The Radar Musical Instrument

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Hello!

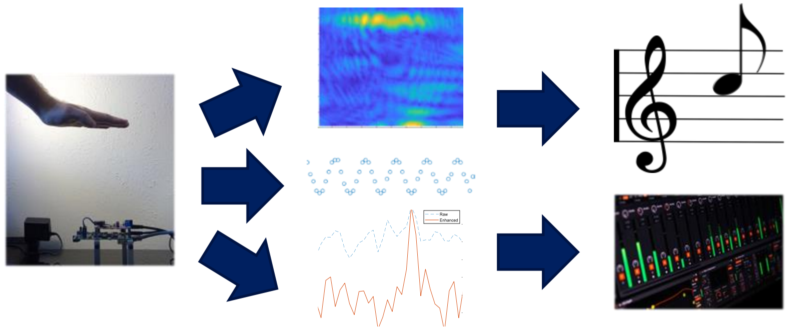
Josiah Smith

- BS Electrical Engineering – UT Dallas
  - Radar + machine learning research
  - 2x senior capstone 1st place (team leader)
  - 3 years start to finish
- PhD Electrical Engineering – UT Dallas
  - Signal processing + hybrid algorithms
  - Radar imaging, tracking, localization
  - 3 years start to finish
- Industry Experience
  - Texas Instruments Research
  - IMEC Research
  - Apple

Ecuador with my wife Morgan

Radar Musical Instrument – Outline

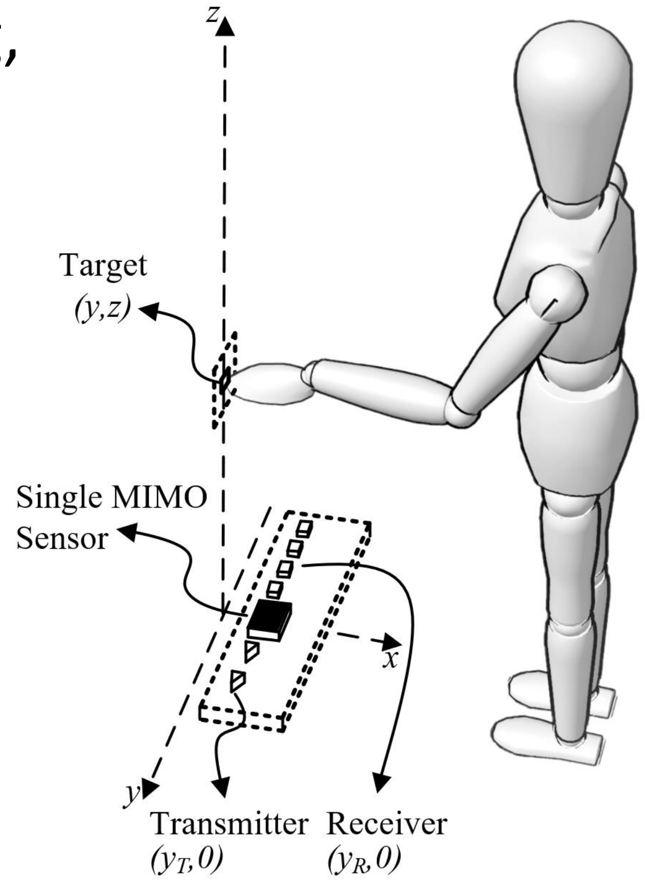
1. Radar Signal Model for Musical Control
   - MIMO-FMCW mmWave Radar
2. Conventional Feature Extraction
   - Range, Cross-range, Doppler Signatures
   - Mapping Spatial and Temporal Features to Music
3. Enhanced Feature Extraction & Tracking
   - Image-to-Image Super-Resolution Neural Processor
   - Doppler-Corroborated Particle Filter



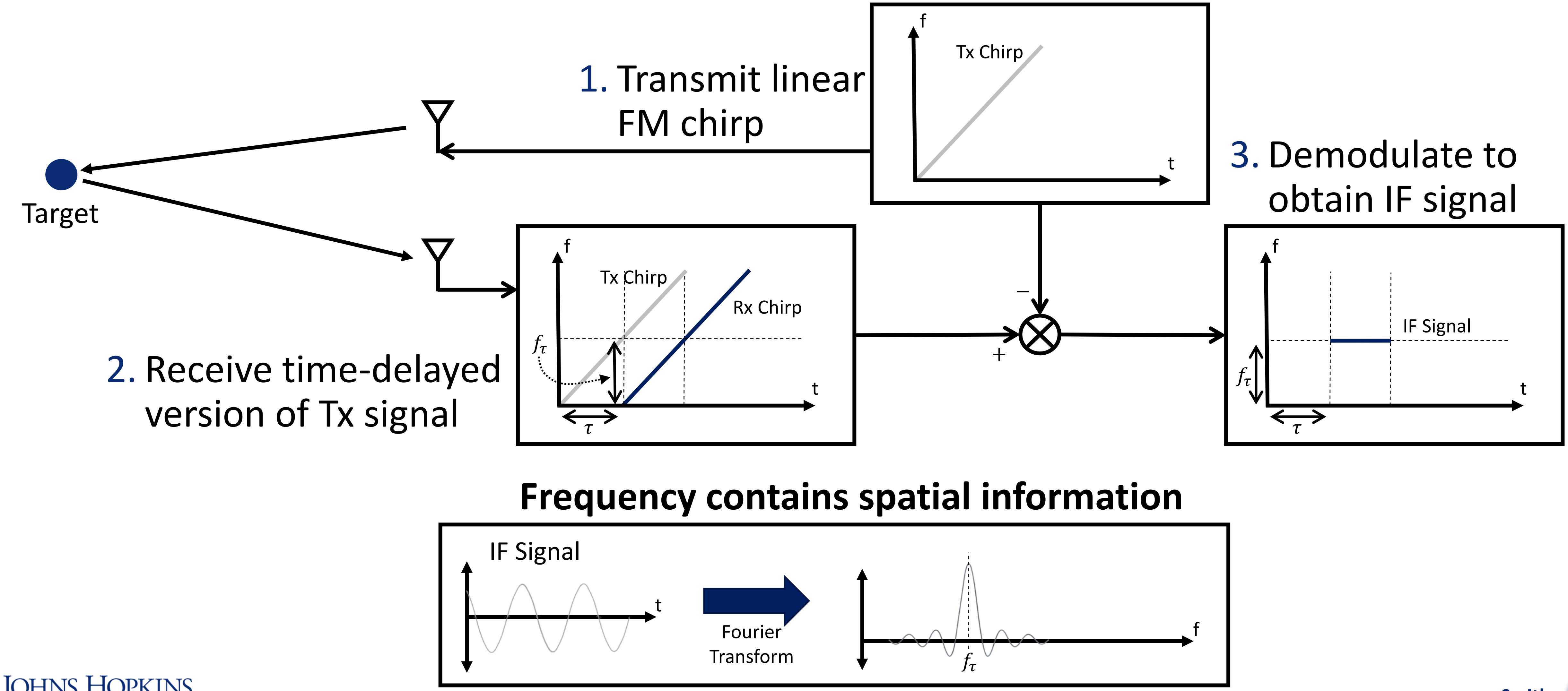
Introduction / Motivation

- Low-cost millimeter-wave (mmWave) radar has a host of applications from commercial sensing, security screening, medical imaging, and **human-computer interaction**

- **Problem Statement:** leverage the richness of the mmWave return signal to create an efficient, high spatial-resolution framework for precise human-computer interaction and digital instrument control.
- Prior work:
  - Camera, RGB+D camera, camera + radar systems, Theremin
  - Issues: spatial resolution, privacy

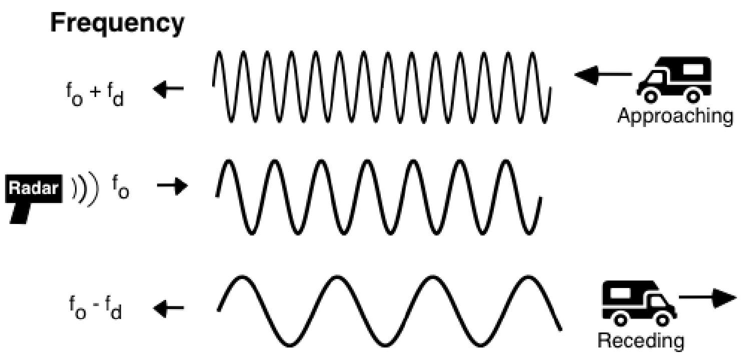


Frequency-Modulated-Continuous-Wave Radar

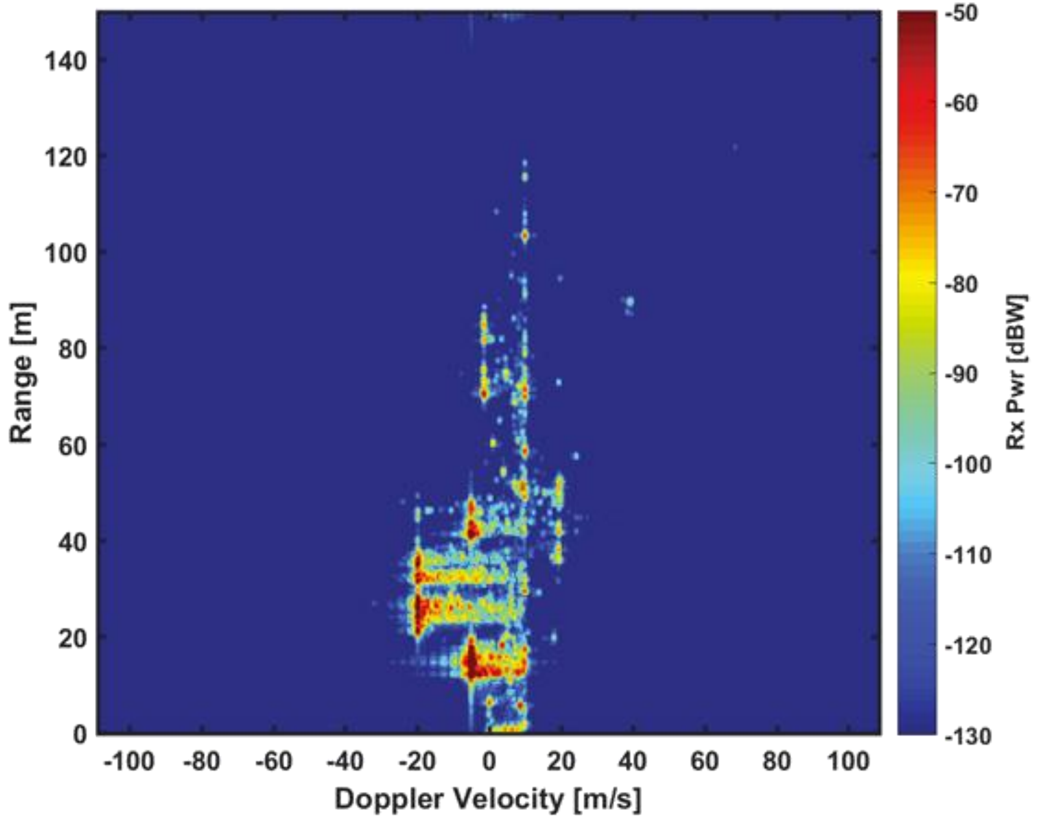


Doppler Radar

- Doppler Effect
  - FFT across multiple FMCW pulses



- Sensing distance: < 1 m
- Goal: 3-D x-y-z localization
- Issue: efficient MIMO near-field image reconstruction



Range-Doppler is not enough

Multistatic-to-Monostatic Compensation

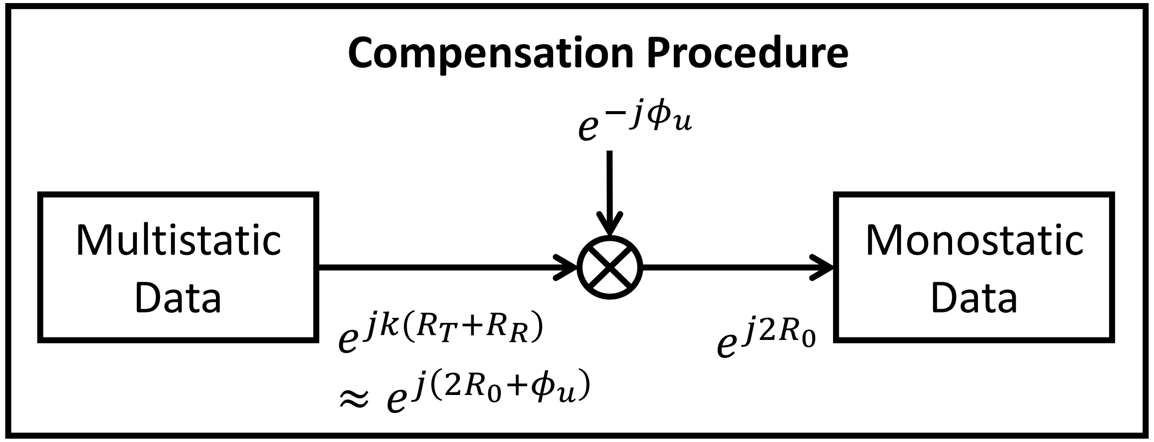
Round-trip distance

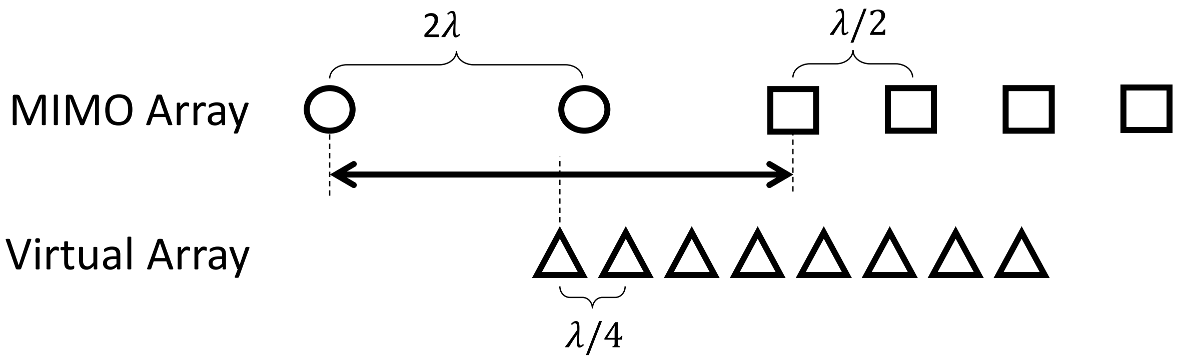
$$R_u = R_T + R_R$$

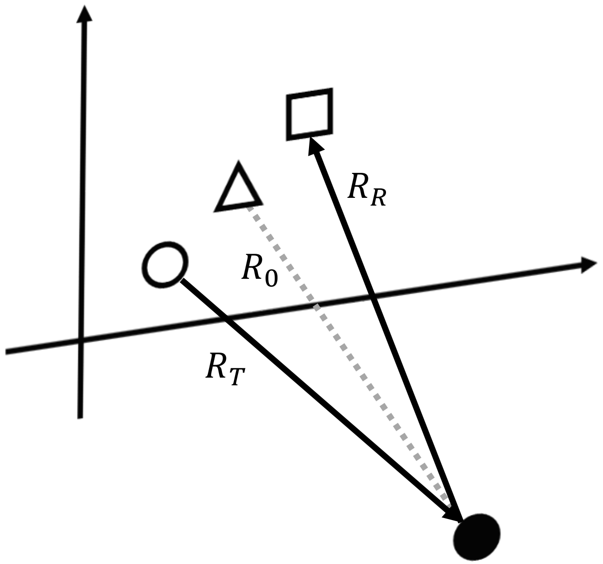
$$R_u = \sqrt{(x_T - x)^2 + (y_T - y)^2 + (Z_0 - z)^2} + \sqrt{(x_R - x)^2 + (y_R - y)^2 + (Z_0 - z)^2}$$

For small distances between Tx/Rx pairs

$$R_u \approx 2R_0 + \frac{(d_u^x)^2 + \left(d_u^y\right)^2}{4Z_0} = 2R_0 + \phi_u$$

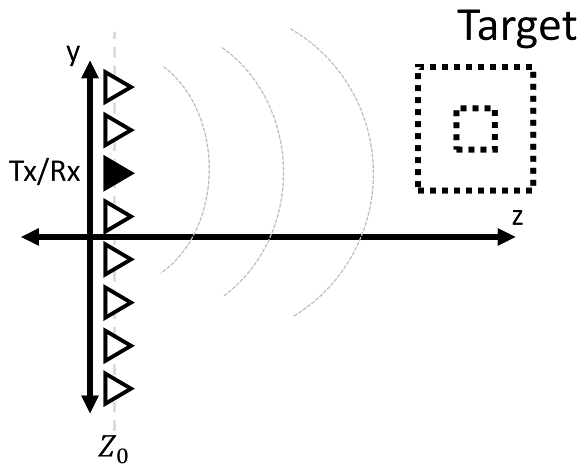






Efficient Near-Field Spatial Imaging

- Near-field $\Longrightarrow$ spherical wavefront



- Received signal

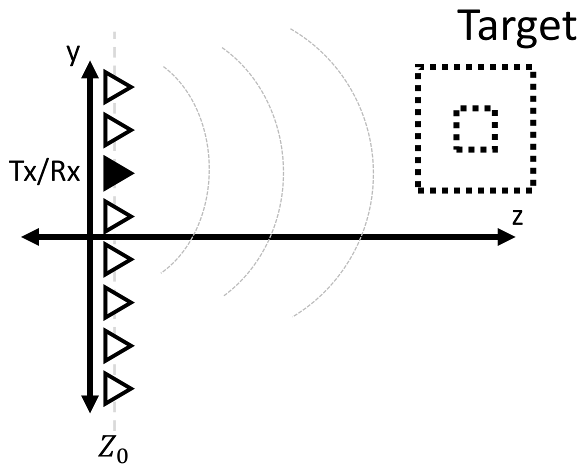
$$s(x', y', k) = \iiint \frac{p(x, y, z)}{R_0^2} e^{j2kR_0} dxdydz$$

- Naïve approach (matched filter beamformer)

$$p(x, y, z) = \iiint s(x', y', k) e^{-j2kR_0} dx'dy'dk \quad \Longrightarrow \quad \boldsymbol{O}\left(\boldsymbol{n}^6\right)$$

Efficient Near-Field Spatial Imaging

- Near-field $\Longrightarrow$ spherical wavefront



- Received signal

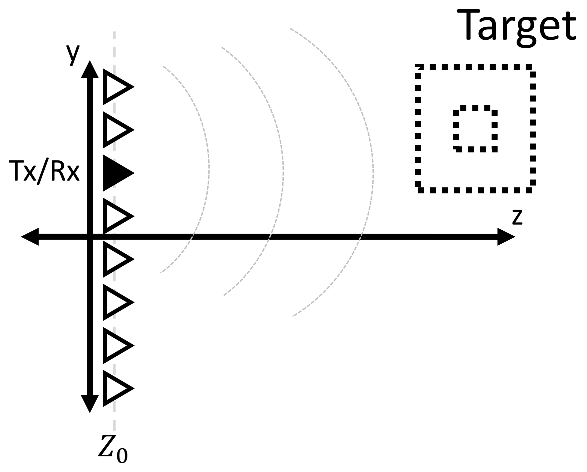
$$s(x',y',k) = \iiint \frac{p(x,y,z)}{R_0^2} e^{j2kR_0} dxdydz$$

- Efficient approach – **key step**

$$\frac{e^{j2kR_0}}{R_0} \approx \iint \frac{e^{j(k_x(x'-x)+k_y(y'-y)+k_z Z_0)}}{k_z} dk_x dk_y$$

Efficient Near-Field Spatial Imaging

- Near-field $\Longrightarrow$ spherical wavefront



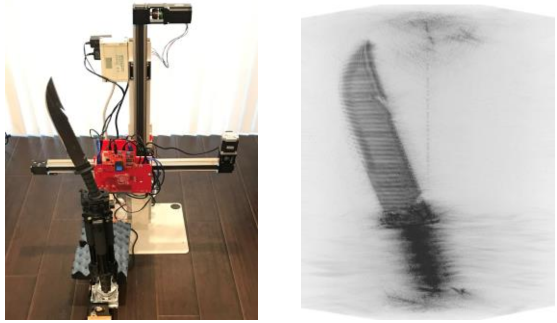
- Received signal

$$s(x',y',k) = \iiint \frac{p(x,y,z)}{R_0^2} e^{j2kR_0} dxdydz$$

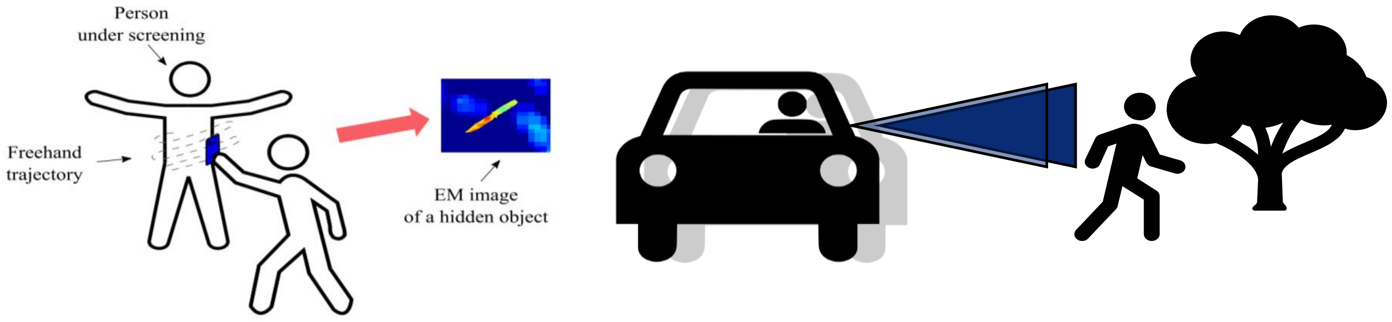
- Efficient approach (Range Migration Algorithm – RMA)

$$p(x,y,z) = IFT_{3D}^{(k_x,k_y,k_z)}\left[\mathcal{S}\left[FT_{2D}^{(x',y')}[s^*(x',y',k)]k_z\right]\right] \quad \Longrightarrow \quad \boldsymbol{O\left(n^3 \log n\right)}$$

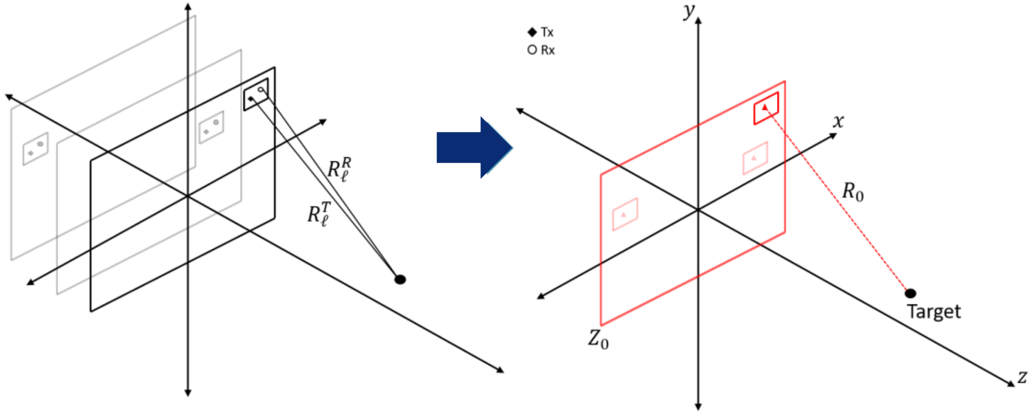
Tangent – Efficient Freehand Imaging

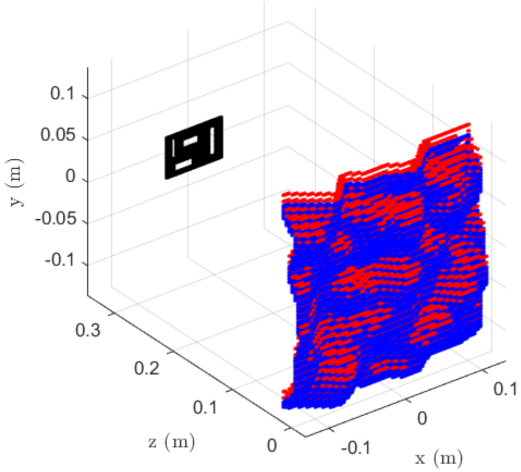


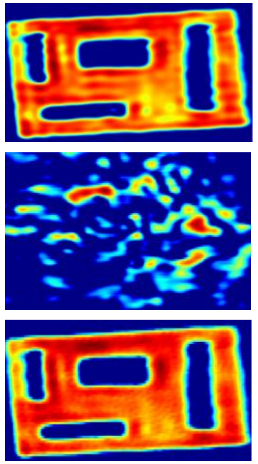
Traditional Array Imaging



Emerging Imaging Applications – Arbitrary Scanning Geometry







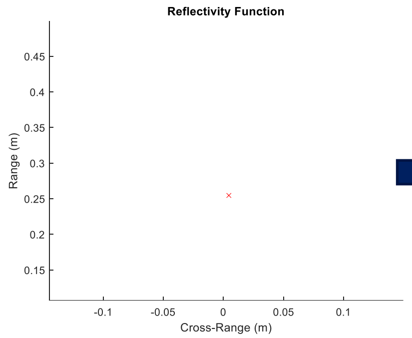
BPA – 3 hr

RMA – 1 s

Ours – 1 s

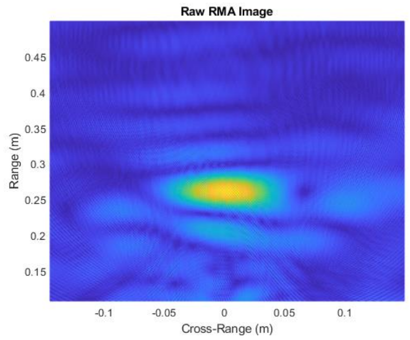
Conventional Feature Extraction

- Maximum likelihood estimator of **range (z), cross-range (y), and Doppler (v_z)**

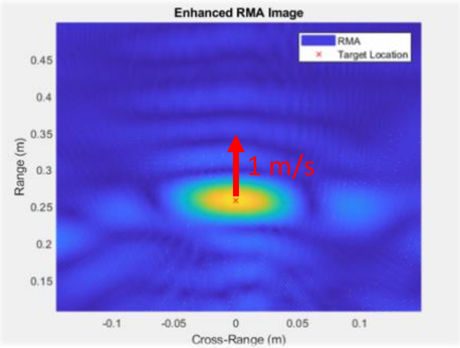


RMA

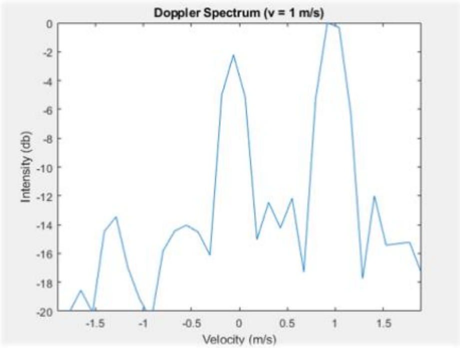
$$p(y,z) = IFT_{2D}^{(k_y,k_z)}\left[\mathcal{S}\left[FT_{1D}^{(y')}[\hat{s}^*(y',k)]\right]\right]$$



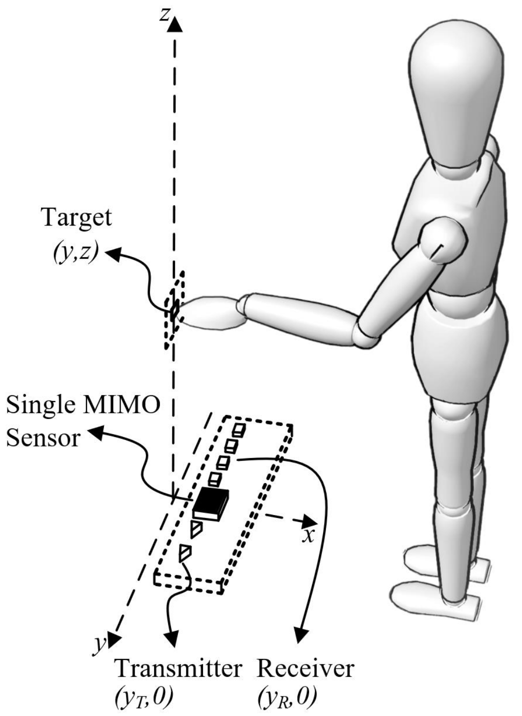
y, z



Doppler FFT

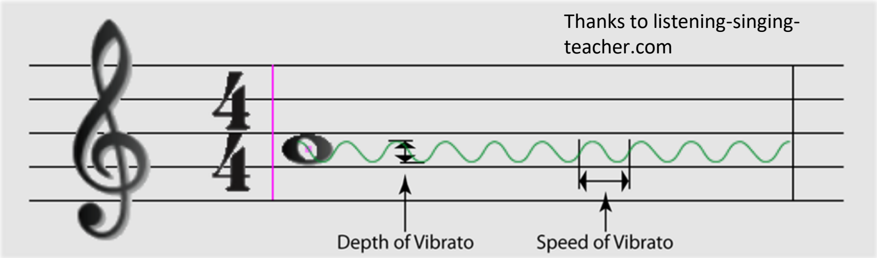


v_z



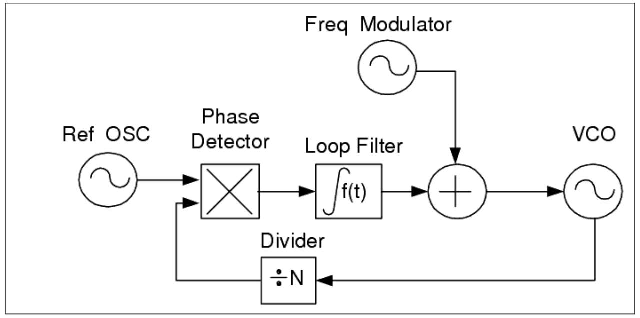
Music Theory for Engineers

- Notes and Pitch
  - Pitch = fundamental frequency
  - Single frequency sinusoid with natural acoustic harmonics



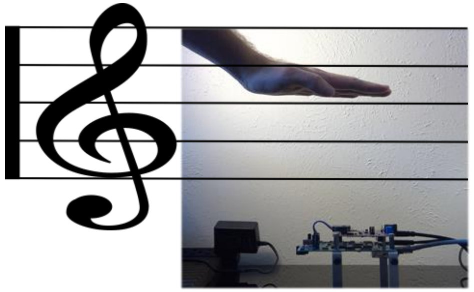
- Frets
  - Quantize finger placement on some stringed instruments

- Vibrato
  - Frequency modulation applied to pitch

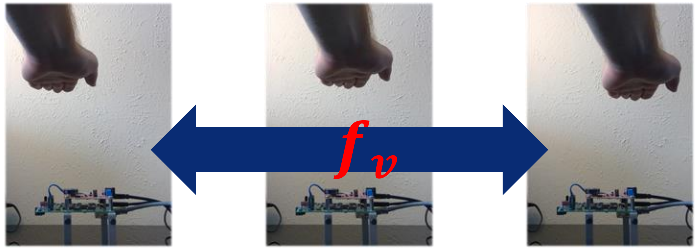


Mapping Radar Signatures to Music

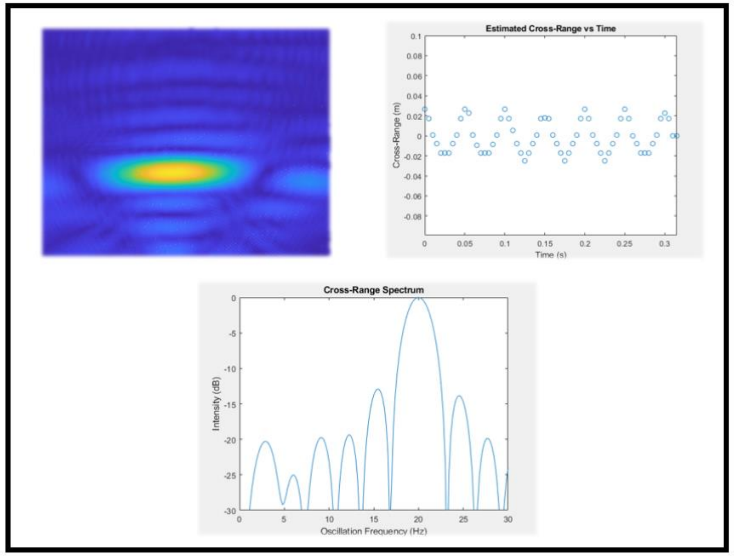
1. Range → note selection
   - Vertical position to select desired note
   - Virtual fret quantize range into regions



2. Cross-range oscillation → vibrato

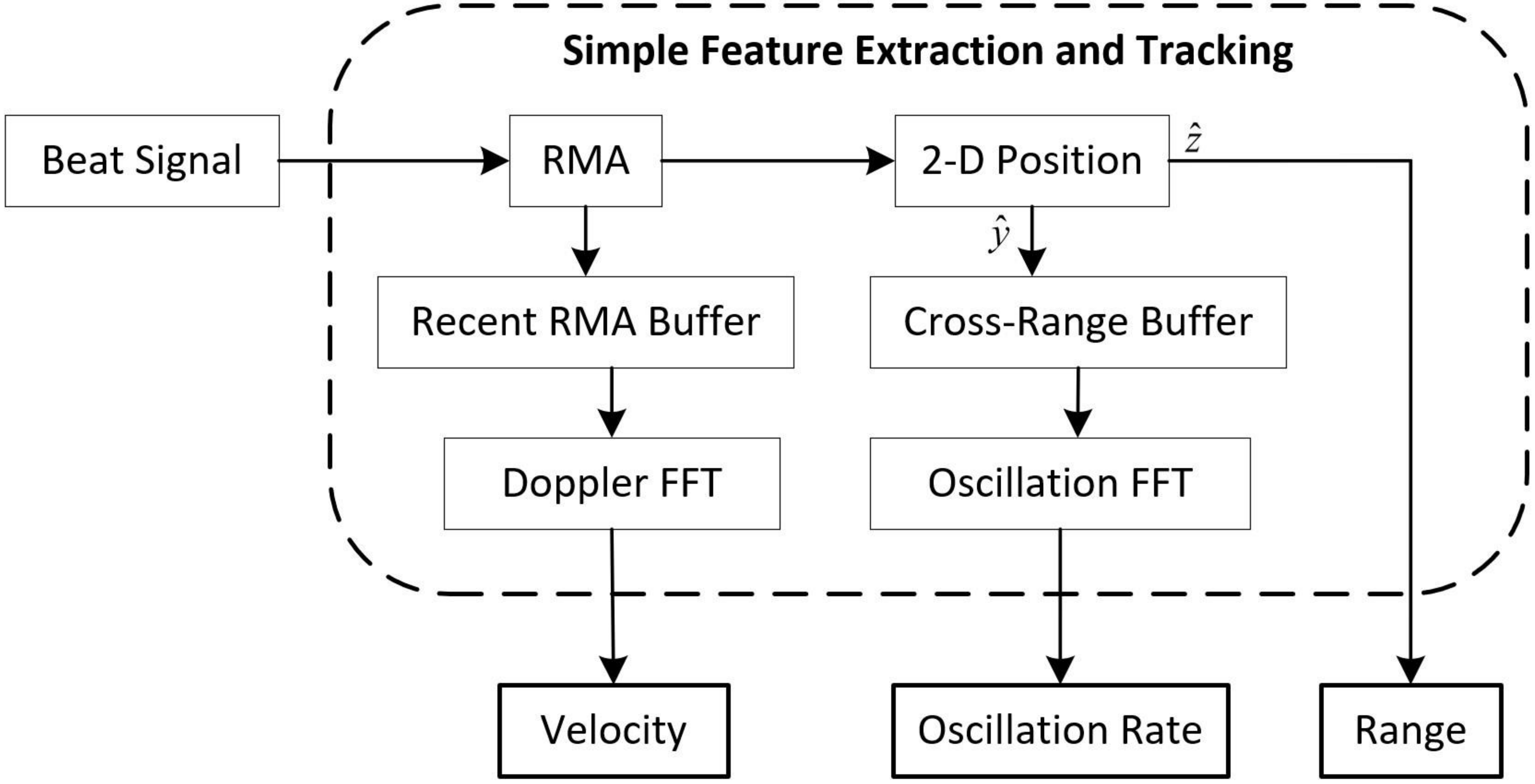


→ $\cos(2\pi \times \cos(2\pi f_v t) \times t)$



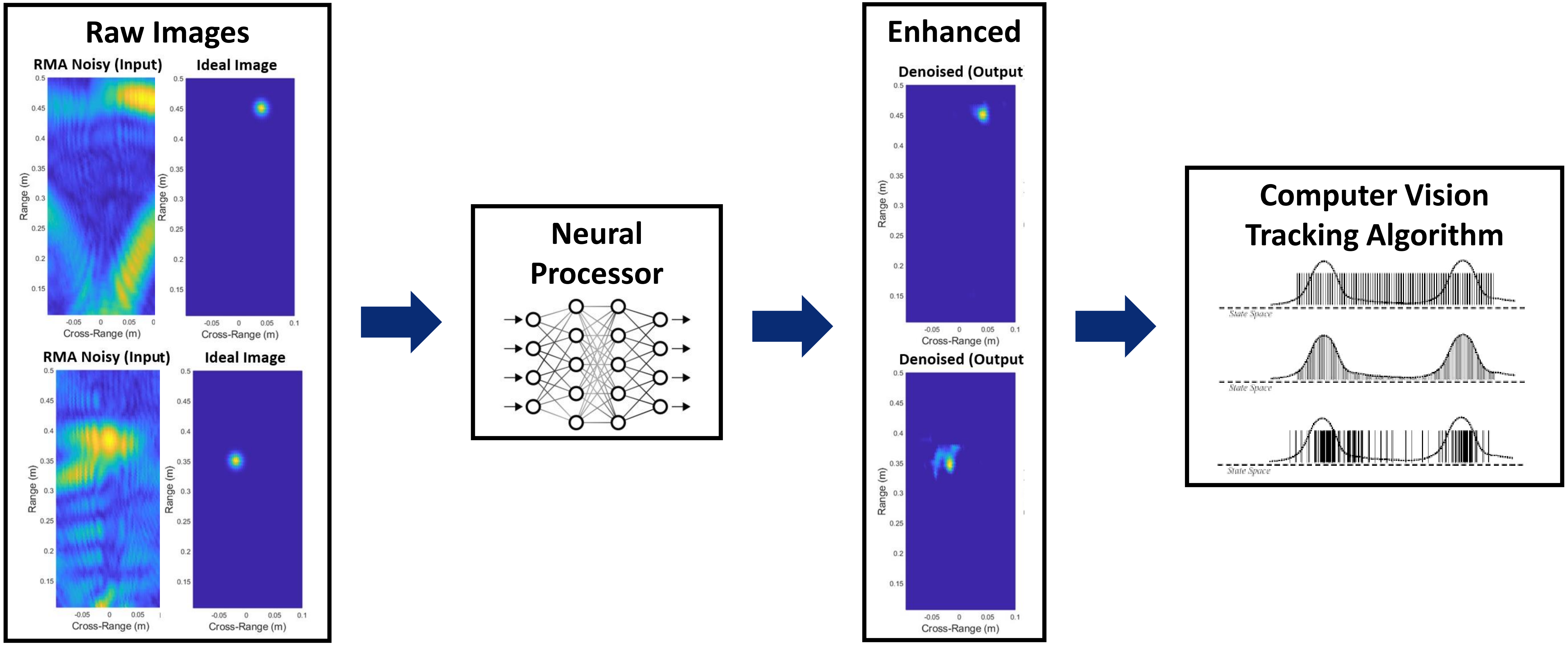
3. Doppler → MIDI parameter

Simple Methods



Enhanced Feature Extraction

- **Enhance RMA images with neural processor prior to feature extraction**
- **Feed extracted-enhanced features to computer vision tracking algorithm**



Spatial Super-Resolution

- Image super-resolution emerging in ML / DL arena
- Image upscaling akin to spatial super-resolution
- Non-linear approach to leverage context / prior on images and signals
- **Can hybrid methods employ signal theory + ML for spatial and frequency super-resolution?**

0793 from DIV2K [26]

HR (PSNR / SSIM)

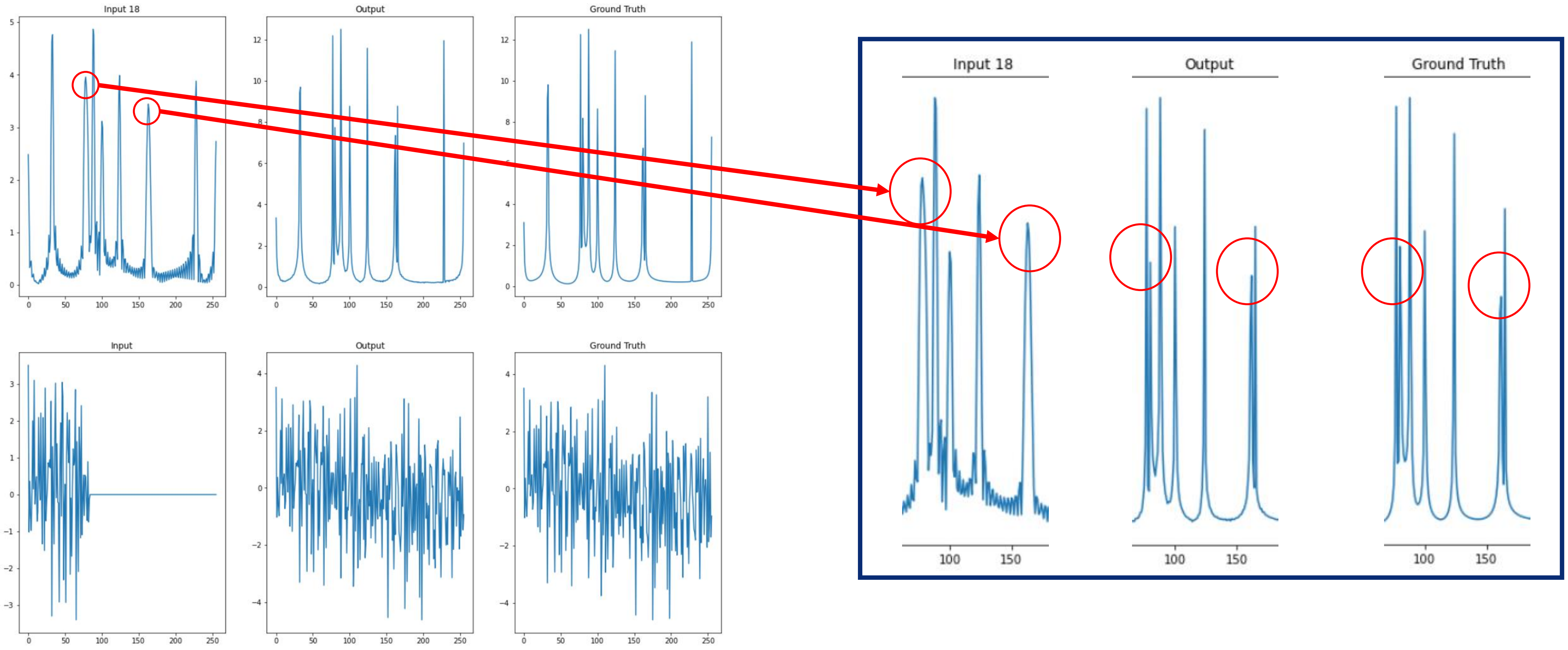
Bicubic (23.81 dB / 0.8053)

EDSR (Ours) (30.94 dB / 0.9318)

MDSR (Ours) (30.81 dB / 0.9301)

Tangent – Frequency Super-Resolution

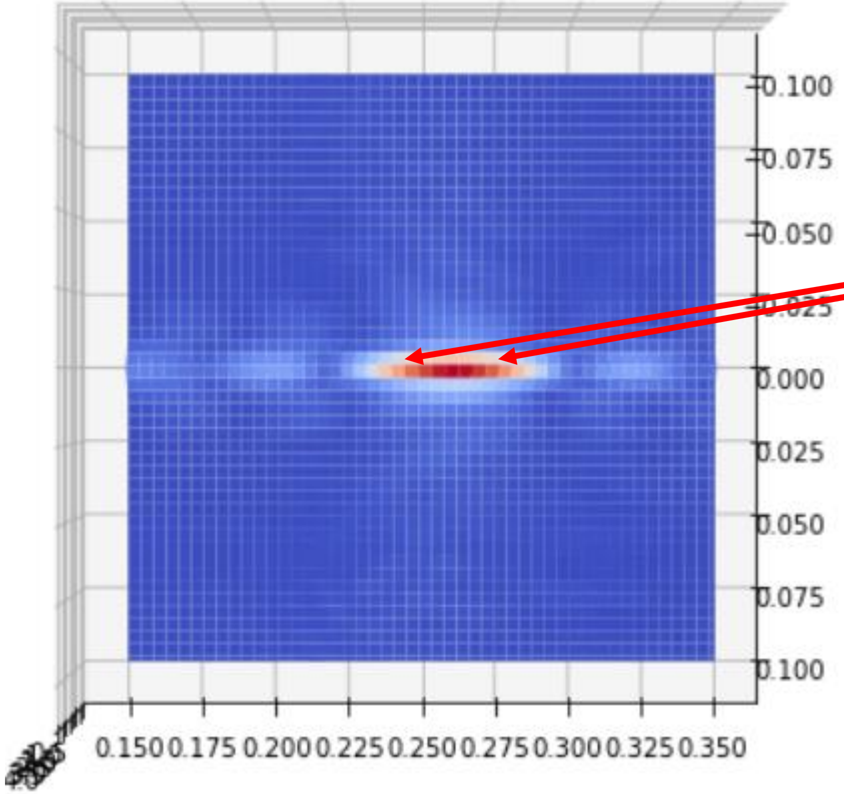
- Frequency super-resolution ⟺ signal extrapolation
- **Proposed Solution:** hybrid algorithms (signal processing + ML)



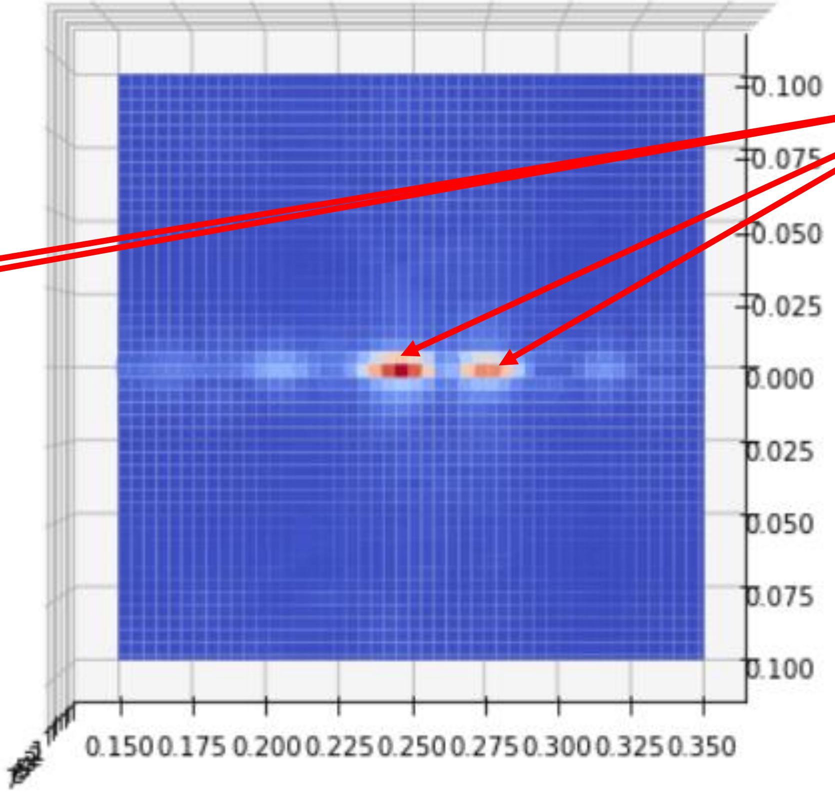
Tangent – Frequency Super-Resolution

Artificially / blindly improve spectral → spatial resolution

Raw 4 GHz Data



4 GHz → 8 GHz Bandwidth Extrapolation



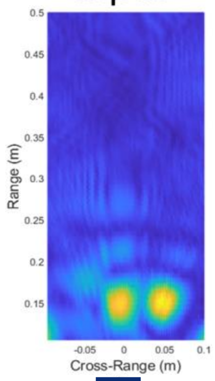
Two scatterers separated by 2 cm

- 4 GHz bandwidth → 3.75 cm resolution
- 8 GHz bandwidth → 1.875 cm resolution

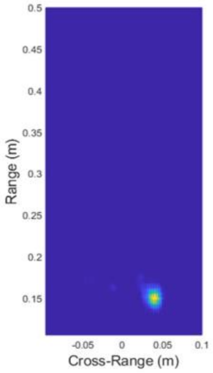
Spatial Super-Resolution FCNN

Noisy/Blurry RMA Image
↓
Conv. + ReLU
kernel 25 x 25 x 1 x 16
↓
Conv. + ReLU
kernel 15 x 15 x 16 x 16
↓
Conv. + ReLU
kernel 5 x 5 x 16 x 16
↓
Conv. + Clipped ReLU
kernel 3 x 3 x 16 x 1
↓
Regression Layer
↓
Enhanced Image

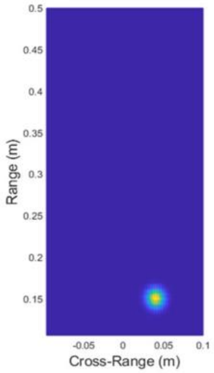
Input



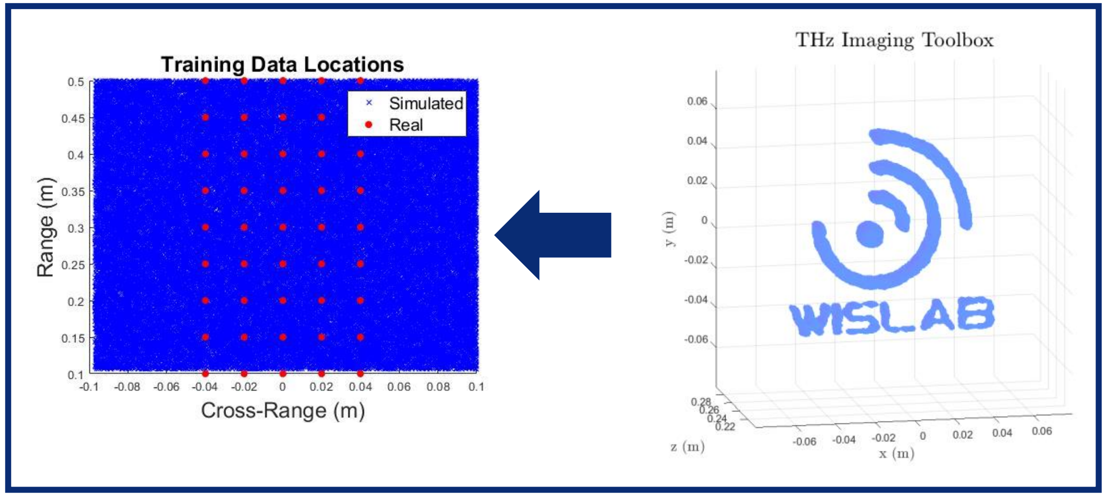
Output



Ground-Truth

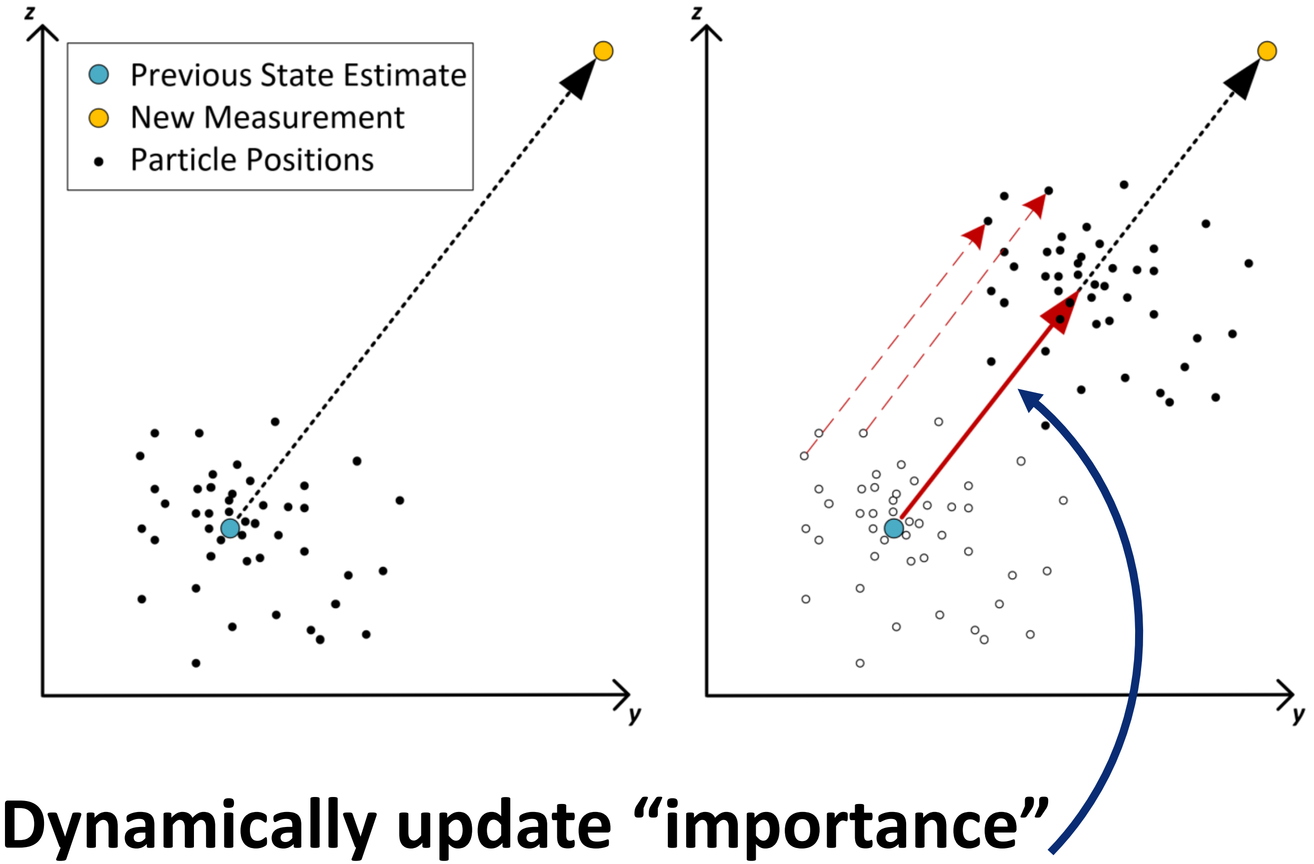


- Image-to-image enhancement
  - Remove distortion, blur, noise, clutter, etc.
  - Improve subsequent feature extraction
- Train on **real data from human hands + synthetic simulated data**



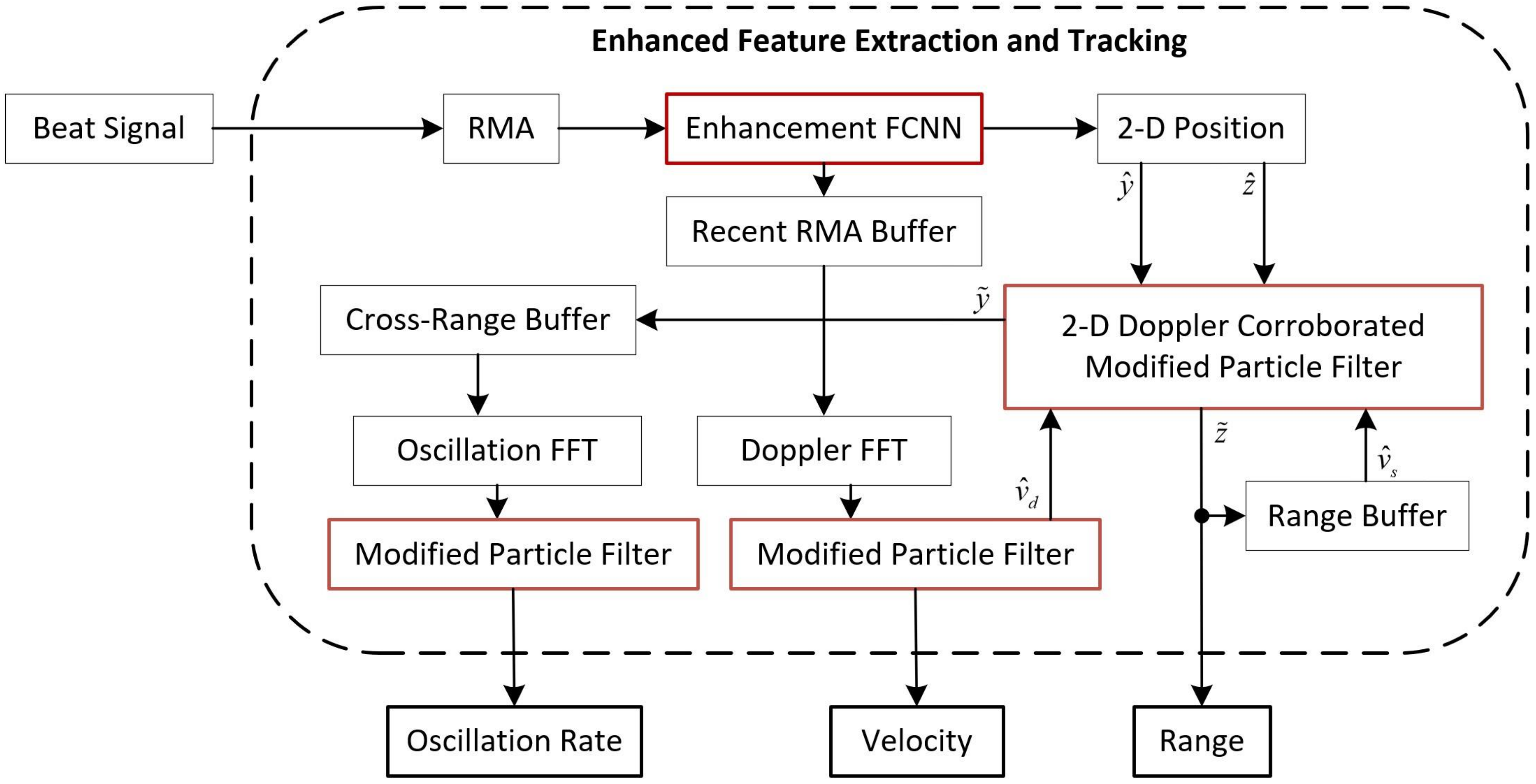
Particle Filter Tracking

- Particle filter (condensation algorithm) tracking
  - Computer vision approach
  - Can handle sudden movements and non-linear dynamics
- **Leverage Doppler for dynamic particle drift weighting**

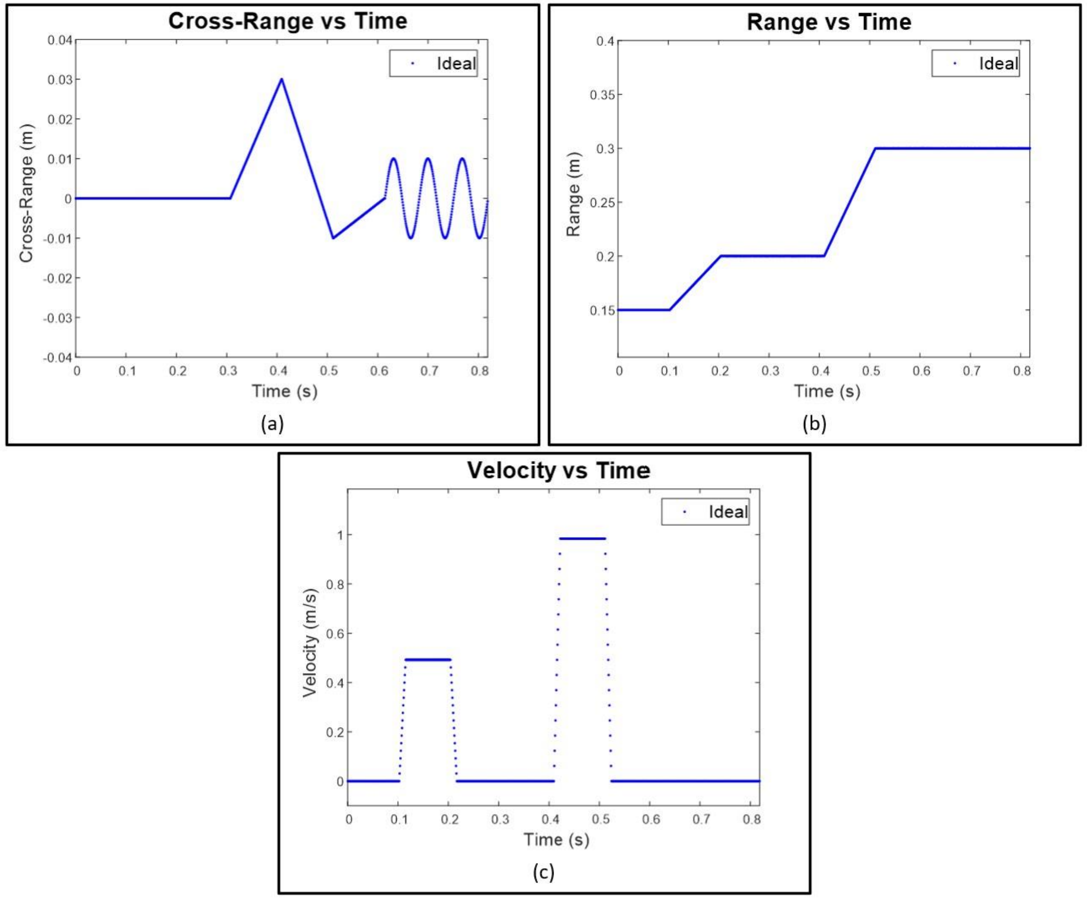


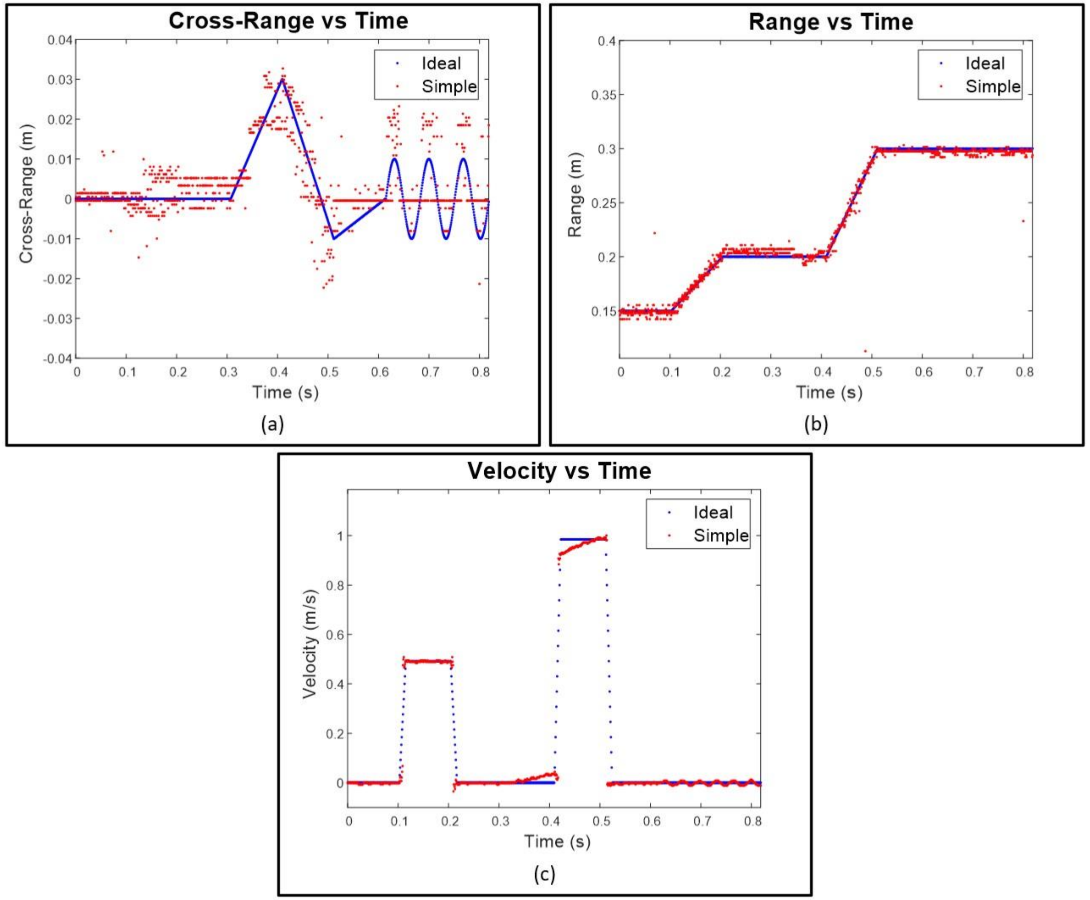
Dynamically update "importance" weight of new measurement

Enhanced Methods

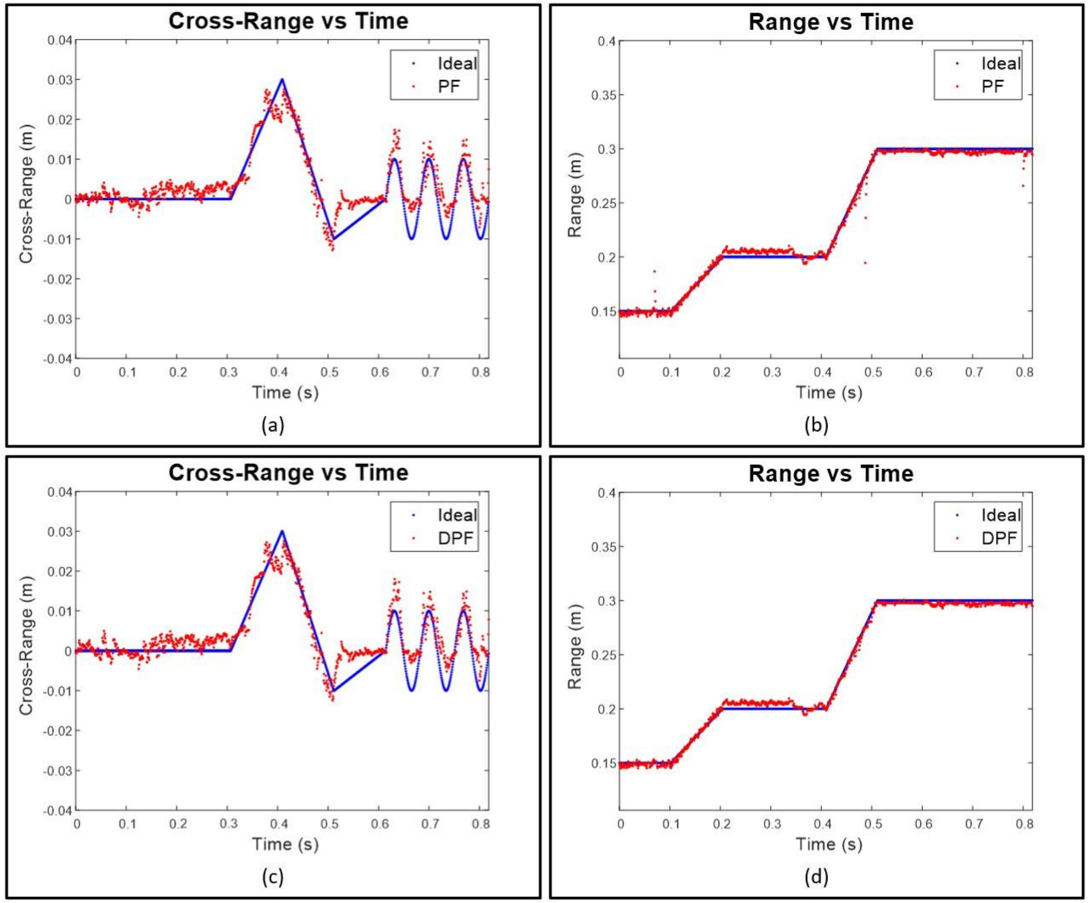


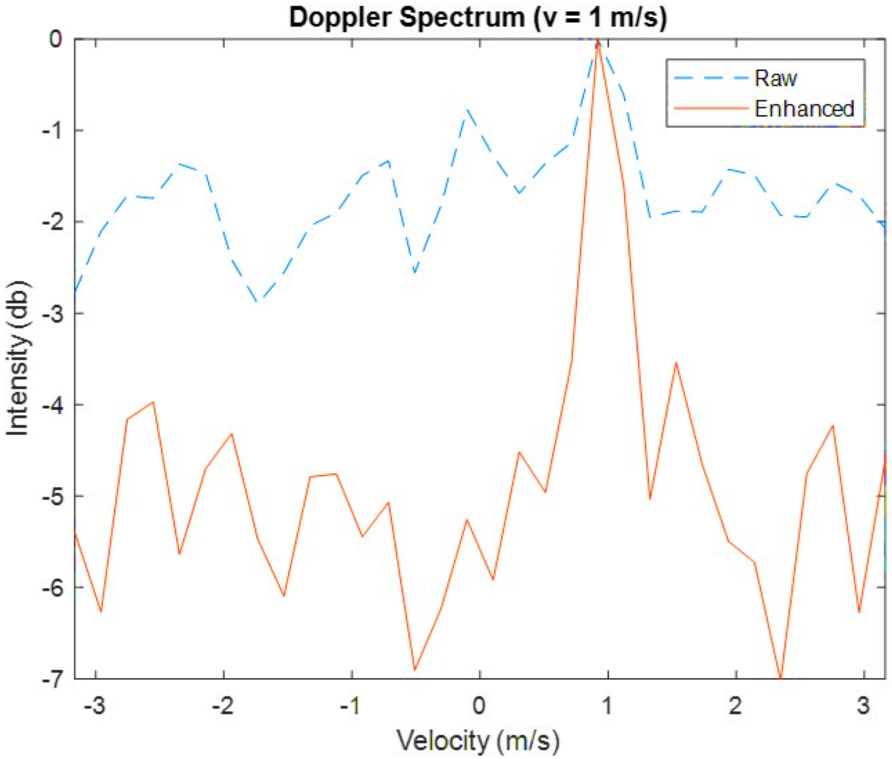
Results – Ground Truth + Simple Methods





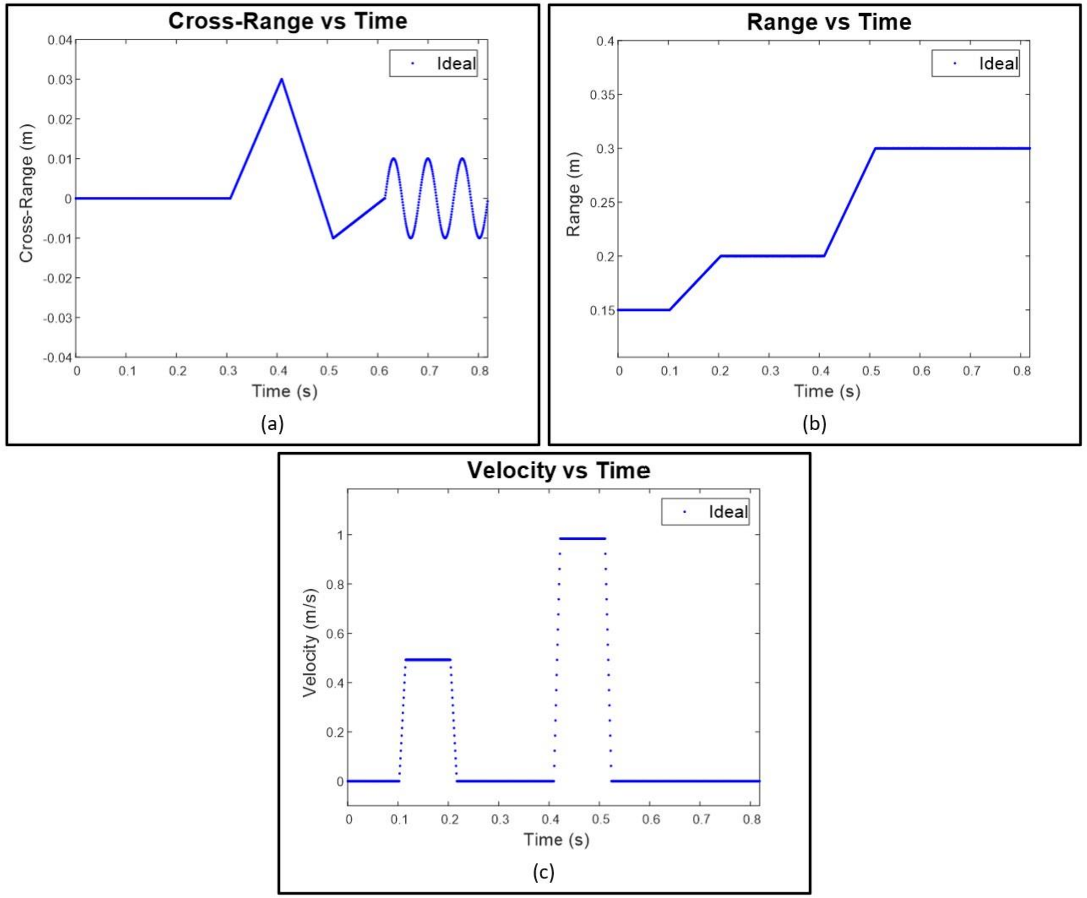
Results – Particle Filter + Doppler

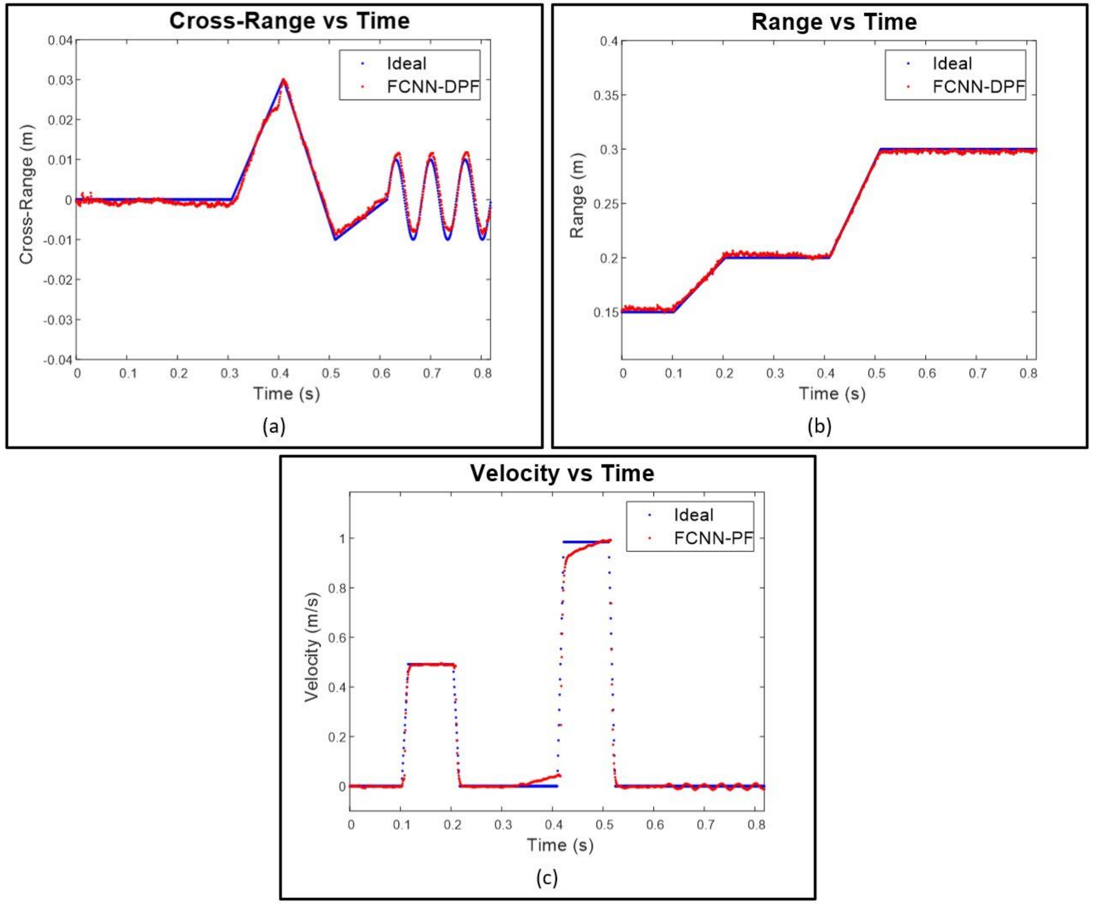




FCNN Improves Doppler SNR

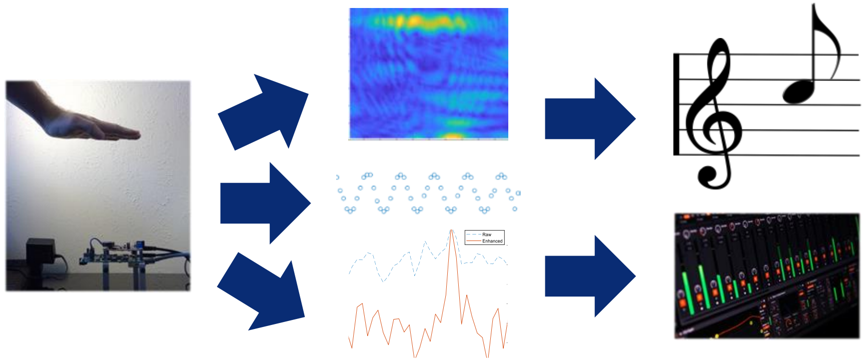
Results – Ground Truth + Simple Methods

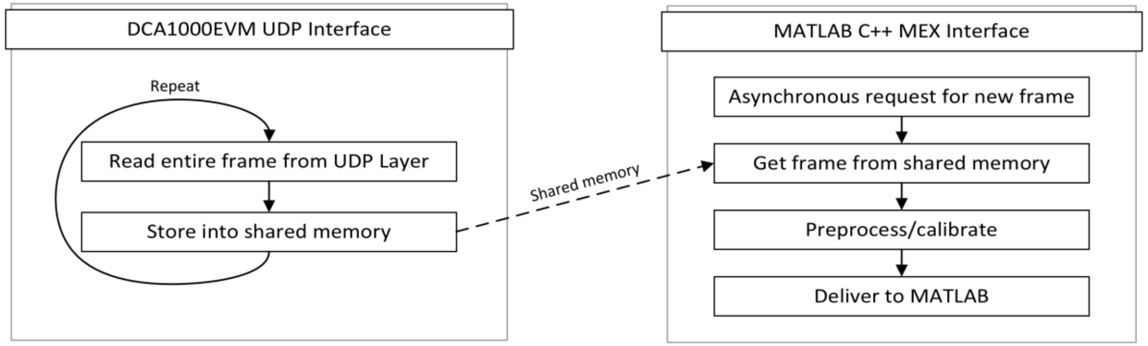


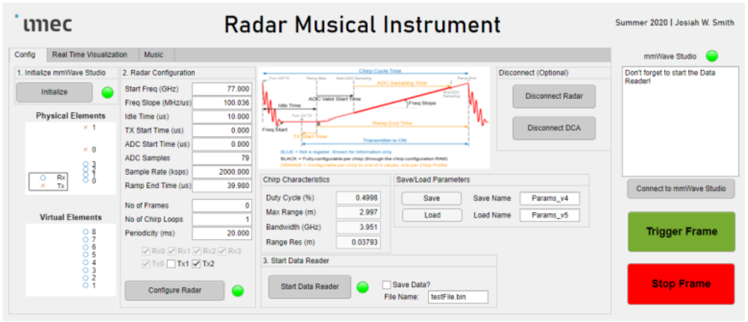


Hardware & Software Implementation

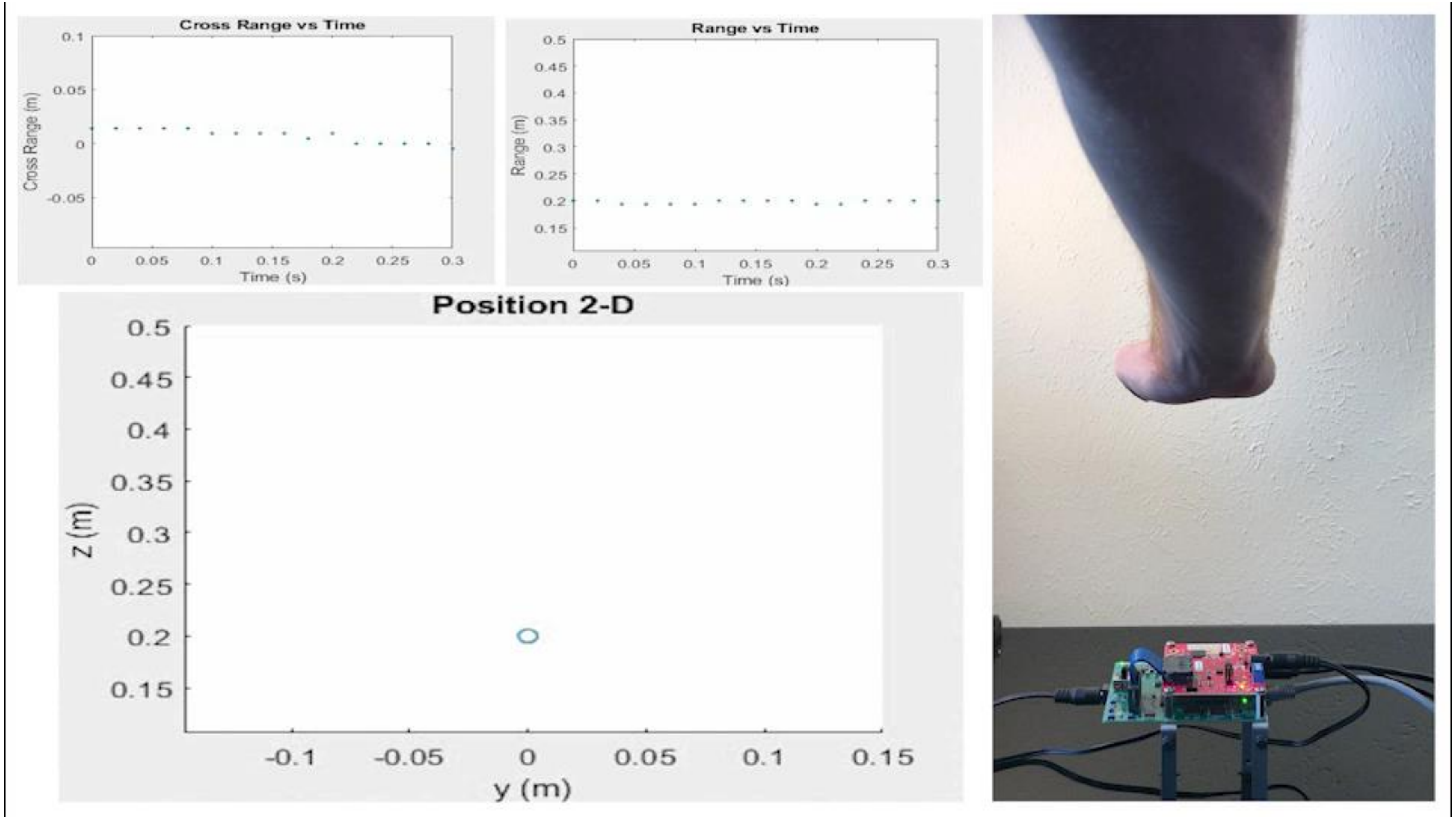
- Hardware Setup
  - TI 77 GHz mmWave MIMO-FMCW Radar
  - TI High Speed Data Capture Card
- Software Implementation
  - MATLAB Interface
  - Custom C++/MEX software stream data from TI radar to MATLAB in real-time







Results – Simple Methods



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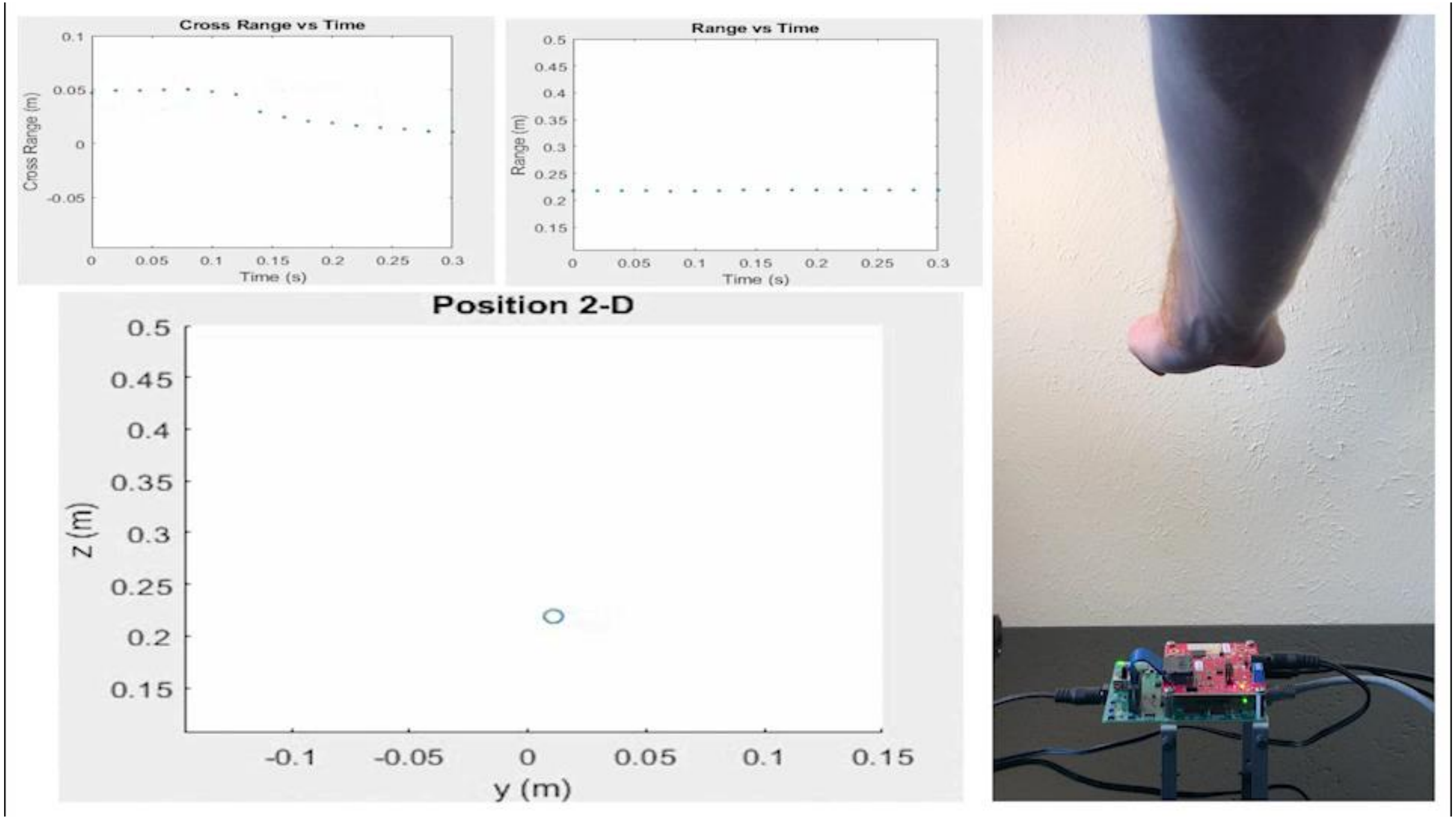
Results – Enhanced Methods



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Conclusions

- Radar Musical Instrument
  - **Signal processing + machine learning + computer vision = hybrid-algorithms**
  - High-fidelity tracking framework without any optical sensor
  - Surpass theoretical spatial resolution limitations
- Why APL?
  - Intersection of research and defense industry
  - Impactful work on critical challenges
  - Rapid learner & contributor
  - Solving new problems and "owning the problem"

Music Demo

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