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3-D MIMO-SAR IMAGING USING MULTI-CHIP CASCADED MMWAVE SENSORS

Muhammet Emin Yanik[1], Dan Wang[2], and Murat Torlak[1]

[1]Dept. of Electrical and Computer Engineering, The University of Texas at Dallas
[2]Radar and Analytics, Texas Instruments

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Semiconductor Research Corporation
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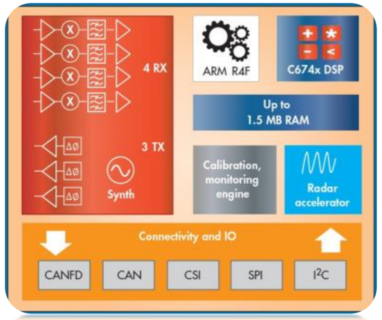
MOTIVATION

- 3-D holographic millimeter-wave (mmWave) imaging technology has a wide range of applications including security, packaging, automotive, medical, aerial imaging, etc.

Texas Instruments



System-on-Chip Solutions

L3

Problems:

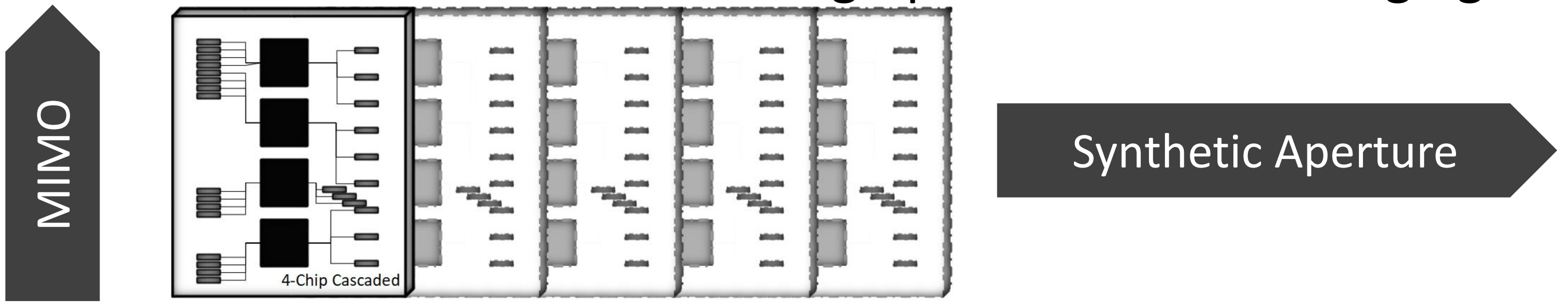
- Achieve high-resolution with as few antenna elements as possible
- Multiple-input multiple-output (MIMO) radars increase the degrees of freedom
- The complexity of extremely dense transceiver electronics limits the use of MIMO-only solutions

Proposed Solution:

- Hybrid concepts combining synthetic aperture radar (SAR) techniques and MIMO arrays:
  - Present a good compromise to achieve short data acquisition time and low-complexity.

RESEARCH OBJECTIVES

- Use 4-chip cascaded radar board in near-field 3-D holographic MIMO-SAR imaging



- Develop a novel and complete signal processing chain from data capture to image reconstruction

- Design a system-level imager prototype to demonstrate the proof-of-concept
  - Understand the challenges
  - Develop toolset and algorithms
  - Work towards real-world applications

DATA CAPTURE

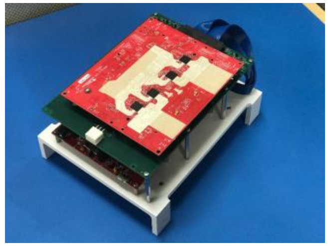
Problem:

- Develop a system to capture real MIMO-SAR data for demonstration

1 Data Capture → Near-Field Calibration → 3-D Image Reconstruction

Tasks:

- Develop familiarity with 4-chip cascaded mmWave board and data collection toolset



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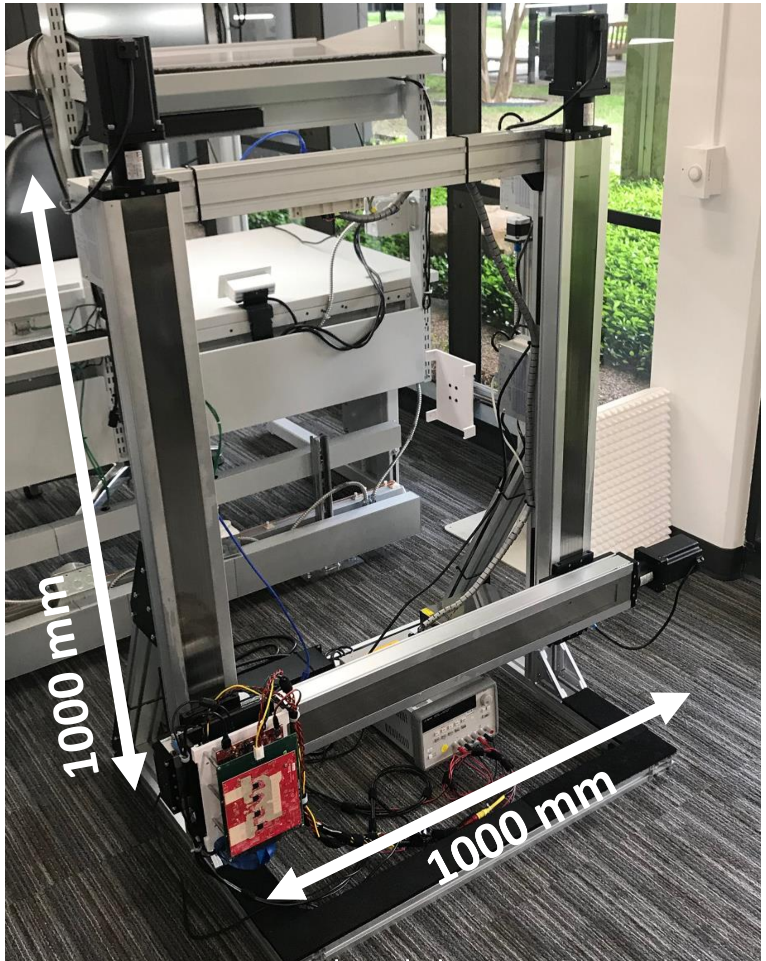
+ MATLAB

- Build a 2-D mechanical scanner to synthesize a larger aperture
- Integrate 4-chip cascaded board to the scanner
- Develop a complete software package in MATLAB to capture MIMO-SAR data

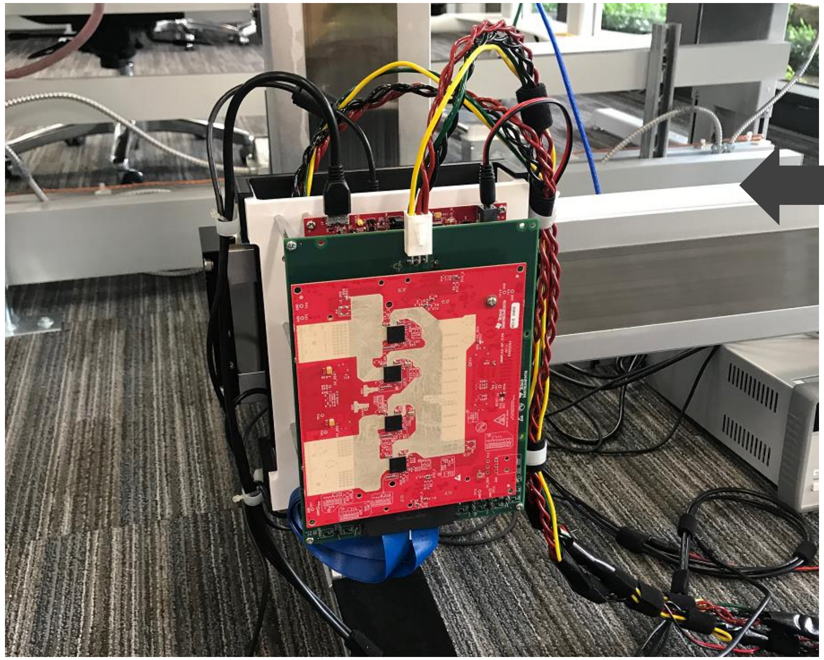
DESIGNING A NEW IMAGER PROTOTYPE

- A mechanical scanner has been designed, multi-chip cascaded sensors has been integrated

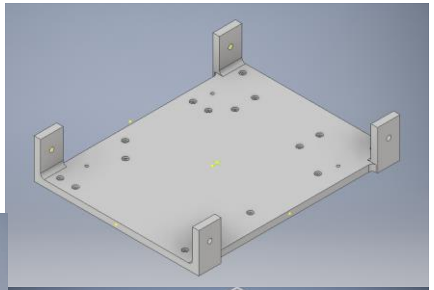


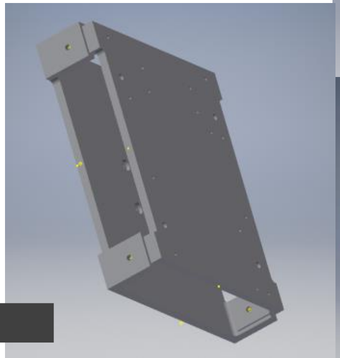
- Acknowledgement: Pete Mendoza

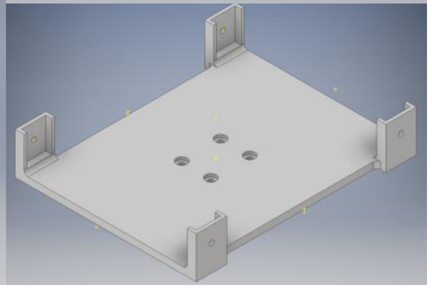
- Scanning area:
  - **1000 mm by 1000 mm**
- Maximum speed:
  - **400 mm/s at both axes**



- 3D printed.



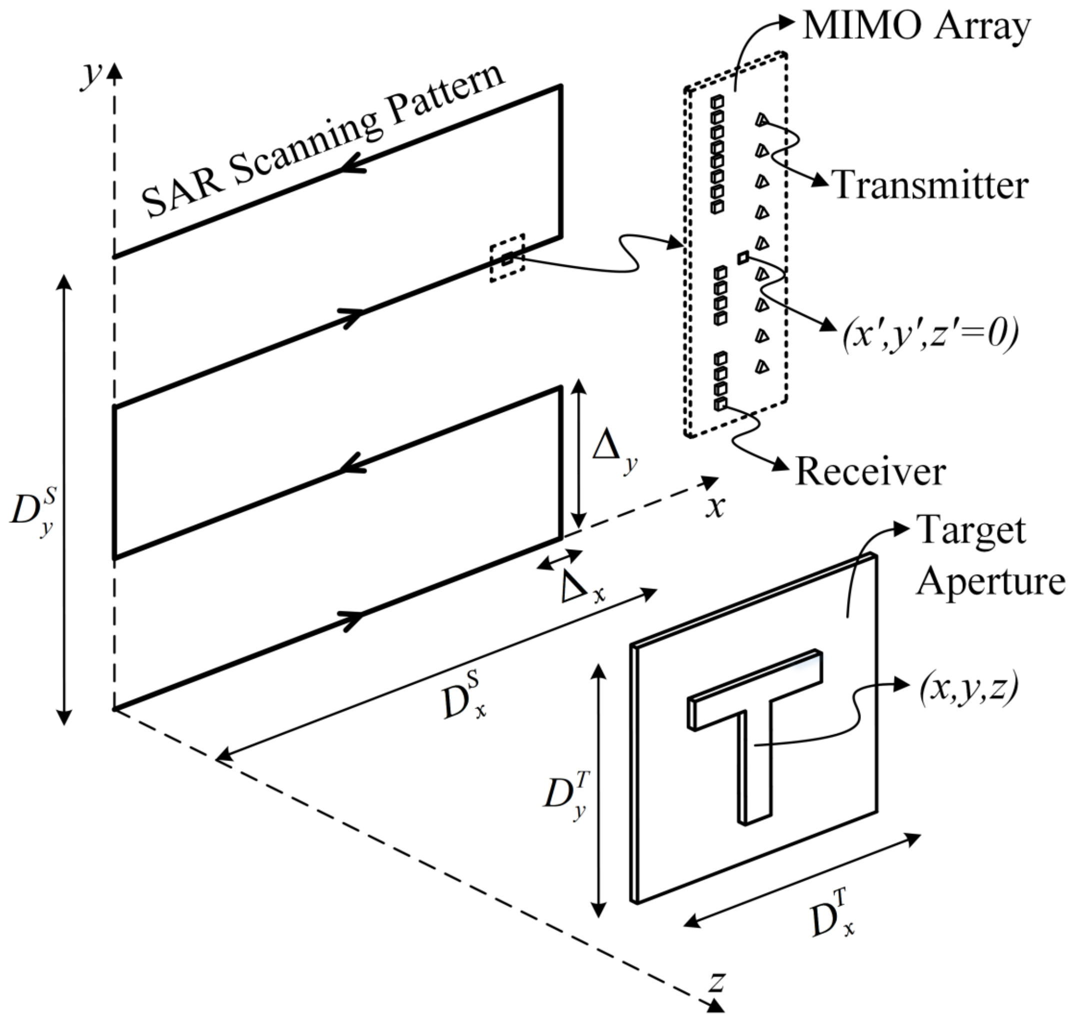




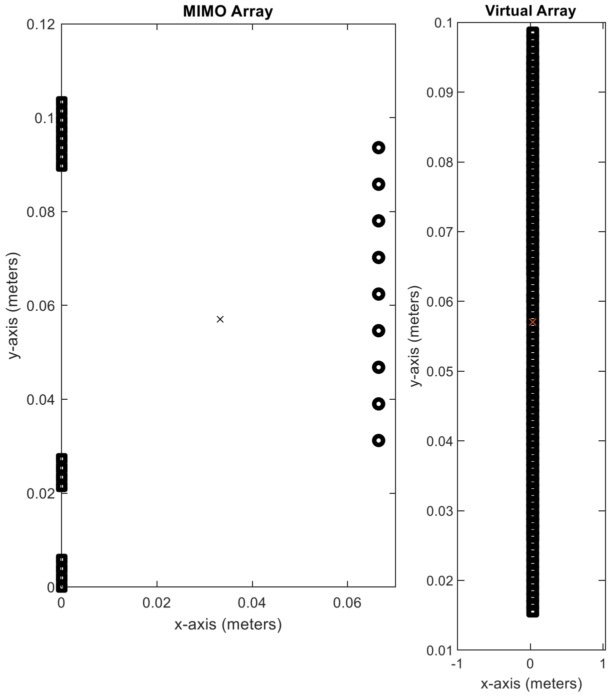
- The mmWave sensor hardware stack is integrated:
  1) 4-Chip cascaded board
  2) TSW14J56
  3) Mother Board + Adapter Board

4-CHIP CASCADED BASED MIMO-SAR SYSTEM

- Data collection is performed by moving the **4-chip cascaded MIMO radar** along a trajectory in $x - y$ plane



- MIMO array topology of 4-chip cascaded (9Tx and 16Rx)
- 86 non-overlapped virtual channels



- Typical SAR parameters:

$D_x^S = D_y^S \approx 400$ mm

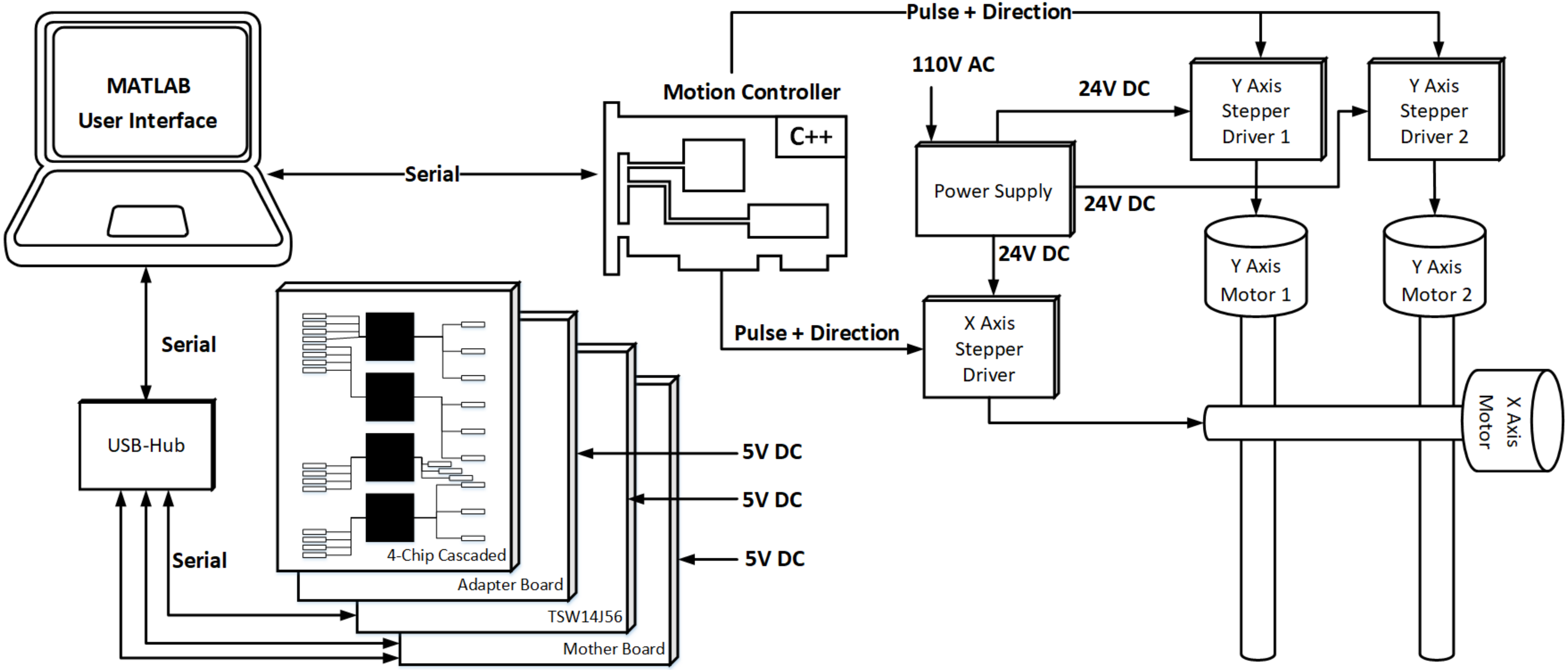
$\Delta_y \approx 83.86$ mm

# of vertical scans = 5

$85\lambda/4 = 82.88$ mm

HIGH-LEVEL SYSTEM ARCHITECTURE

- MATLAB GUI is developed to control the platform and the radar



- Radar hardware is integrated into MATLAB GUI
- Two-axis rail system is integrated into MATLAB GUI

DATA CAPTURE GUI – SAR SCENARIO GENERATION SCREEN

SAR configuration page:

- Fully automated process

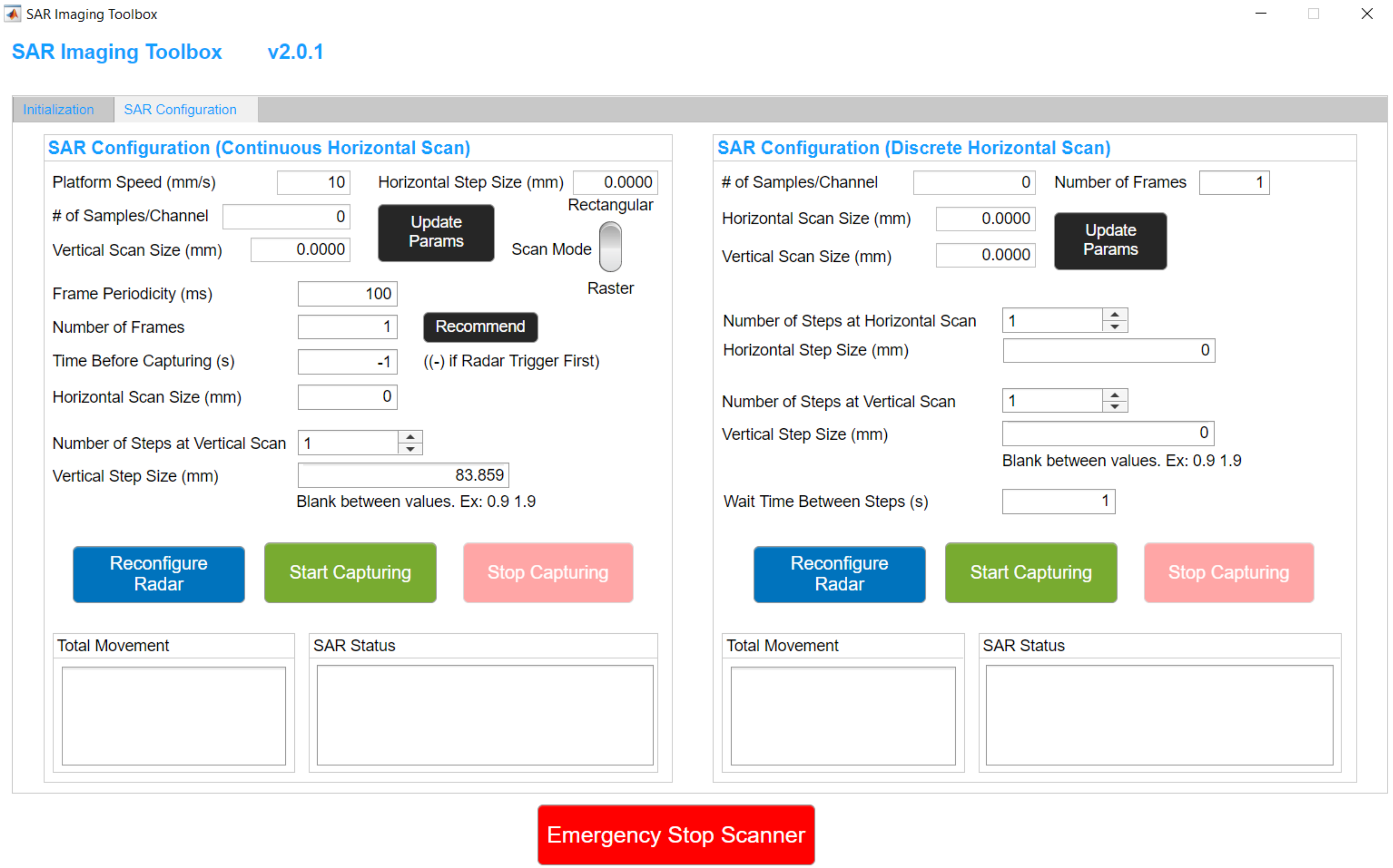
Define sensor configuration

↓

Define SAR configuration

↓

Run SAR scenario and capture data



NEAR-FIELD MIMO ARRAY CALIBRATION

Problem:

- In a practical system, measurement errors in the MIMO array arise due to antenna gain and phase mismatches (because of imperfections in antenna layouts on the board: **RF delays**, etc.)
- Uncorrected phase error leads to unacceptable defocused blur and range shift in images

Tasks:

- Propose a calibration method based on the ideal backscattered signal model from a reference point target

Solution:

- The uncalibrated measured beat signal: $\tilde{s}_\ell(t) = a_\ell e^{j2\pi(f_0+Kt)\underbrace{(\tau_i+\tau_\ell)}_{\text{The total round-trip delay}}}$
- Rewrite: $\tilde{s}_\ell(t) = \underbrace{a_\ell e^{j\psi_i}}_{\eta_\ell} e^{j2\pi f_i t} \underbrace{s_\ell(t)}_{\text{Reference beat signal}}$
- Estimate: $f_i = K\tau_i$ and η_ℓ

NEAR-FIELD MIMO ARRAY CALIBRATION

- The accuracy of the presented approach depends on the reference beat signal
- The target needs to be precisely positioned in calibrating process!

Near-Field Calibration → ❶ Estimate the position of the reference target → ❷ Estimate the calibration parameters

❷ Given the measurements $\tilde{s}_\ell(t)$, the calibration error signal can be computed by:

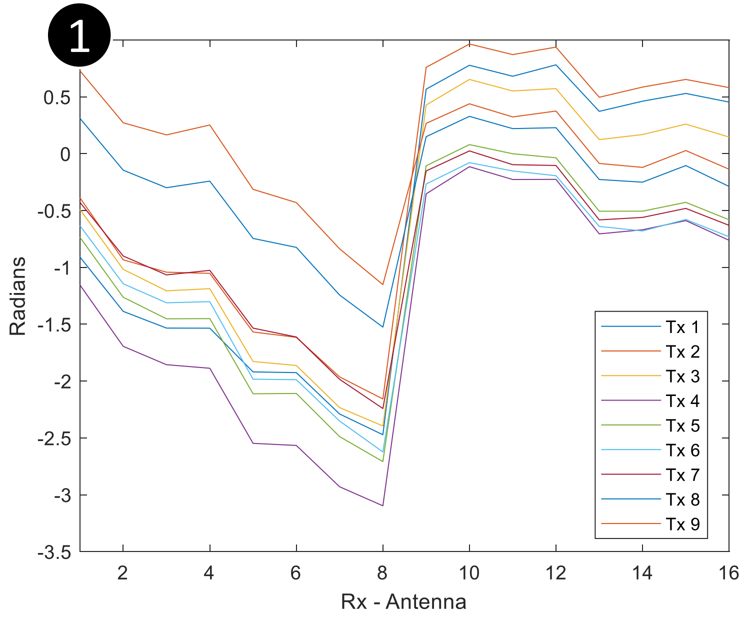
$$w_\ell(t) = \tilde{s}_\ell(t) s_\ell^*(t) = \underbrace{\eta_\ell e^{j2\pi f_i t}}$$

- Simple demodulation process
- Parameter estimation problem of a single-frequency complex tone

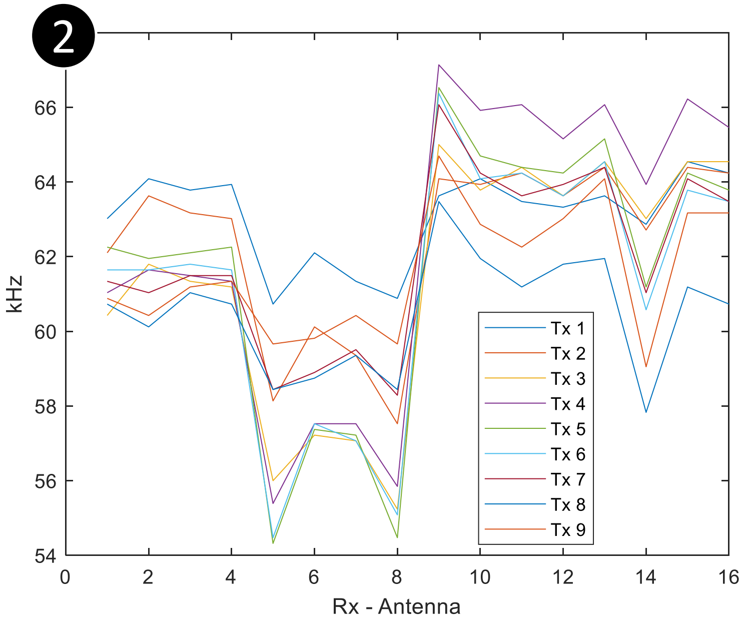
- Estimate: $\hat{f}_i = \arg\max \sum_{<\ell>} |W_\ell(f)|^2 \qquad W_\ell(f) = \int_o^T w_\ell(t) e^{-j2\pi f t} dt$
- Estimate η_ℓ by plugging the estimate $\hat{f}_i$ into $w_\ell(t)$

NEAR-FIELD MIMO ARRAY CALIBRATION

- Simulate the backscattered signal for each channel based on the exact target location
- Calculate complex calibration data η_ℓ and range (beat frequency) offset $K\tau_i$



Complex calibration data



Beat frequency offset

3-D MIMO SAR IMAGE RECONSTRUCTION IN NEAR-FIELD

Problems:

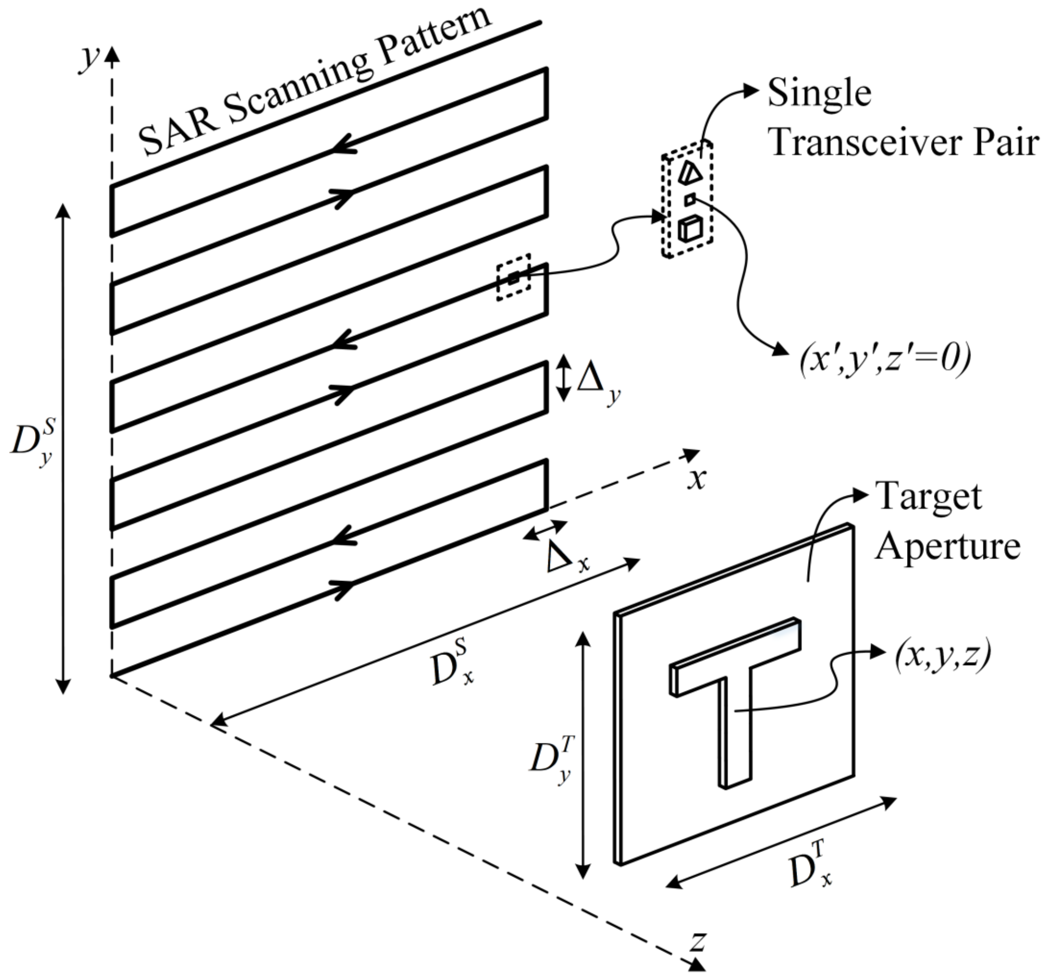
- Near-field: the plane-wave assumption is invalid and the spherical wave model has to be used
- MIMO sampling: different trajectories of the incident and reflected electric fields has to be considered
- Proposed algorithm has to be computationally efficient

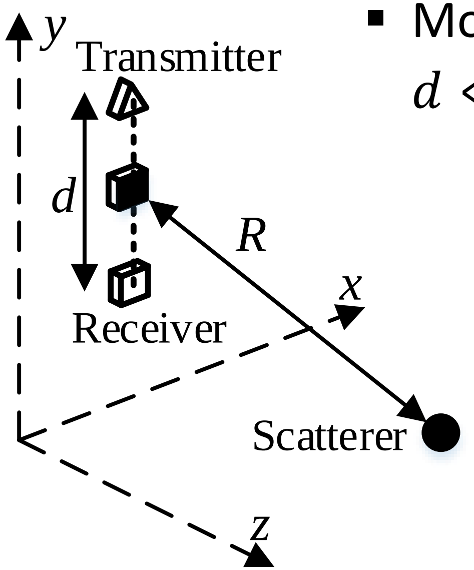
Tasks:

- Develop low-complexity and novel image reconstruction algorithms for MIMO-SAR configuration
- Validate the algorithms using simulation environment
- Demonstrate the real high-resolution 3-D imaging results using prototyped imager

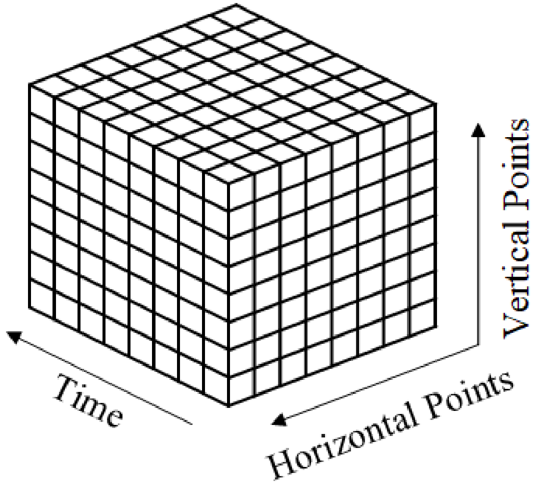
CONVENTIONAL SAR SYSTEM CONFIGURATION

- The complex "**beat**" signal: $s(t) = \sigma \exp(j2\pi(f_0\tau + K\tau t - 0.5K\tau^2))$ Delay: $\tau = 2R/c$ Gain: $\sigma = p/R^2$





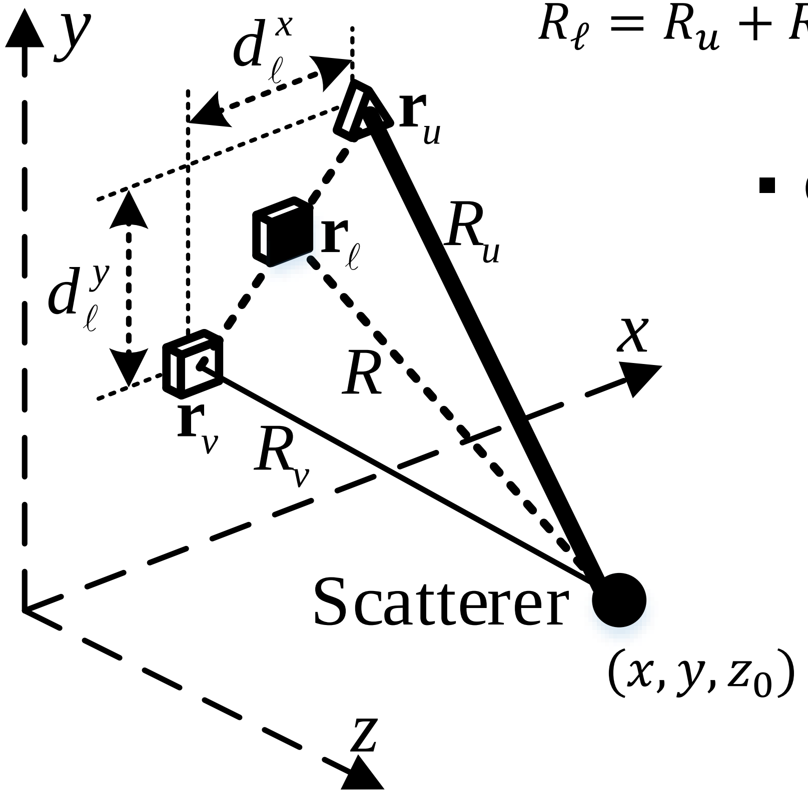
- Monostatic approximation: $d \ll \sqrt{4\alpha\lambda R}$



- 3-D radar cube is captured as $s(x', y', t)$
- The target image is characterized by:
  - 3-D reflectivity function $p(x, y, z)$
- **Goal:** Estimate $p(x, y, z)$ from $s(x', y', t)$ **efficiently**

MULTISTATIC EFFECT IN NEAR-FIELD

- Midpoint approximation: $|\mathbf{r}_u - \mathbf{r}_v| \le \sqrt{4\alpha\lambda R}$ for a small α doesn't hold in near field
- The total round-trip distance for the ℓ-th virtual channel



$$R_\ell = R_u + R_v = \sqrt{(x_u - x)^2 + (y_u - y)^2 + z_0^2} + \sqrt{(x_v - x)^2 + (y_v - y)^2 + z_0^2}$$

- Complex solution: $s_\ell(x', y', k) = \iiint p(x, y, z) \dfrac{e^{jk(R_u + R_v)}}{R_u R_v} dxdydz$
  - Taylor expansion

$$R_\ell \approx 2R + \frac{(d_\ell^x)^2 + (d_\ell^y)^2}{4R} - \frac{\left((x - x')d_\ell^x + (y - y')d_\ell^y\right)^2}{4R^3}$$

  - Multistatic to monostatic phase correction is proposed
  - The received signal by the ℓth hypothetical monostatic element:

$$s_\ell(k) \approx p \frac{\exp(jkR_\ell)}{R^2} \approx s(k) e^{j\phi_\ell(k)} \quad \phi_\ell(k) \approx k \frac{(d_\ell^x)^2 + (d_\ell^y)^2}{4z_0}$$

3-D MONOSTATIC IMAGE RECONSTRUCTION

- Recall the beat signal: $s(t) = \sigma \exp(j2\pi(f_0\tau + K\tau t - 0.5K\tau^2))$ → Residual video phase (RVP) is negligible
- Rewrite in the wavenumber domain as:

$$s(k) = p\frac{\exp(j2kR)}{R^2} \qquad R = \sqrt{(x'-x)^2+(y'-y)^2+z^2}$$

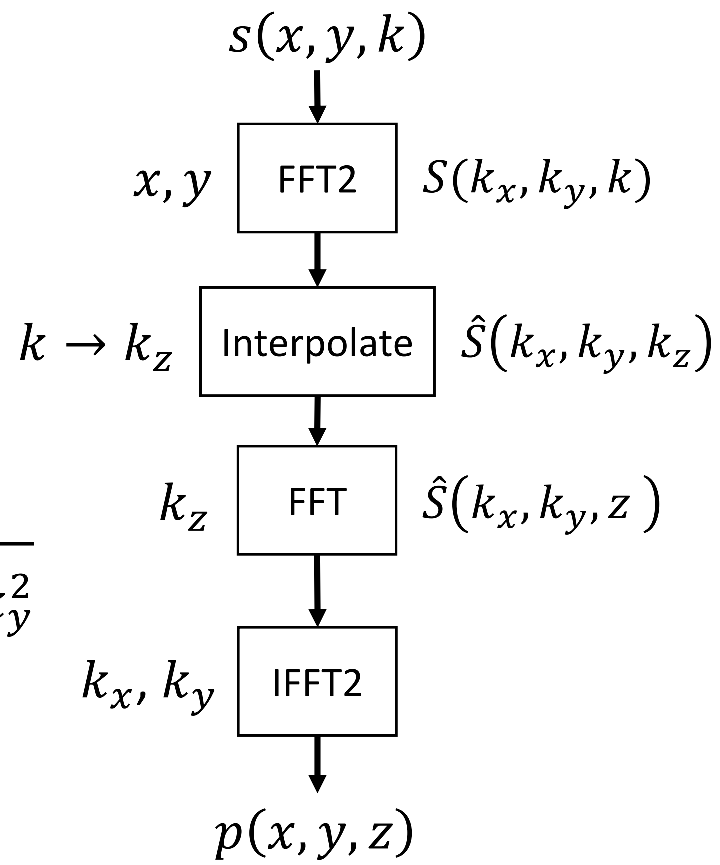
- The received monostatic backscattered data from a 3-D target

$$s(x',y',k) = \iiint p(x,y,z)\frac{e^{j2kR}}{R}dxdydz \qquad R^{-2} \approx (z_0R)^{-1}$$

- Representation of a spherical wave as a superposition of plane waves

$$\frac{e^{j2kR}}{R} = \frac{j}{2\pi}\iint \frac{e^{j(k_x(x'-x)+k_y(y'-y)+k_z z)}}{k_z}dk_x dk_y \qquad k_z = \sqrt{4k^2-k_x^2-k_y^2}$$

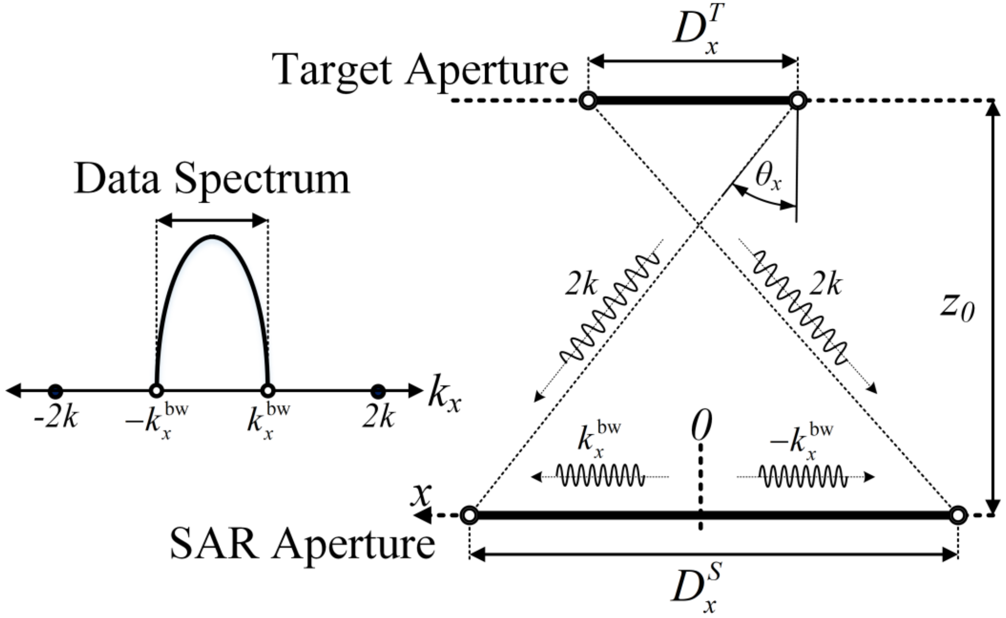
- The final 3-D image in spectral domain: $P(k_x,k_y,k_z) = \hat{S}(k_x,k_y,k_z)$
- Interpolation step with k_z: $k_z S(k_x,k_y,k) \rightarrow \hat{S}(k_x,k_y,k_z)$



- 3-D image formation

PERFORMANCE PARAMETERS – MONOSTATIC ANALYSIS

- Data bandwidth depends on:
  - Wavelength (λ)
  - Size of the radar aperture (D_x^S, D_y^S)
  - Size of the target aperture (D_x^T, D_y^T)
  - Distance between the target and the radar apertures (z_0)



- The total bandwidth:

$$\Delta k_x \approx 2k_x^{\mathrm{bw}} \approx 4k\sin\theta_x$$

- The cross range resolution:

$$\delta_x \approx \frac{2\pi}{\Delta k_x} = \approx \frac{\boldsymbol{\lambda z_0}}{\boldsymbol{2D_x^S}}$$

- Nyquist rate: $k_x^s \geq 2k_x^{\mathrm{bw}} = \dfrac{4\pi(D_x^S + D_x^T)}{\lambda\sqrt{(D_x^S + D_x^T)^2/4 + z_0^2}}$

- Sampling interval:

$$\Delta_x \leq \frac{2\pi}{k_x^s} = \frac{\lambda\sqrt{(D_x^S + D_x^T)^2/4 + z_0^2}}{2(D_x^S + D_x^T)}$$

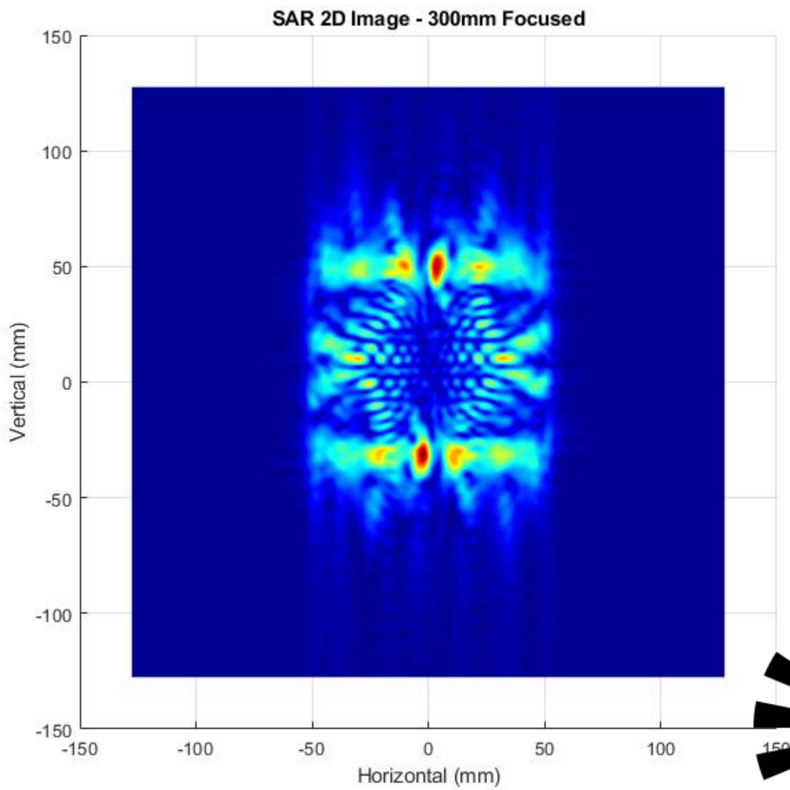
- Phase center concept: $\dfrac{\mathbf{r}_u + \mathbf{r}_v}{2}$ ⟵

- For $D_x^S \gg z_0$

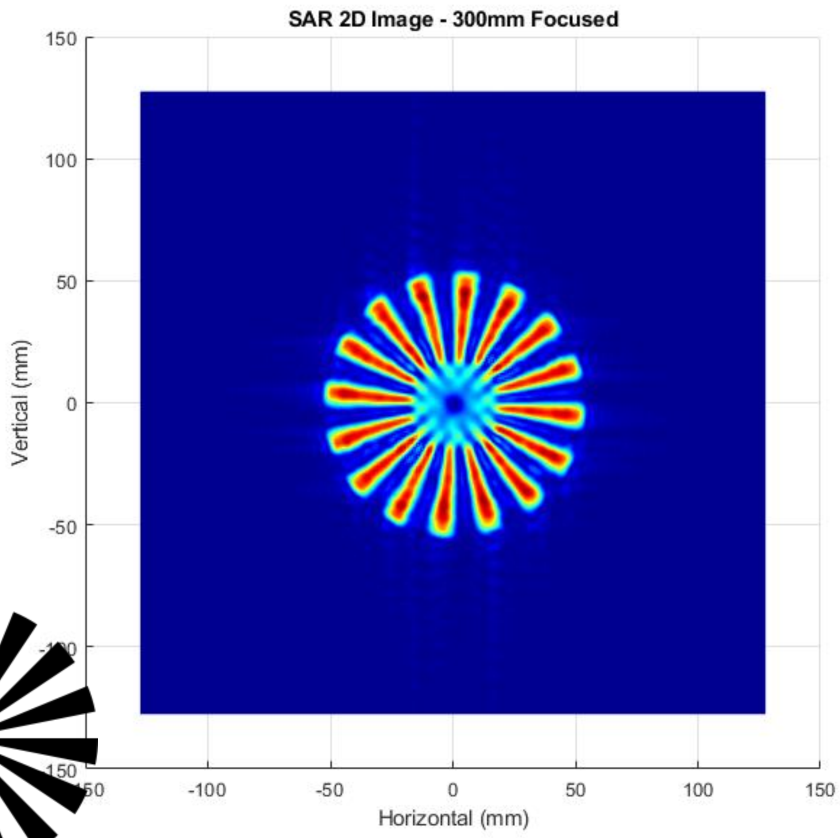
$$\Delta_x \leq \frac{\boldsymbol{\lambda}}{\boldsymbol{4}}$$ Virtual elements!

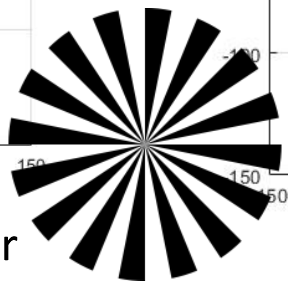
MIMO-SAR SIMULATIONS – MULTISTATIC EFFECT

- Simulated uniform array with 86 non-overlapped virtual elements, **two captures** in vertical axis
  - **Multistatic** data capture
  - Monostatic image reconstruction



  - **After multistatic to monostatic phase correction**
  - Monostatic image reconstruction





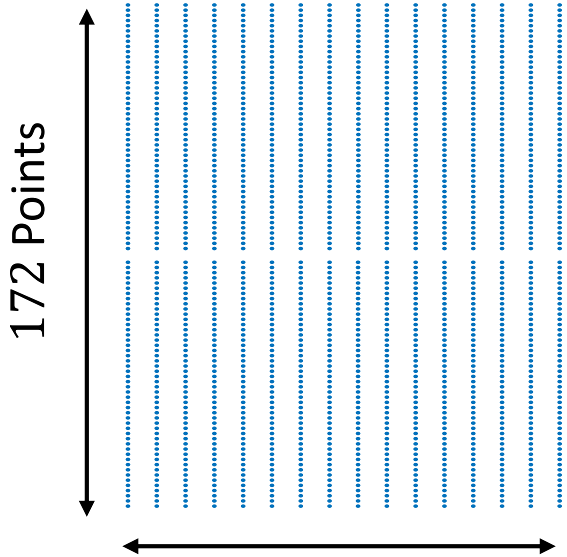
Siemens star

$\Delta_x = \lambda/4 \quad D_x^S \approx 180$ mm

$\Delta_y = \lambda/4 \quad D_y^S \approx 170$ mm

$f_0 = 77$ GHz (Single tone)

$z_0 = 300$ mm

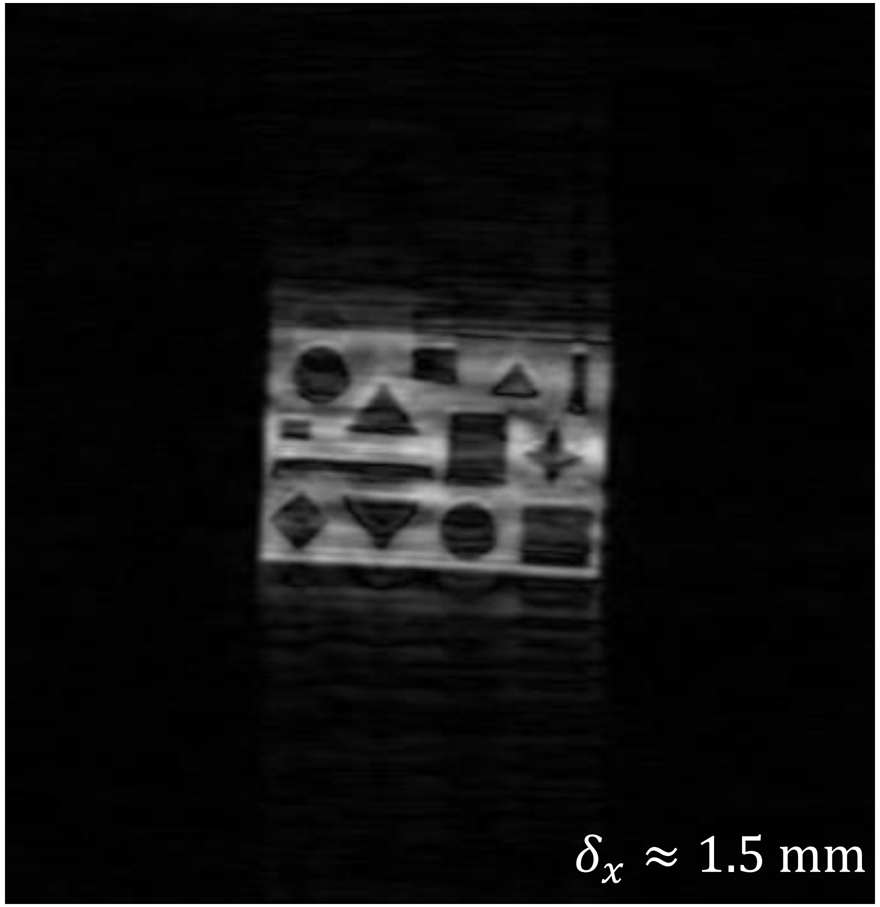


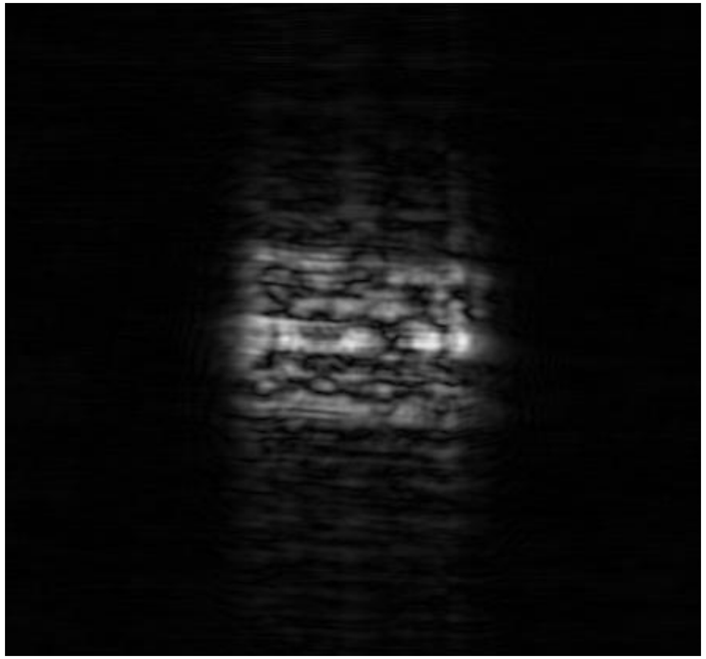
$D_x^S = 180$ mm

$\delta_x = \delta_y \approx 3.6$ mm

MIMO-SAR EXPERIMENTS

- Image reconstruction using 4-Chip Cascaded Radar (86 virtual channels)



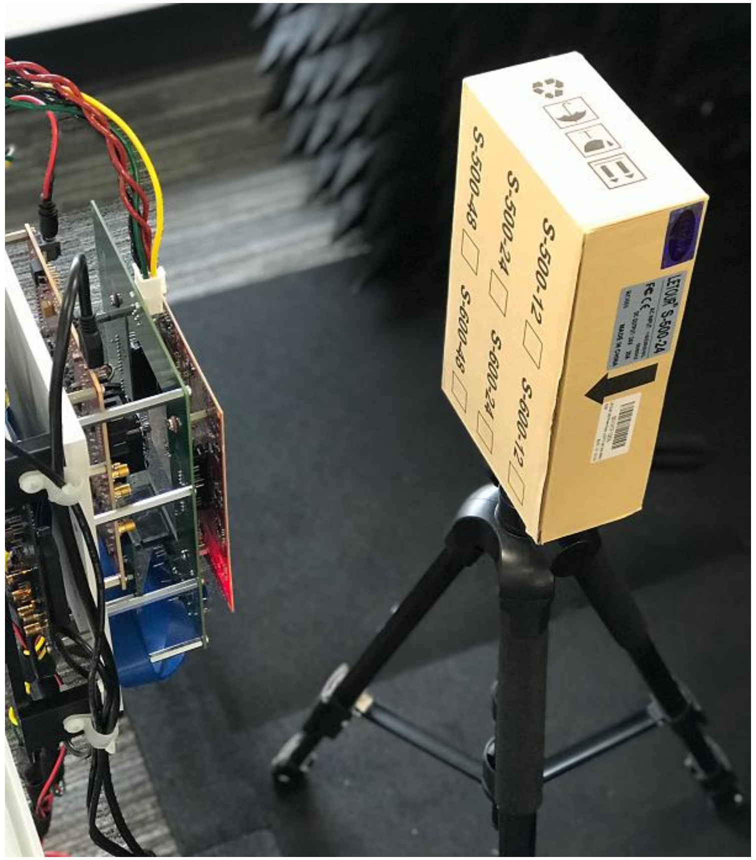


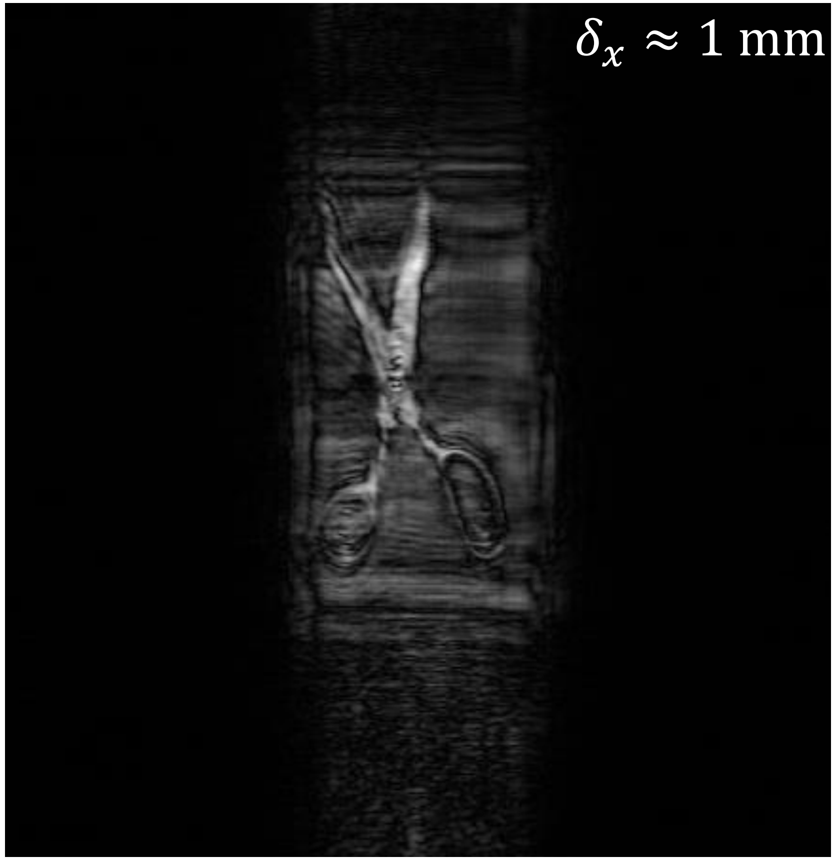
- Image result without calibration!!

$\boldsymbol{D_x^S \approx D_y^S \approx 500}$ **mm** $\quad \Delta_x = 1 \text{ mm} \approx \lambda/4 \quad \Delta_y = 83.859 \text{ mm} = 86\lambda/4 \quad z_0 \approx 400 \text{ mm}$

IMAGING OF CONCEALED PHYSICAL OBJECTS

- Experiment with scissors concealed in a cardboard box
- Image reconstruction using 4-Chip Cascaded Radar (86 virtual channels)





$D_x^S \approx D_y^S \approx 500$ mm $\Delta_x = 1$ mm $\approx \lambda/4$ $\Delta_y = 83.859$ mm $= 86\lambda/4$ $z_0 \approx 250$ mm

SUMMARY

- Developed a near-field mmWave imaging prototype utilizing 4-chip cascaded board in SAR configuration
- Proposed a complete signal processing toolset from data capture to image formation
  - Developed a fully automated data capture software
  - Presented a calibration method for MIMO arrays
  - Proposed an efficient image reconstruction method based on monostatic reconstruction framework
- Investigated the design considerations including the spatial sampling criteria, and image resolution.
- Demonstrated the real imaging results using prototyped imager (1st image of the 4-chip cascaded board)
- Investigated the future improvements and challenges to work towards real-world applications

THE END

THANK YOU

QUESTIONS?