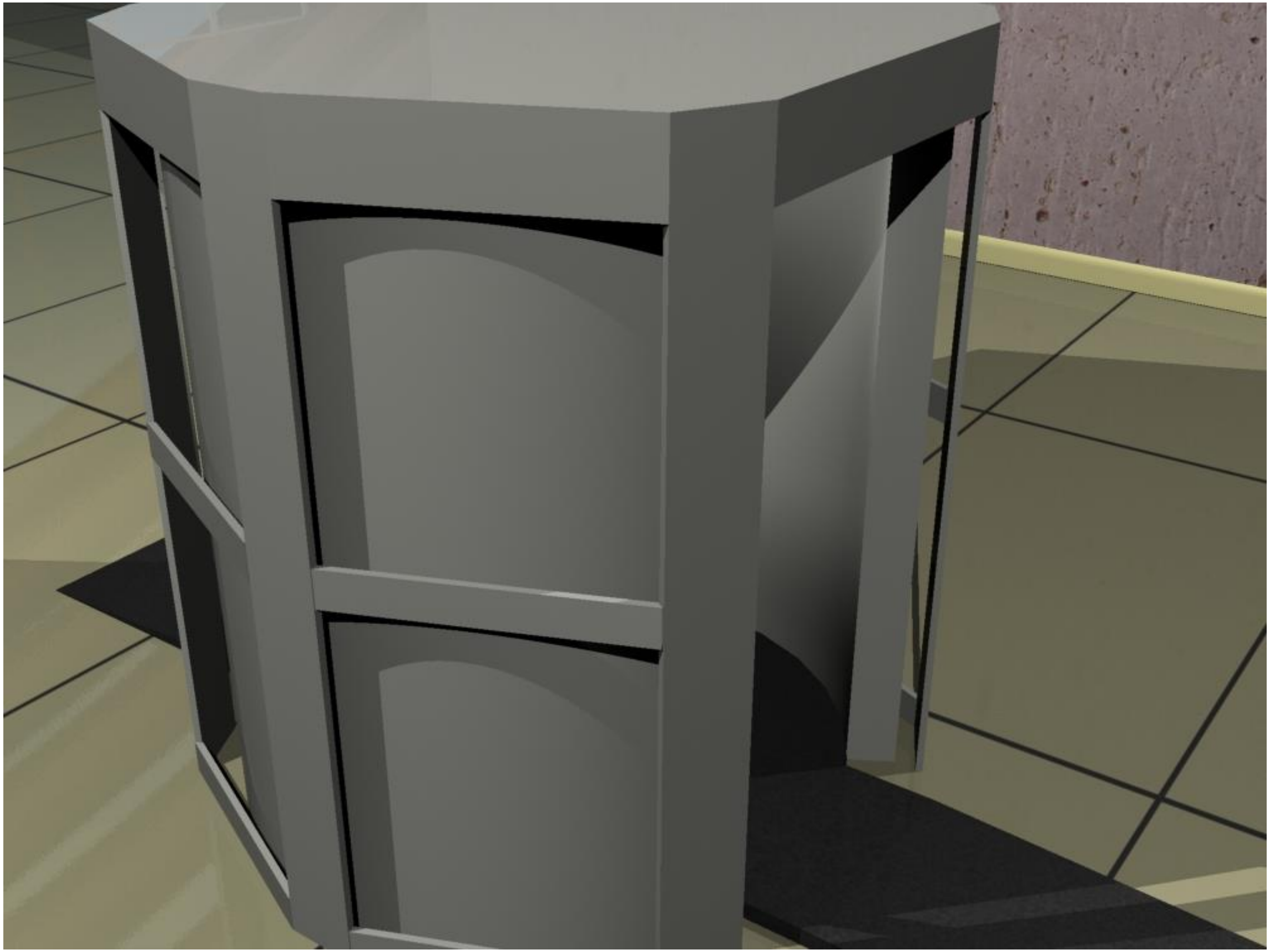
Current Standard in Airport Screening (L3 Pro-Vision)



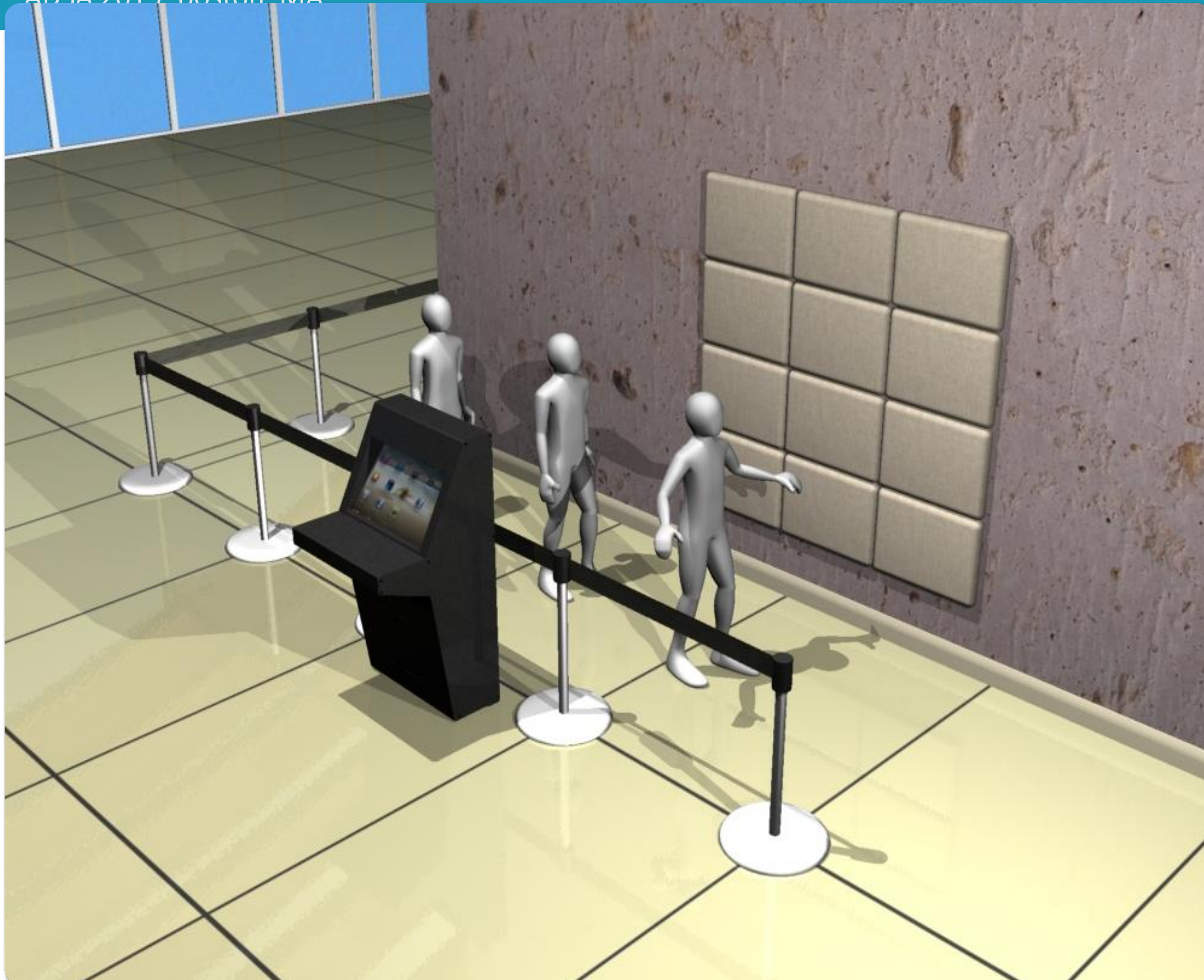
Millimeter wave screening via mechanical scanning of an array of antennas. A 3D image is obtained.





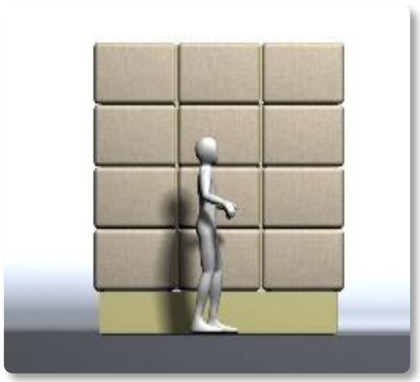
Limitations of The Current Technology:

- Detection: The current technical approaches are beleaguered by blind spots and false positives.
- Deployment: The Bulky form factors and infrastructure needs (power, structural) set limits on equipment placement.
- Cost: The Economics determine the number of devices that can be deployed and the resulting passenger throughput (and annoyance). *But further*, it constrain the overall “architecture” of security screening.



Metamaterial Millimeter Wave Imager

The Focus of The AIT Flat Panel Development effort is to:

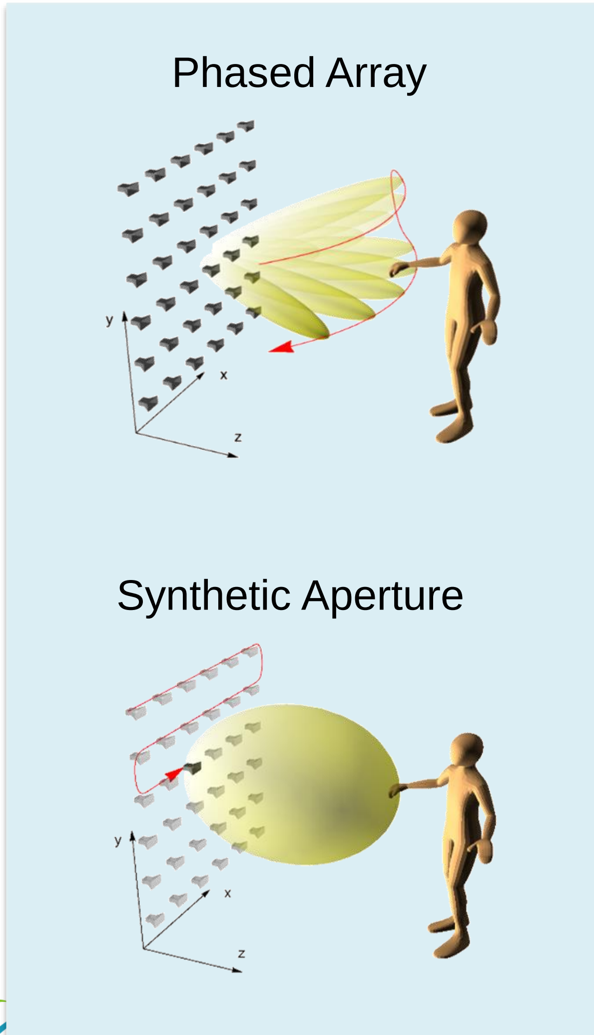


- Develop Real-time imaging that enables dynamic threat monitoring and “no-stop” screening.
- Utilize Sensors with a low-profile and form factor which can be deployed and adopted to a variety of environments.
- Enable a new security paradigm of “graduated” security zones. Inconspicuous sensors that can be deployed in a manner allowing increasing scrutiny as one approaches a secure zone (more appropriate for todays security needs).

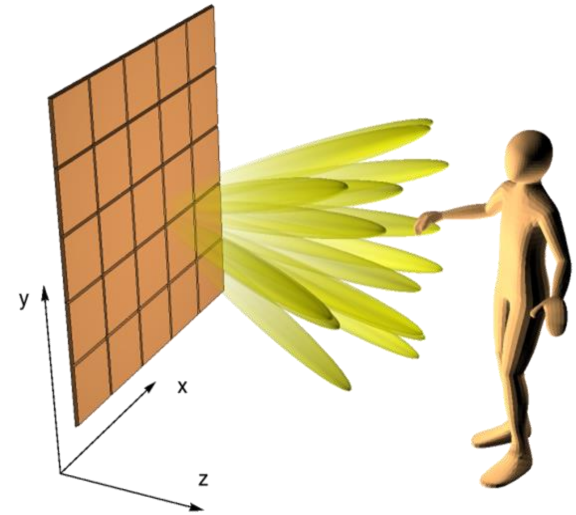
Agenda

- Introduce computational imaging and meta-surfaces as a useful platform for security Imaging.
- Provide an overview of the Meta-Imager architecture and our prototyping effort.
- Discuss our experimental imaging results and current metrics.
- Sketch our future development efforts

Computational Imaging + Aperture Design Flexibility

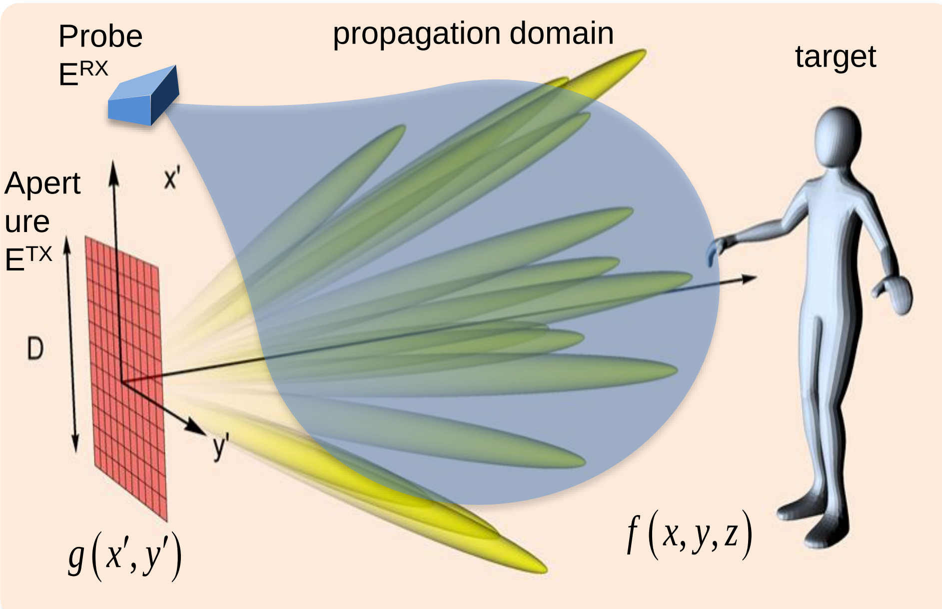


Meta-imager approach



- Complex beam patterns (not necessarily orthogonal) can be used to sample a scene.
- This approach allows flexibility in the aperture design and allows the aperture to be tailored to a particular scene scenario (and their requirements for speed and economics).

Computational Imaging



Generally, the imaging problem can be presented in the discrete form:

$$g = Hf + n$$

Measurement Modes

Measurement · Scene Vector

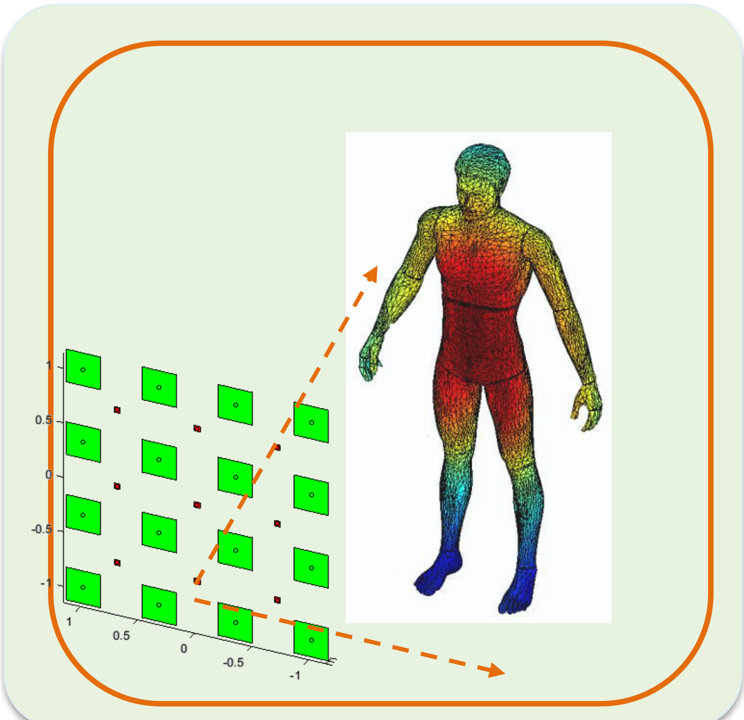
$$\begin{pmatrix} g_1 \\ g_2 \\ \\ g_M \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} & & h_{1N} \\ h_{21} & h_{22} & h_{23} & h_{24} & & h_{2N} \\ \\ h_{M1} & h_{M2} & h_{M3} & h_{M4} & & h_{MN} \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ \\ f_M \end{pmatrix}$$

$$h_{ij} \approx E^{TX}(\mathbf{r}_s - \mathbf{r}_i) E^{RX}(\mathbf{r}_s - \mathbf{r}_j)$$

- Meas. Modes = (freq. steps)(transmit panels)(receive panels)
- Inverse is ill-posed, but matched filter or iterative minimization process can be used (TwIST, etc.):

$$f_{est} = H^{\dagger} g \qquad f_{est} = \arg\min_f \| Hf_{est} - g \|_2^2 + \lambda R(f_{est})$$

System Optimization (Virtualizer Simulator)



Optimization is best performed with a customized simulation software suite (Virtualizer):

- Simplified forward model based on the Born Approximation (no multi-path effects)
- Panels discretized into magnetic dipoles and fields calculated with greens function propagator

The return signal — *The receiver rad. pattern* — *The scene's scattering coefficient*

$$g(\omega) \propto \int \vec{E}_T(\omega,\vec{r}) \cdot \vec{E}_R(\omega,\vec{r}) \sigma(\vec{r}) d\vec{r}^3$$

The transmitter rad. pattern

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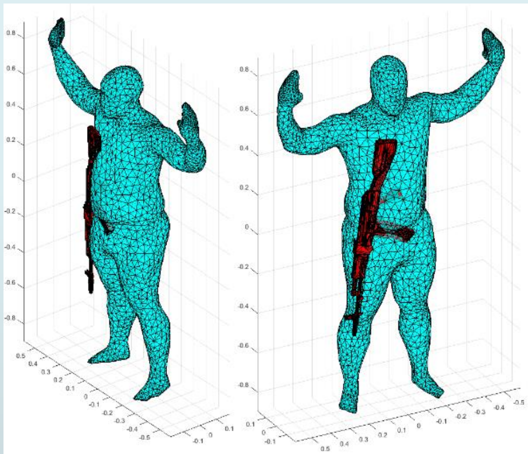
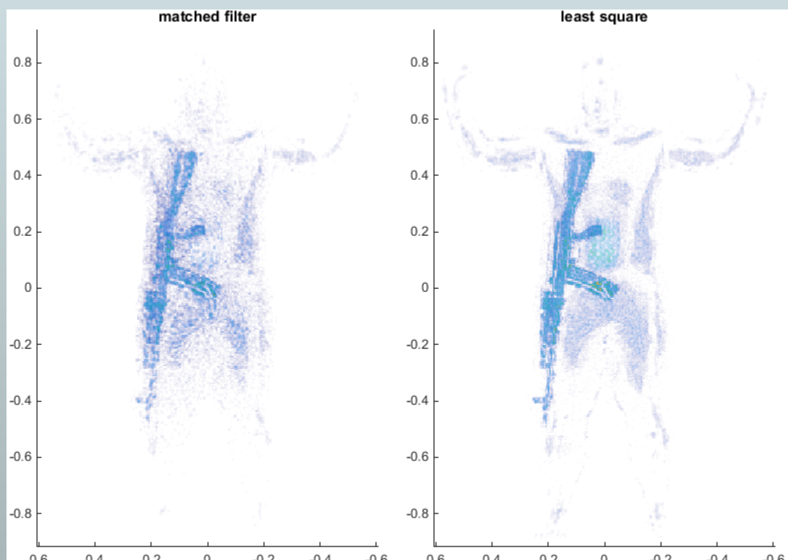
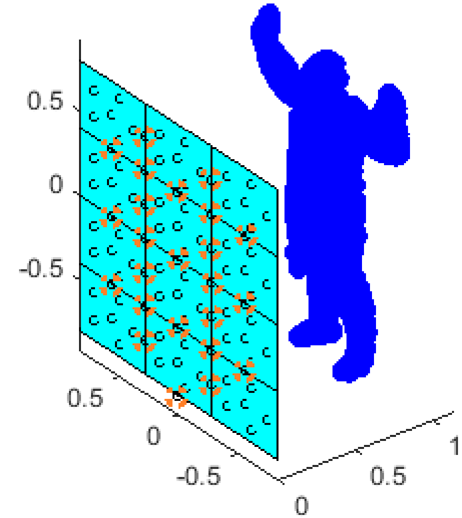
Virtualizer Capabilities







The Virtualizer allows “statistical” optimization of the system (but not direct analytic predictions):

- Analysis of panel/probe Layout
- Analysis of the panel design (element Q, size, feeding)

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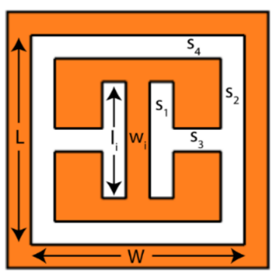
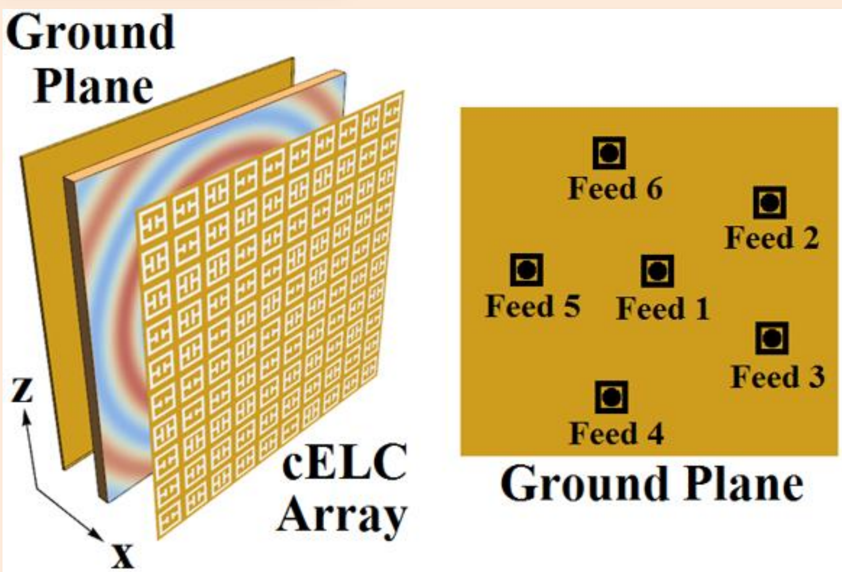
MetaAntenna (Scene Encoder)

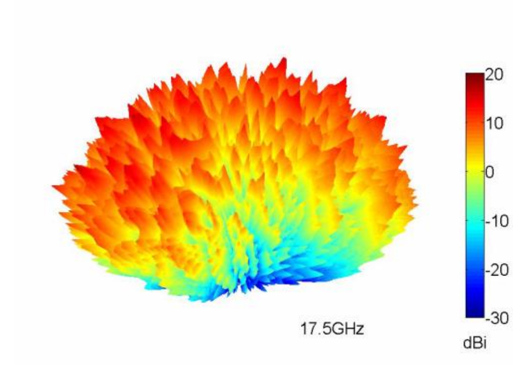
cELCs Design



Each element radiates as a magnetic dipole, with polarizability of:

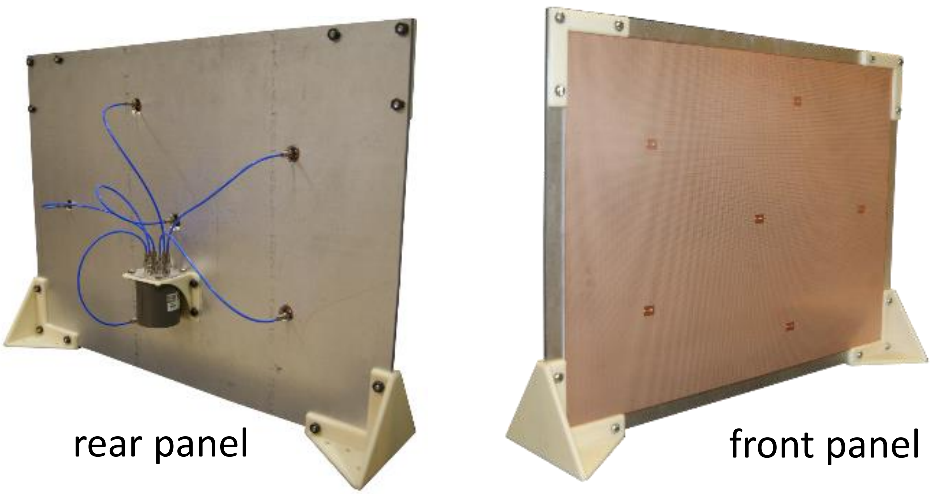
$$\alpha_m(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\gamma}$$

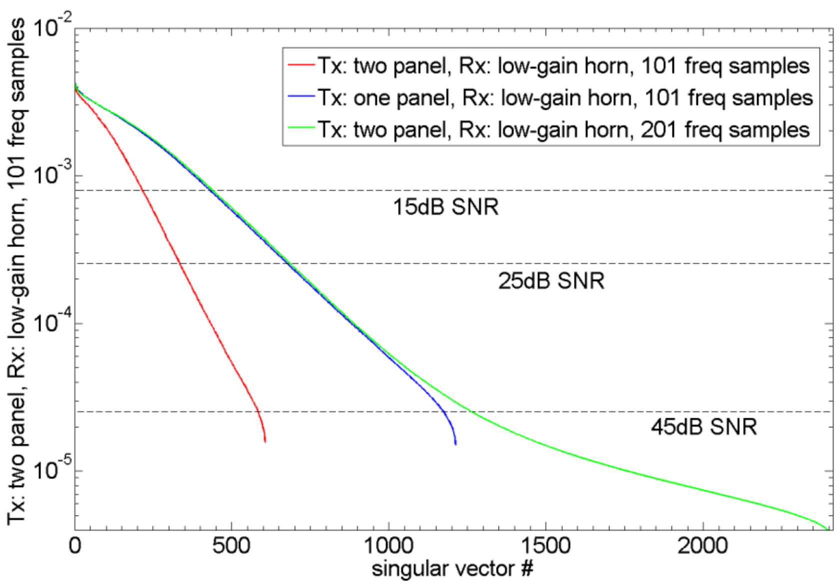




- Aperture consists of metamaterial elements with random resonance frequencies.
- Aperture produces diverse modes as a function of frequency.
- Frequency scan encodes scene information on frequency measurements (18-26 GHz). Both range and cross-range measured.

Panel Fabrication

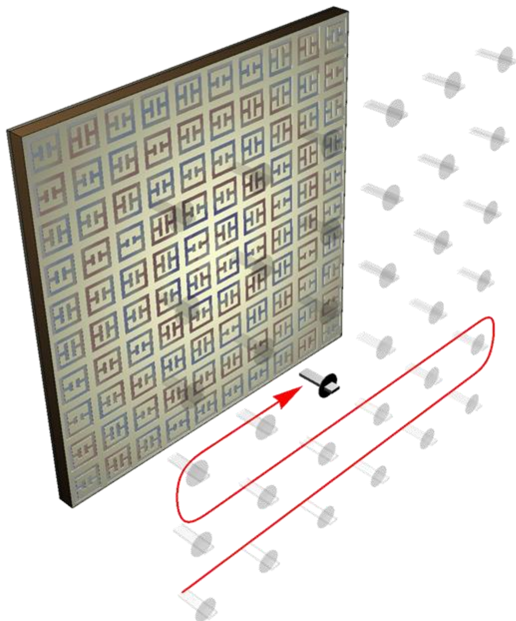




Single Panel Specs

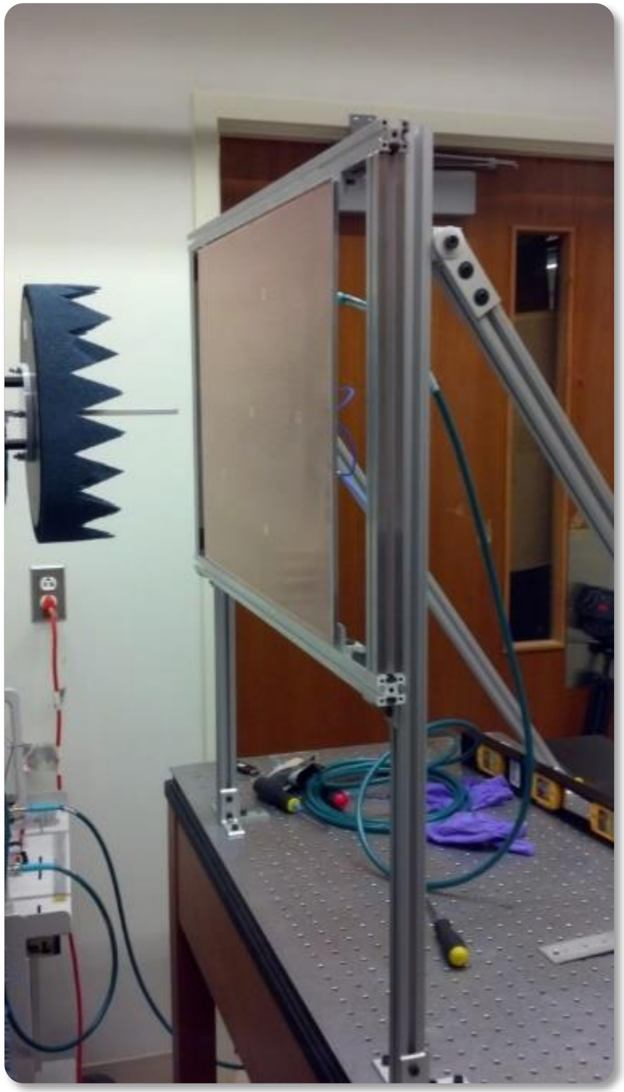
- 56 cm x 44 cm.
- Frequency diversity: 101 independent modes.
- Spatial diversity: 6 feed points.
- ~600 measurement modes, *maximum*.
- Noise reduces number of measurement modes.
- Single low-gain probe for receive.

Panel Characterization

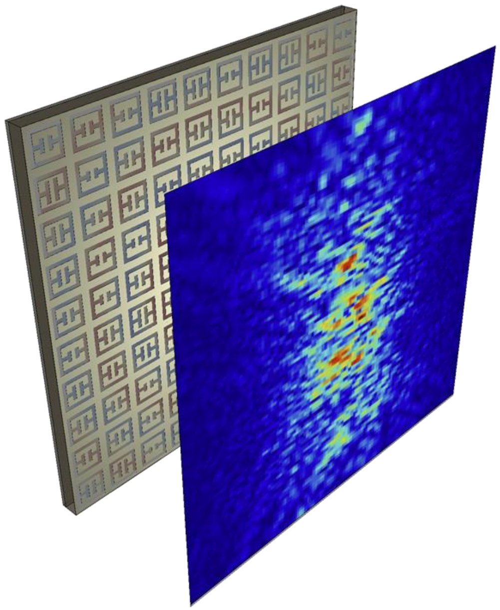


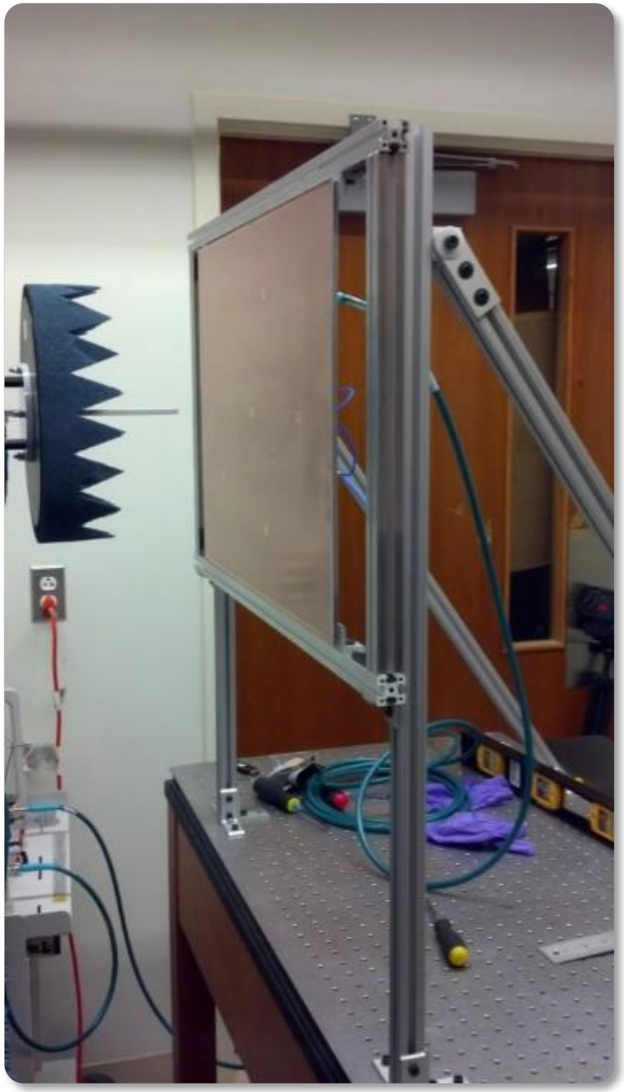
NEAR-FIELD SCANNING

- Complex apertures require detailed characterization of radiated fields.
- Scan area: 76.5 x 68.5 cm^2; step size 5 mm.
- 21k samples.
- 12.1 hours per polarization (6 feeds, 101 frequency samples).



Determining Measurement Matrix





H Generation

- For full scale imaging scene at diffraction limit, 30+ GB of data must be accessed (big data challenges).
- The H-matrix is built on the fly from a set of field lookup tables over the imaging regime.

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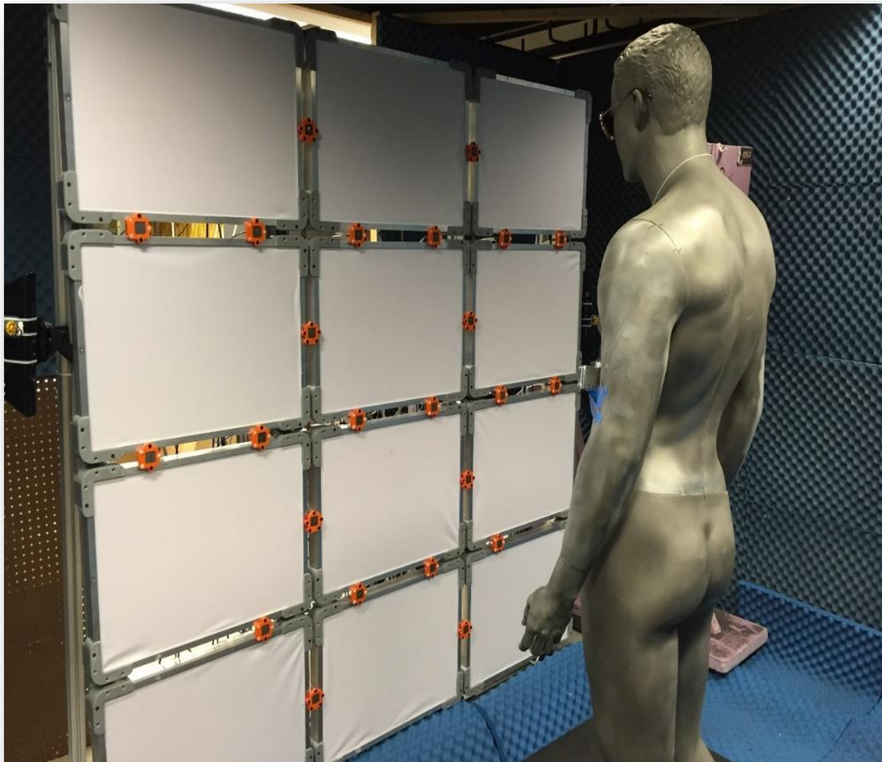
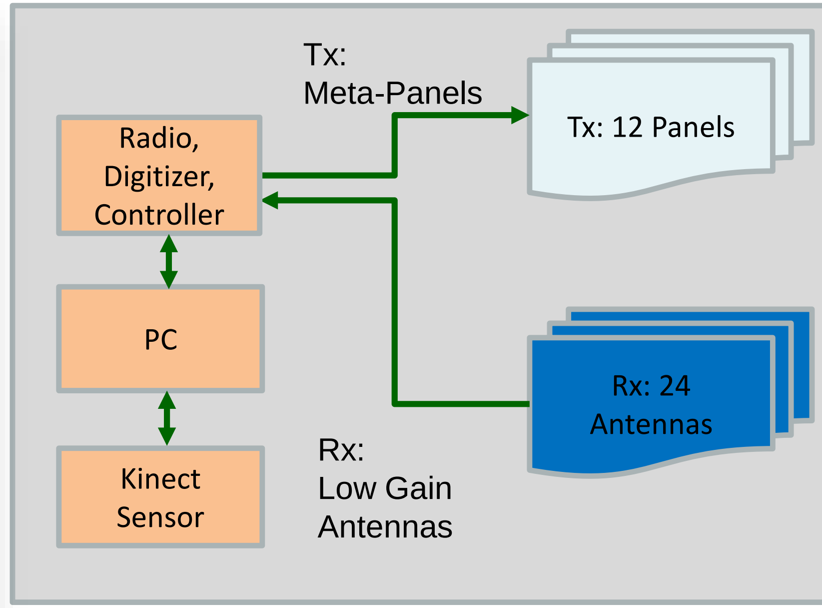
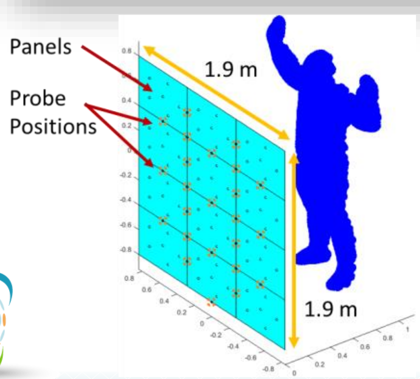
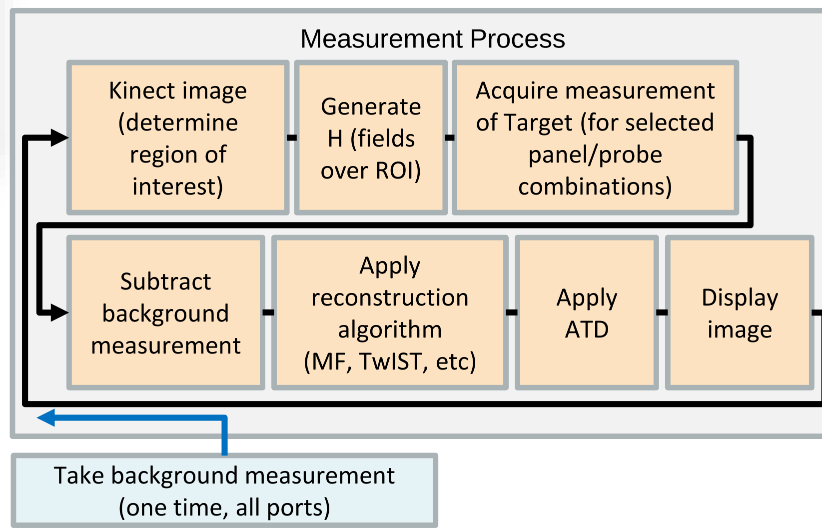
MetaImager: Architecture









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Imaging Results (under review for release)

- Imaging Status: Imaging full-size mannequin target and threat objects
  - Metallic phantoms are clearly observed and dielectric objects have secondary observable properties that can be used for detection
- Reconstruction time: ~1 minute per image (90% is data acquisition that is the result of mechanical switching).
  - Utilizing advanced factorization algorithm for reconstruction.
- Resolution: At the aperture diffraction limit for small objects (<1 cm).
- System architecture: composed of a few core components (single radio, passive panels/probes, and a switching network).

Future System Improvements

- Speed: (Next phase is targeting 10 fps)
  - Moving to electronic switching
  - Upgrading the radio for parallel data acquisition and faster sweeping.
  - Improving panel radiation diversity, Q (reducing the number of necessary measurement modes)

Image Quality: (Coverage)

- Redistribution of panel/probe layout to improve viewing angles
- Implementing multiple look techniques (further down the road)

Summary

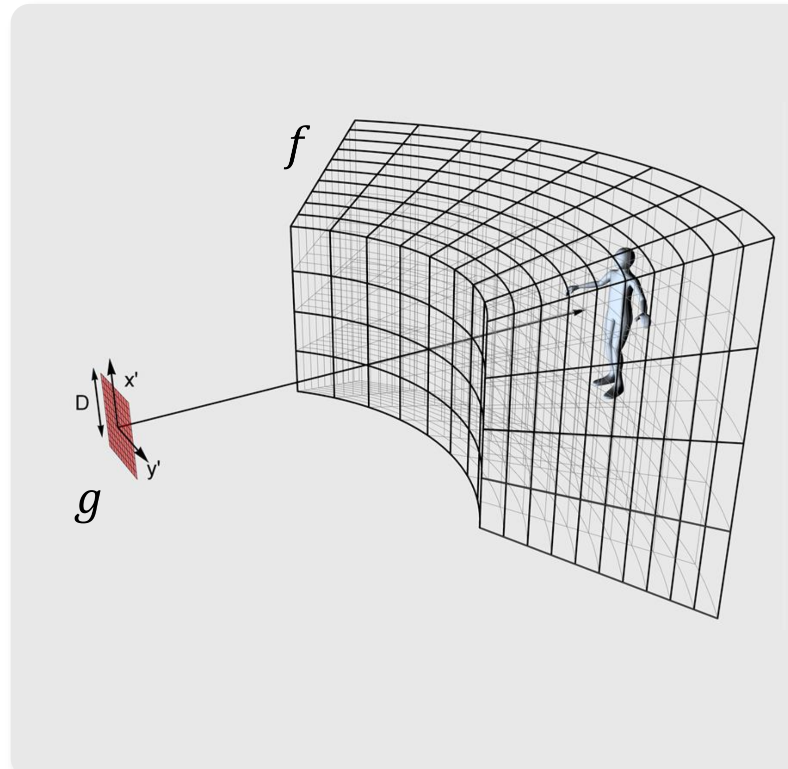
- The MetaImager approach, combined with computational imaging techniques, provides a path towards a real-time security imaging devices and economical deployment of them.
- The Meta-Imager concept can support new strategies for security screening (sensor fusion, redistribution, etc.).

Backup Slides

Computational Imaging

- The scene is represented by a reflectivity function.
- Measurements of the scene can be taken, represented by, either parallel or sequential.
- A *forward model* relates scene reflectivity to the measurements.
- The basic imaging equation can be written:

$$g(\mathbf{x}) = \int H(\mathbf{x},\mathbf{x}')\, f(\mathbf{x}')\, d\mathbf{x}'$$



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Characterizing Imaging Quality

> The set of measurement modes can be characterized by their singular value spectrum:

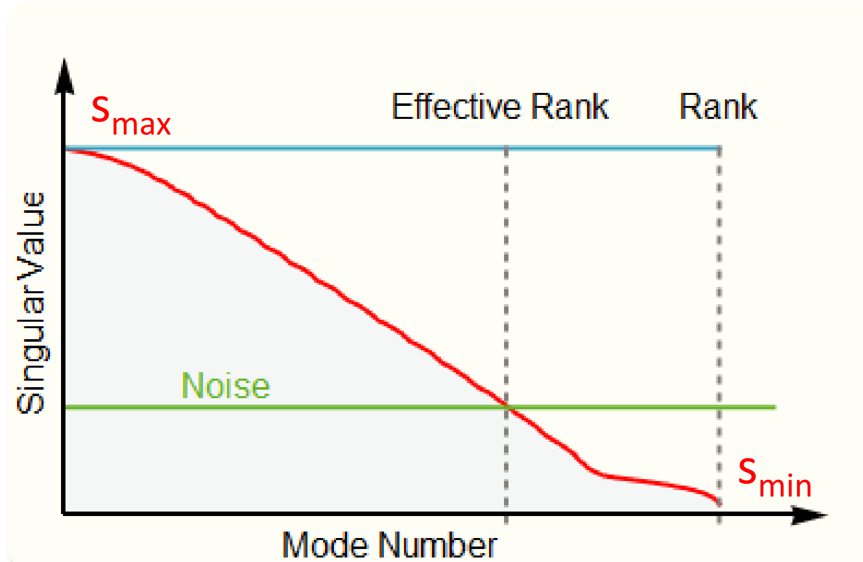
$$H = USV^{+}$$

> If H is NxM, then Σ is NxM diagonal matrix of positve real values.

> Uncorrelated modes have a flat spectrum, while correlated modes lead to non-flat SV.

> Condition number relates the ease of matrix inversion

> Presence of noise truncates SV spectrum (introduces effective rank)



Singular value decomposition relates the actual information contained in the measurement modes over a given imaging regime.