2021UBICOMP
2021ISWC

SquiggleMilli: Approximating SAR Imaging on Mobile Millimeter-Wave Devices

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https://github.com/hregmi77/SquiggleMilli

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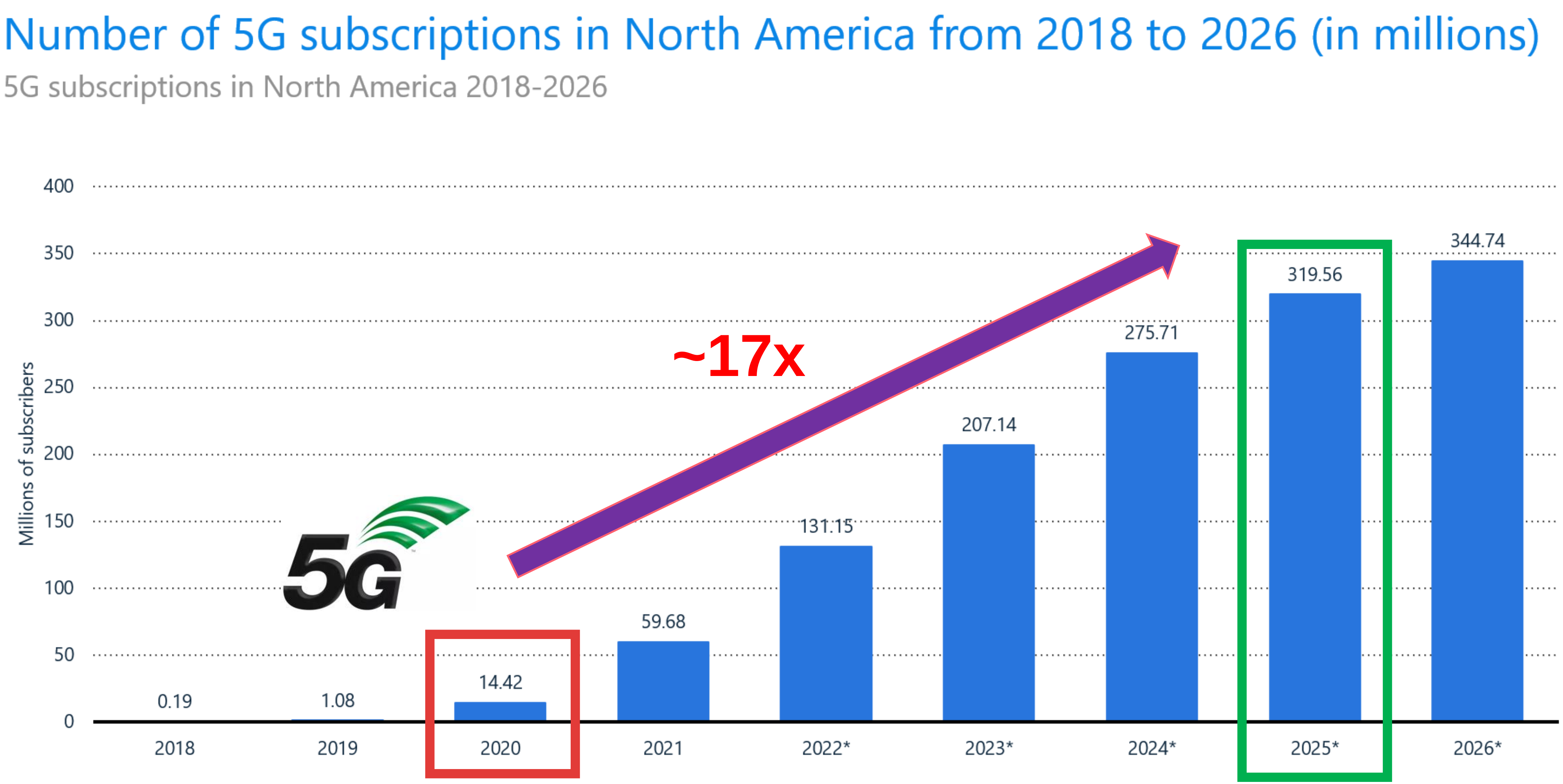
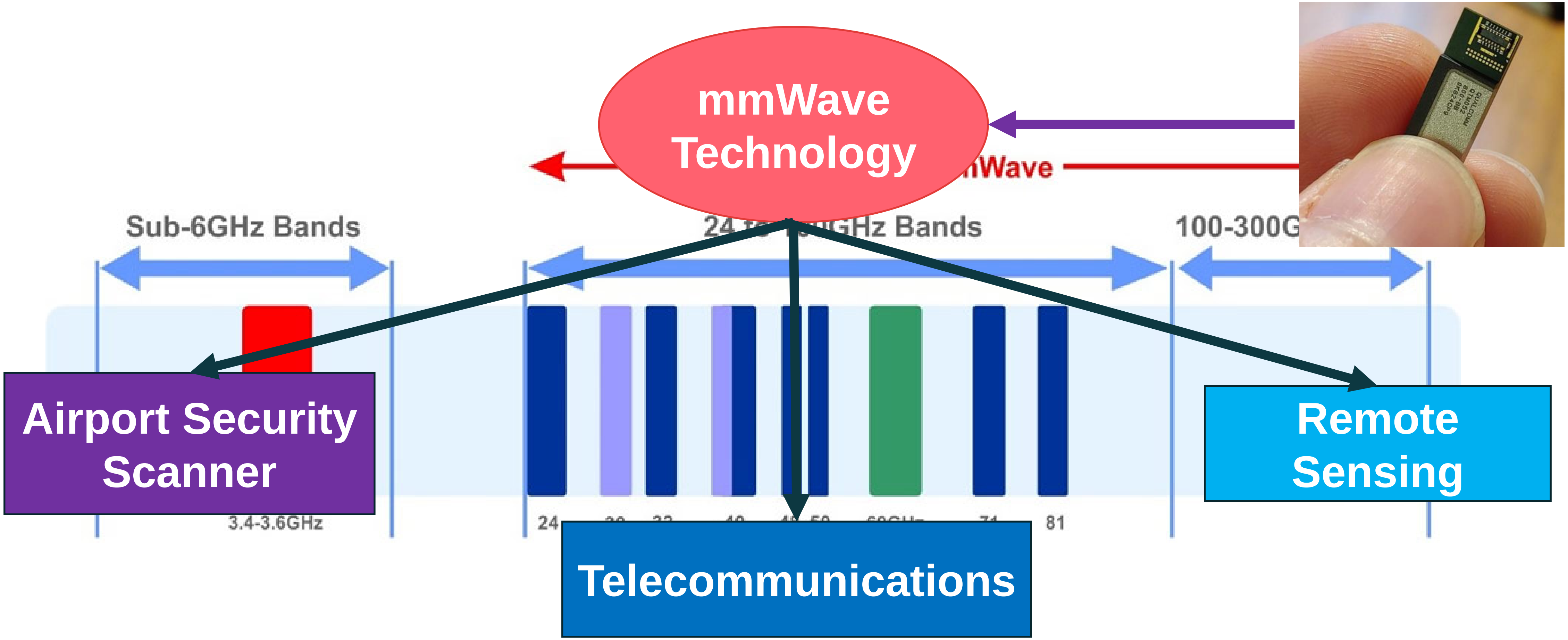


Source: Statista

What Is 5G And Mmwave?



Imaging Concealed Objects

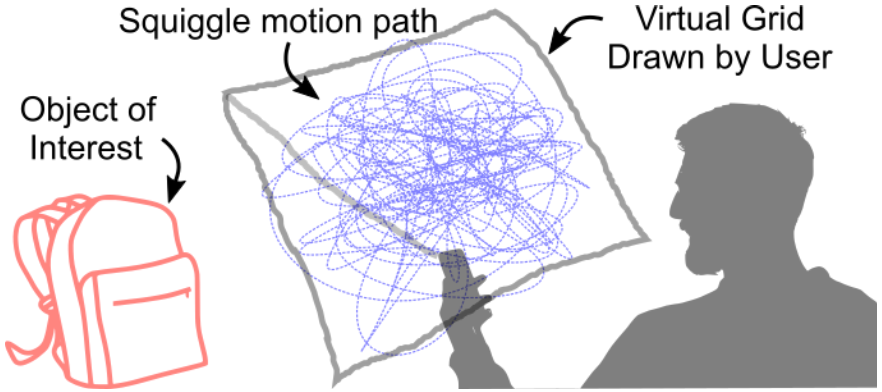
Can we bring these functionalities to commodity 5G smartphones?

Behind Wall Detection

Packaging and Inventory

Airport Contra-band Scanner

SquiggleMilli



Pistol inside bag

SquiggleMilli

Actual Object

What vision camera produces

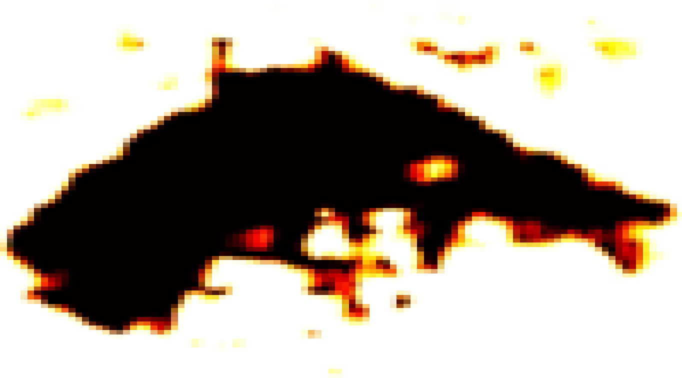
What SquiggleMilli produces

SquiggleMilli

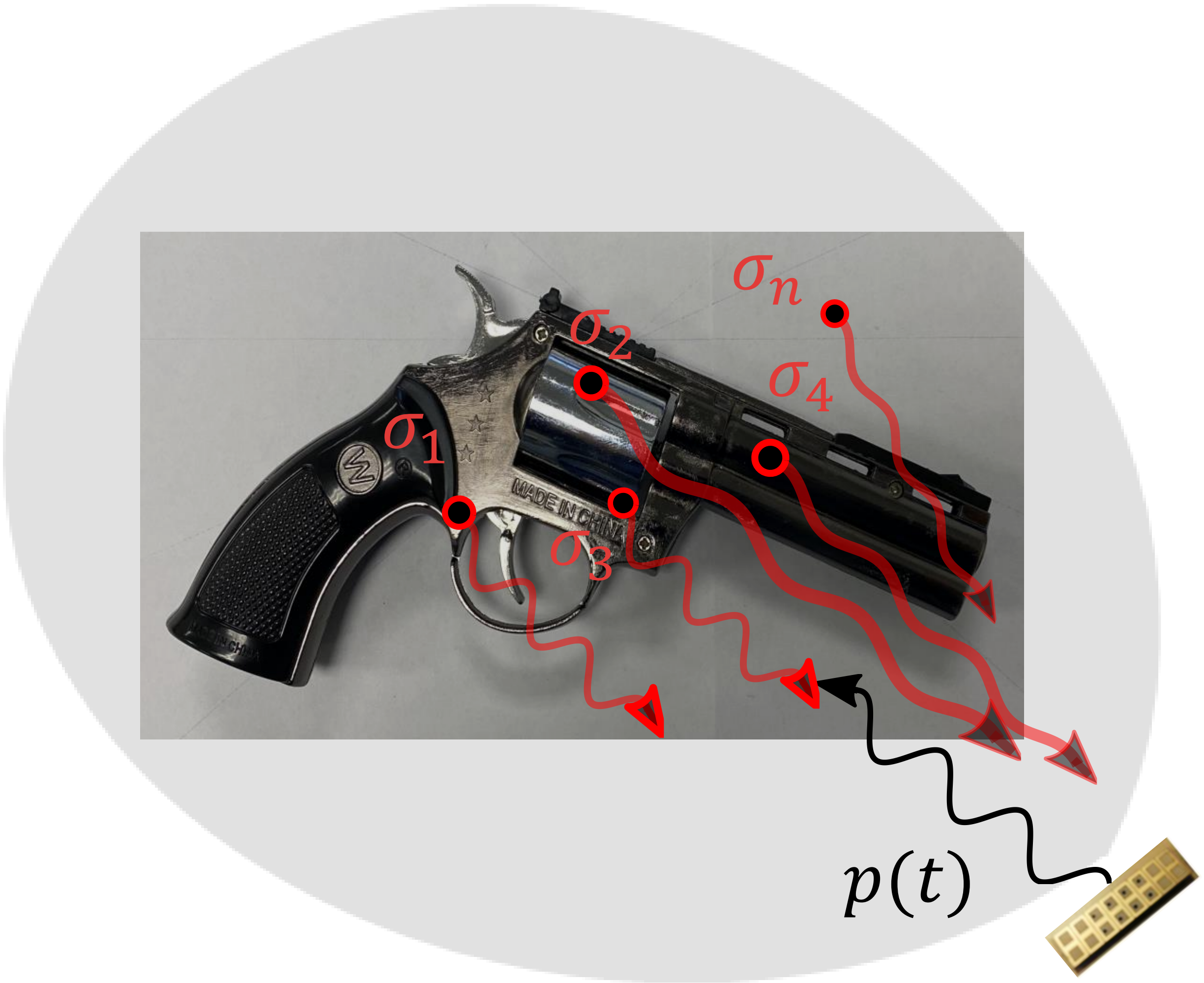
Actual Object

What vision camera produces

What SquiggleMilli produces



Constructing Millimeter-Wave Image



mmWave antenna

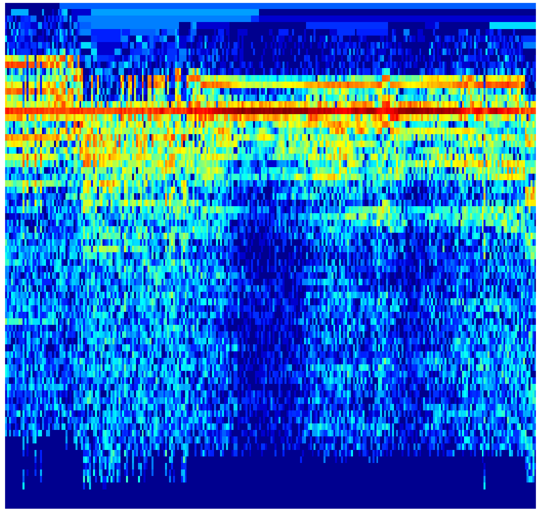
σ_1

σ_n

Reflected signals

Constructing Millimeter-Wave Image

Time (t)

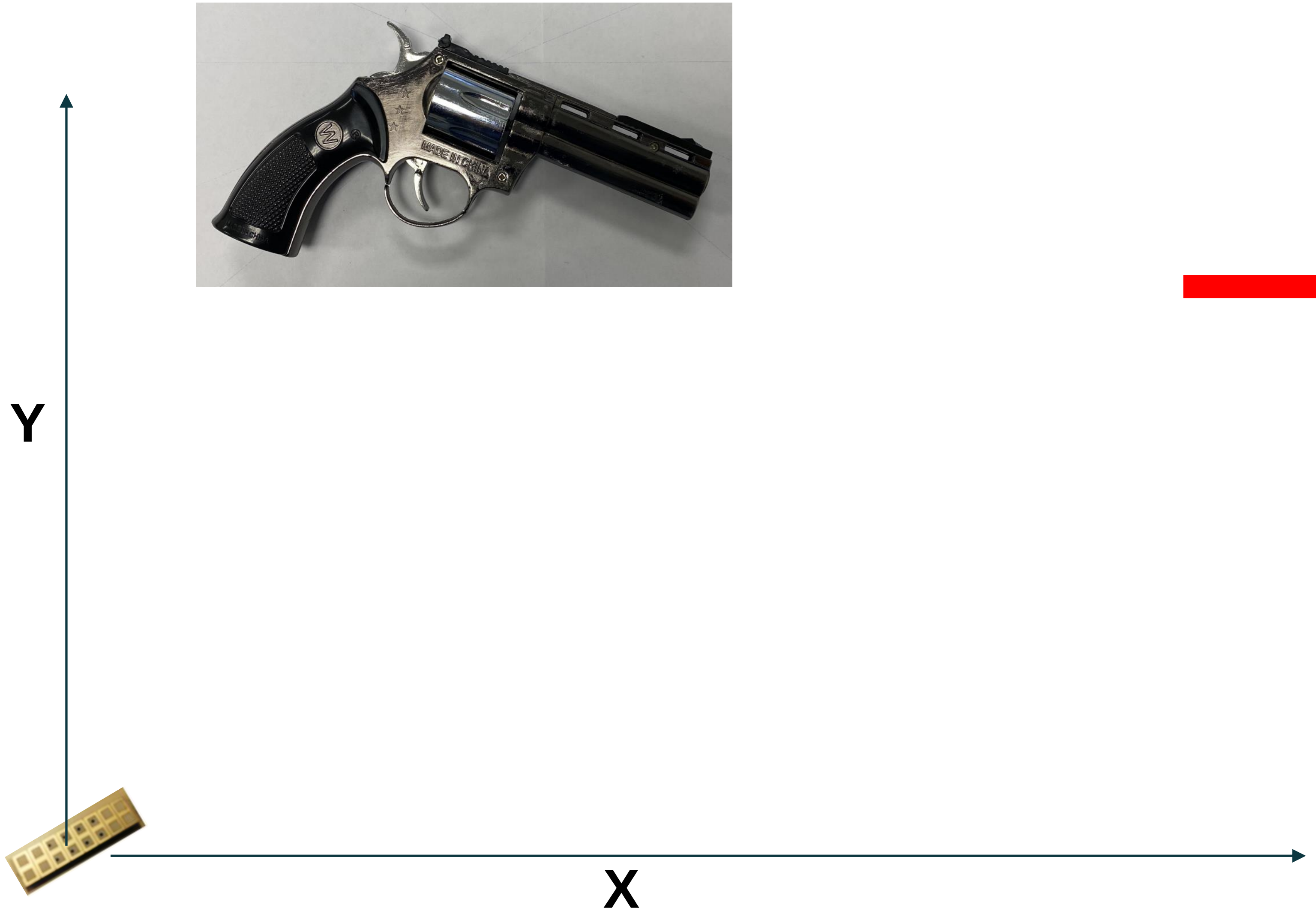


Space (u)

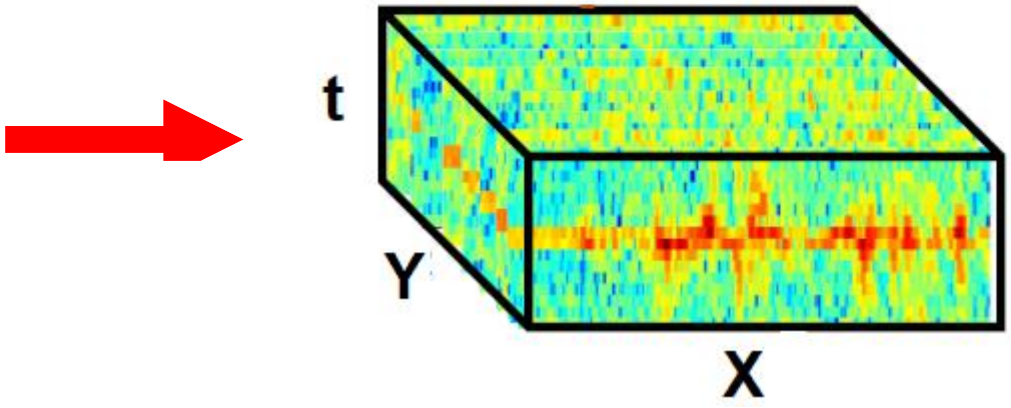
Time (t)

Space (u)

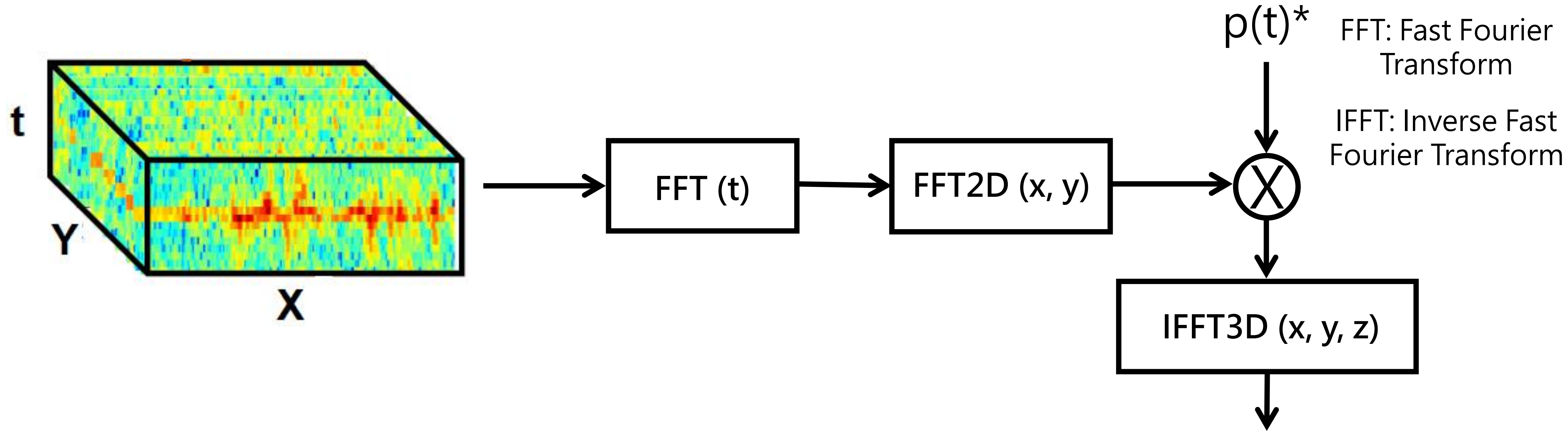
Constructing Millimeter-Wave Image



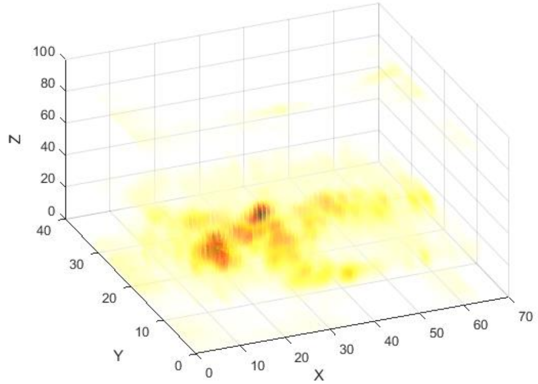
3D Spectrogram



From Measured Signal to Image



Camera image



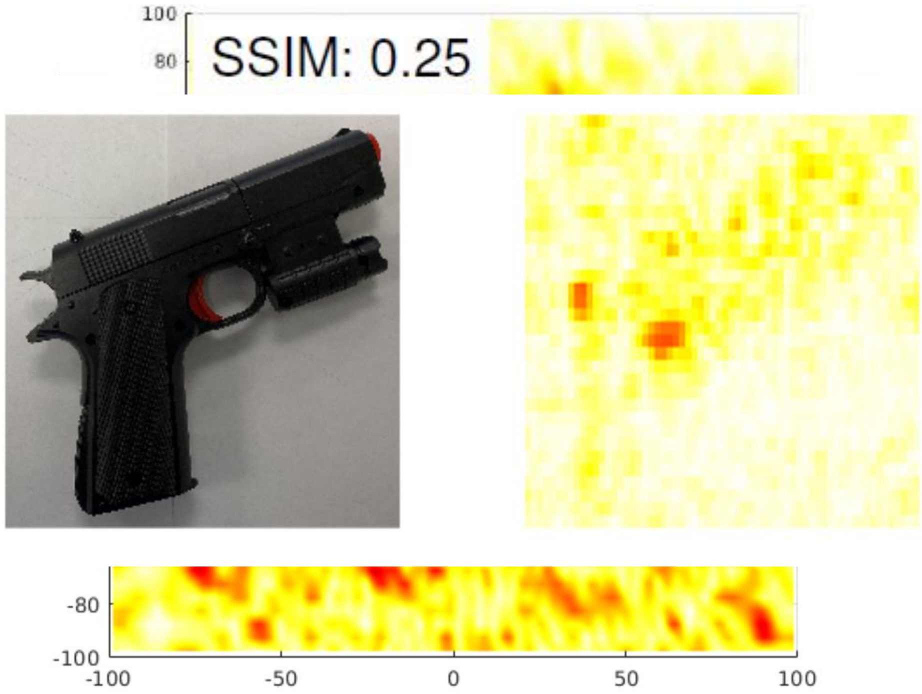
3D mmWave image

Challenges

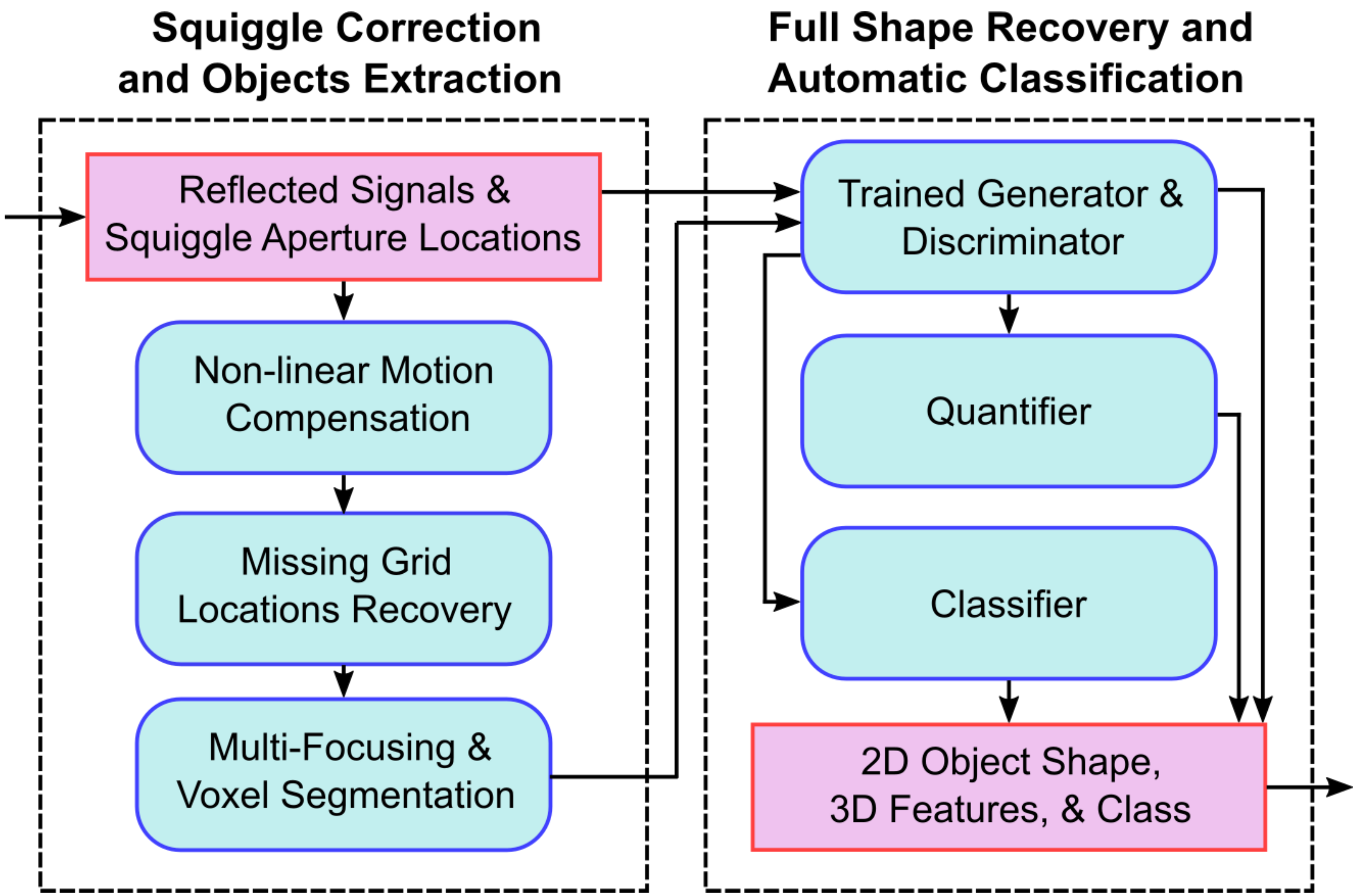
Hand-held imaging

- ❑ Non-linear motion
- ❑ Non-Uniform Sampling
- ❑ Multiple Objects

Specularity and weak reflectivity



SquiggleMilli Overview



Challenges

Hand-Held Imaging

Specularity and Weak Reflectivity

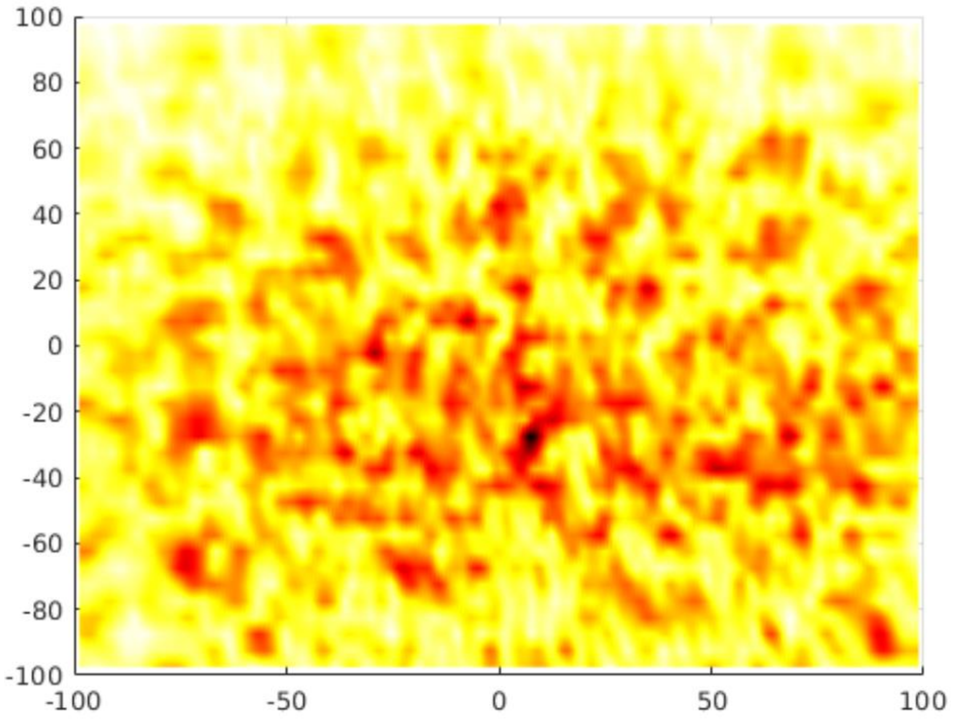
Challenges

Hand-Held Imaging

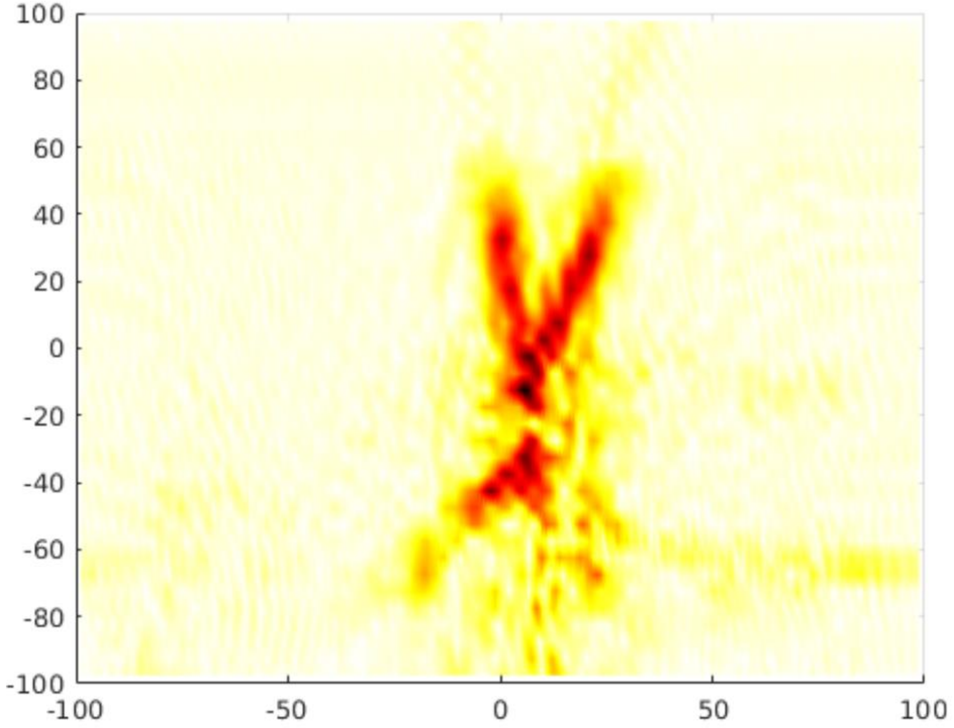
Specularity and Weak Reflectivity

Non-linear Motion

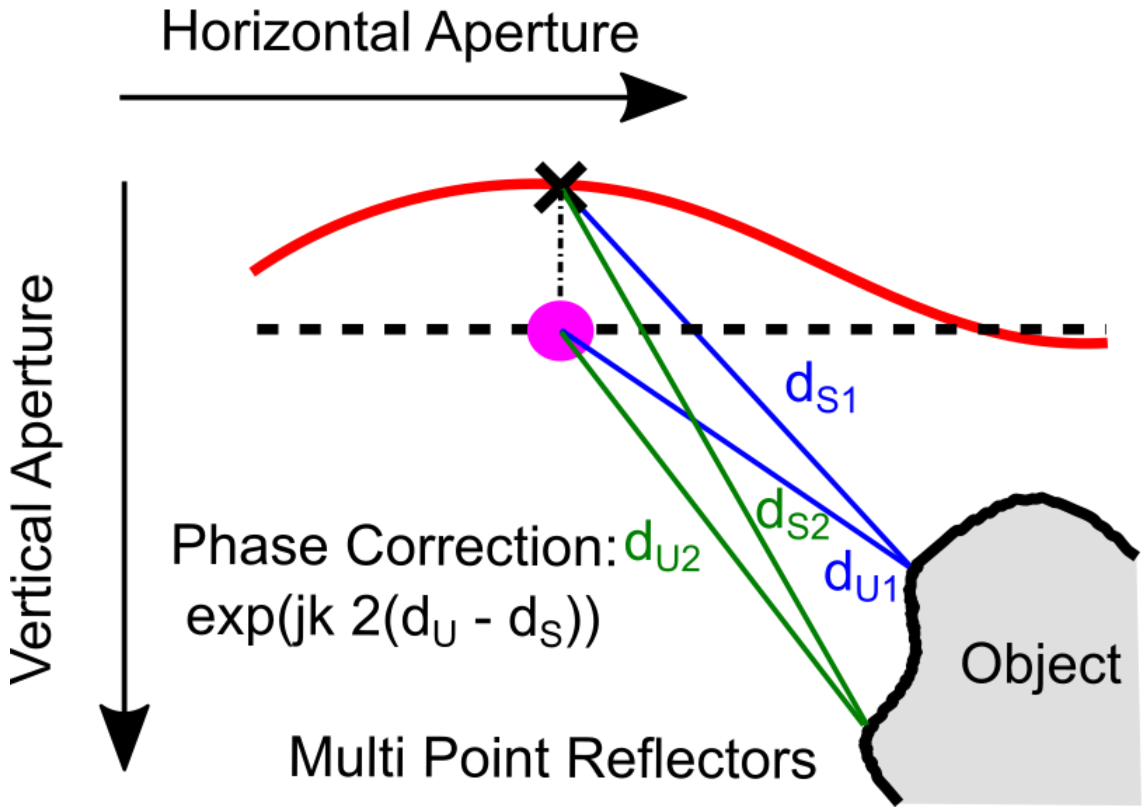
Squiggle Grid



Ideal Grid



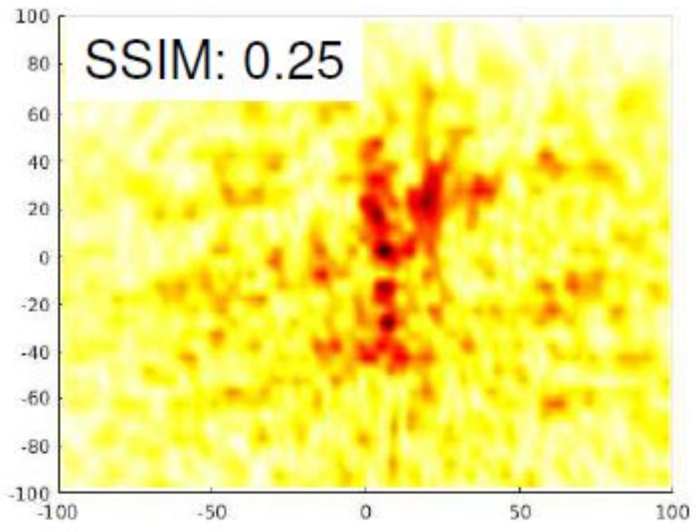
Motion Error Compensation



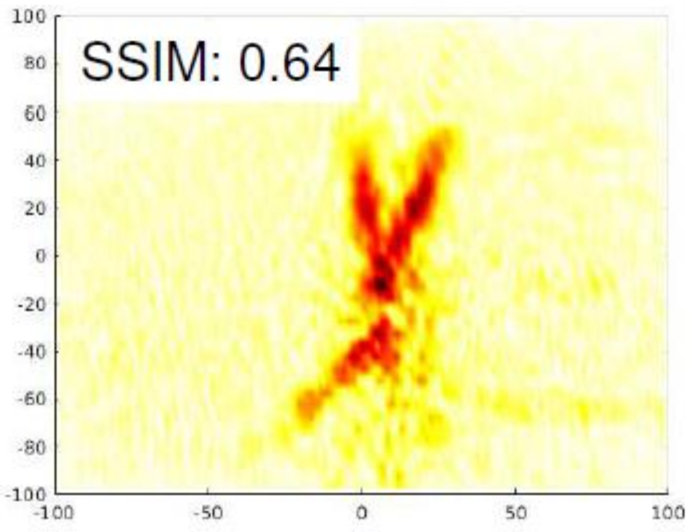
$$\min \sum_{i\in N, j\in N, i\neq j} \left| s_u^i(x_u, y_u, \omega) - s_u^j(x_u, y_u, \omega) \right|_{k=\omega/c} \quad s.\ t. \quad |d_u - d_s| < \lambda/2$$

Missing Samples

Missing Samples



Missing Samples Recovered



More than 50% samples are missing

Missing Samples Recovery

Motion Corrected Samples → Standard Compressed Sensing (CS) Technique → Recovered Samples

CS Customization

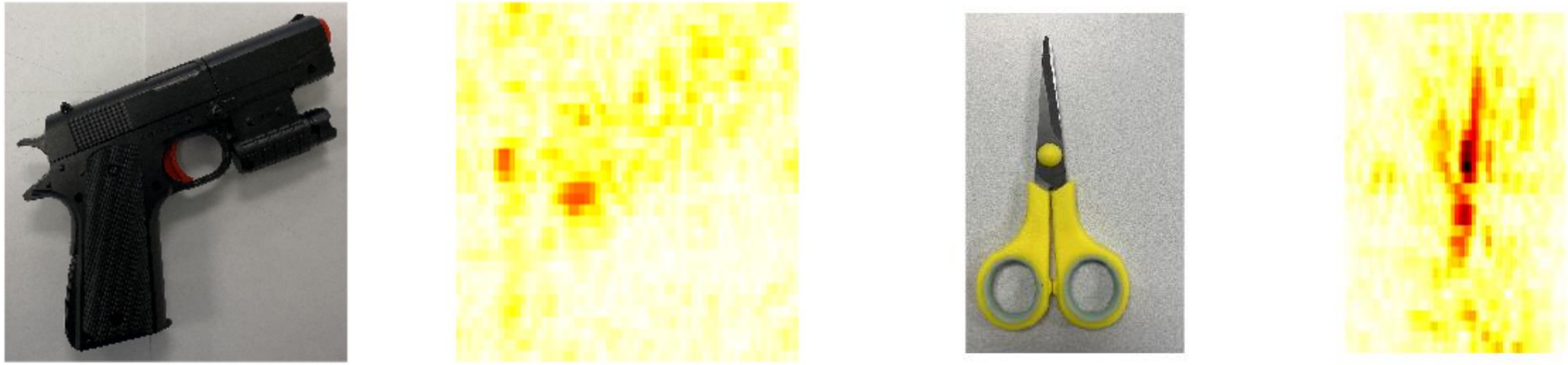
- Compressed Sensing fails if data are **correlated** and **wide**
- Visual-aid ensures **randomness** in data points collected
- we also **limit the range to 4 m** to avoid wide problem as our application is targeted for short range
- Additionally, we use Density based clustering algorithm (DBSCAN) to separate objects in the scene

Challenges

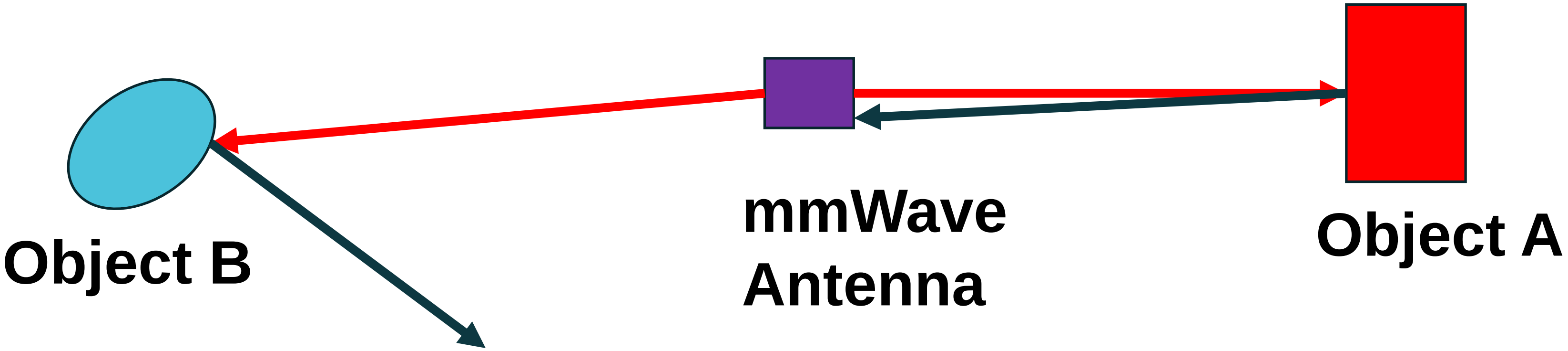
Hand-Held Imaging

Specularity and Weak Reflectivity

Specularity And Weak Reflectivity

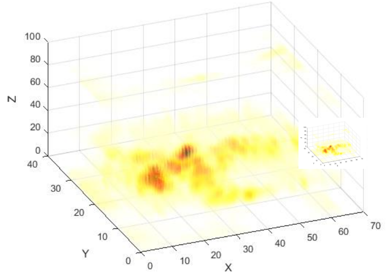


Object surface acts like mirror and transmitted signal bounces off an angle it will not come back to the receiver



Motivation To Use Machine Learning

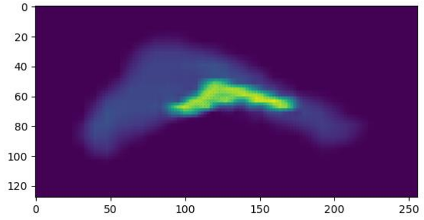
3D mmWave Image



Ground-Truth Image

Conditional Generative Adversarial Networks (cGAN)

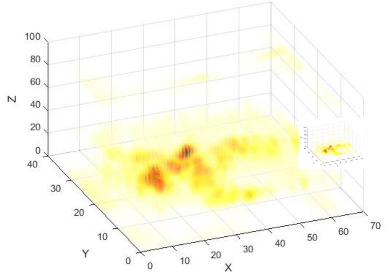
Epoch: 1



Difficult to Recognize Shape

Motivation To Use Machine Learning

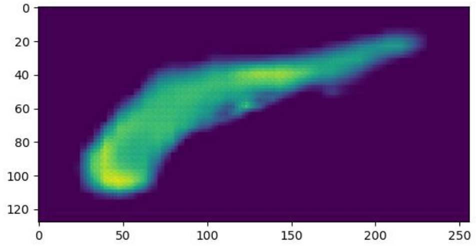
3D mmWave Image



Ground-Truth Image

Conditional Generative Adversarial Networks (cGAN)

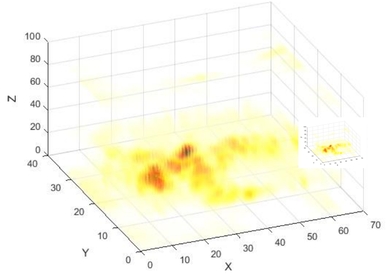
Epoch: 10



Learning real image distribution

Motivation To Use Machine Learning

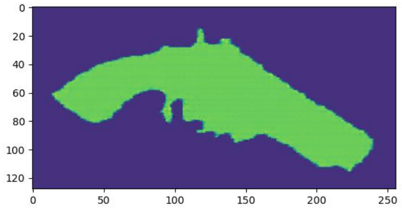
3D mmWave Image



Ground-Truth Image

Conditional Generative Adversarial Networks (cGAN)

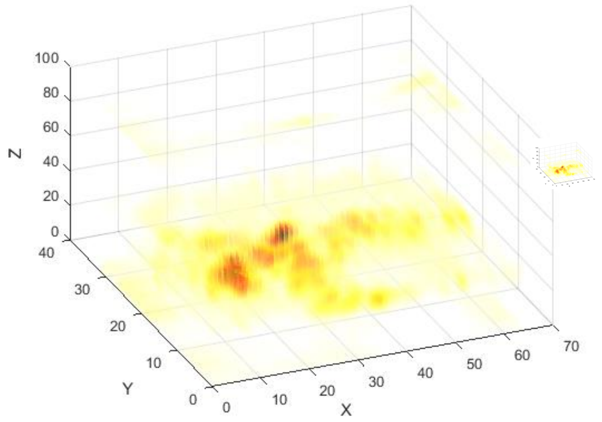
Epoch: 1000



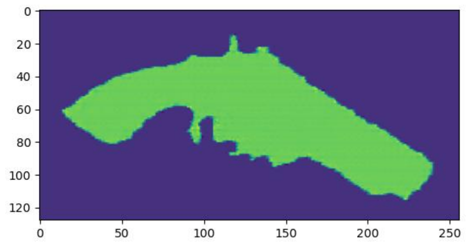
Shape Fully Recovered

Motivation To Use Machine Learning

3D mmWave Image



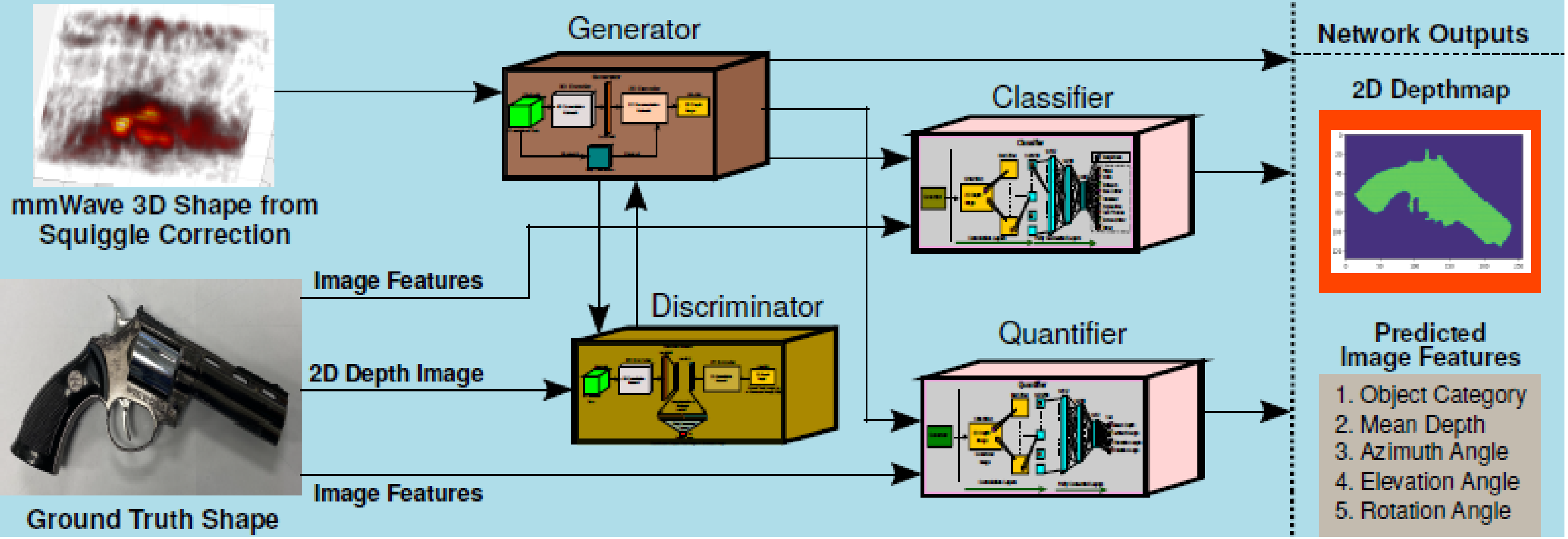
Generator



Post Training

Object is human perceptible

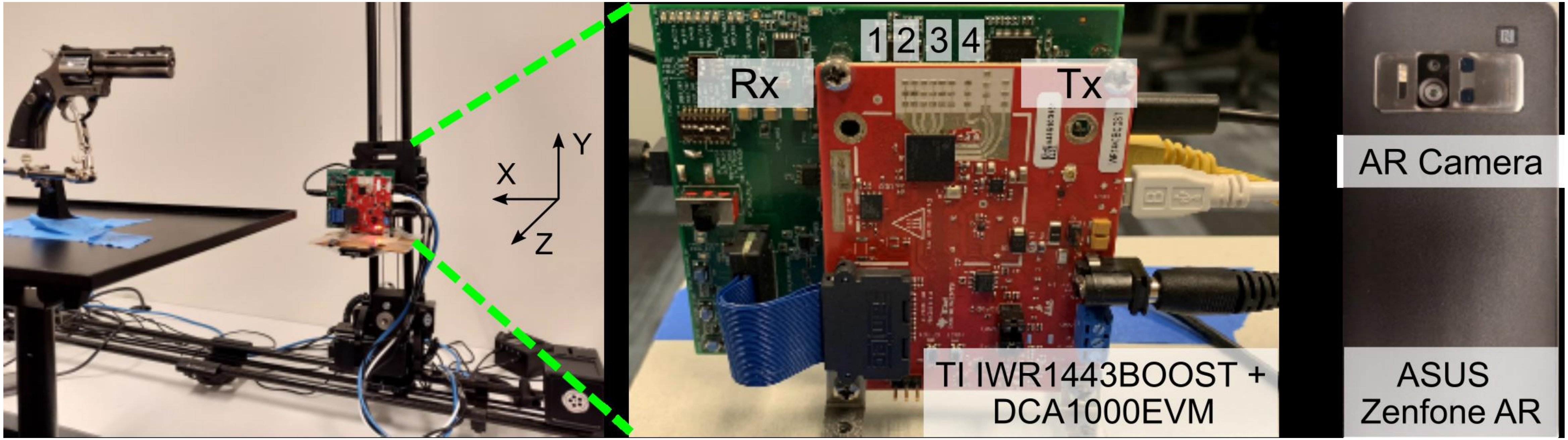
Shape Recovery With SquiggleMilli



Implementation

mmWave Hardware

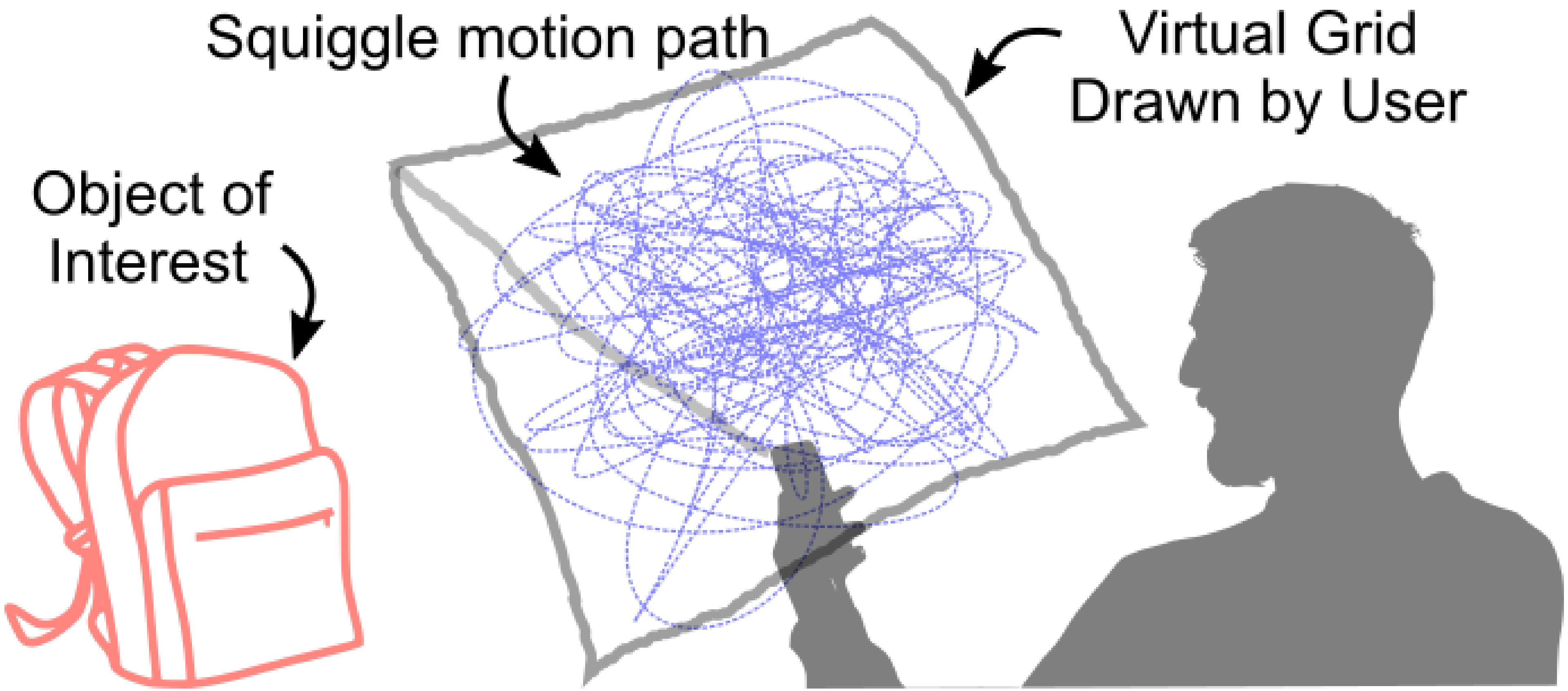
- ❑Start Frequency: 77.33 GHz
- ❑Effective BW: 3.22 GHz



Co-located mmWave hardware and AR Camera

Implementation

Squiggle Pose Collection



Data Collection

Real Data Collection

- Volunteers are asked to squiggle phone to collect pose data
- Then, we place mmWave in precise mechanical controller
- It scans the area of 20 x 20 cm^2
- Apply pose to obtain the squiggle data set

- To collect ground-truth 2D shape, we use co-located AR device
- MmWave 3D image: 40x1000x236 => 32x64x96
- 2D shape ground-truth: 128x256 depth image
- Takes ~ 15 mins/sample

2918 LOS and NLOS Real Samples

Real data collection is slow and ML needs lots of data, what can we do?

Data Collection

Synthetic Data Generation

- Large data scales for mmWave are not available
- We collected multiple 3D shapes from ShapeNet
- We projected the image into 2D shape and apply different 3D rotation matrix to generate 3D voxel
- 3D voxel is then used in **Ray Tracing Algorithm**
- Introduced various noises in simulation
- It generates the mmWave image like the images generated by SAR Imaging Devices
- Single simulation takes ~ 1.5 min in our PC (Intel Xeon @ 32 GB RAM)

9800 Synthetic Samples

Evaluation

Hand-Held Imaging

Specularity and Weak Reflectivity

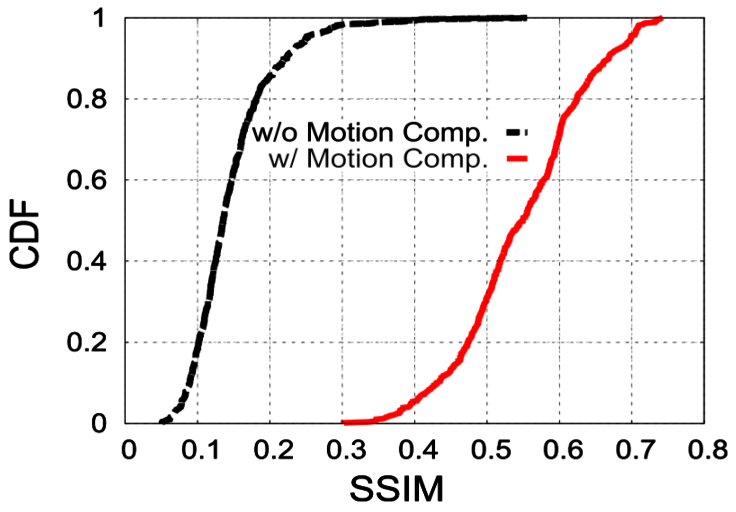
Evaluation

Hand-Held Imaging

Specularity and Weak Reflectivity

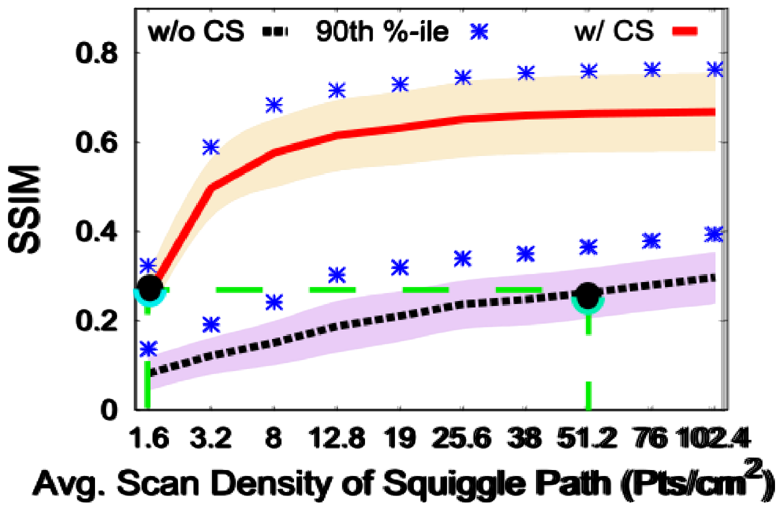
Hand-held Imaging

Motion Correction



Shape quality improved ~4 times

CS Recovery



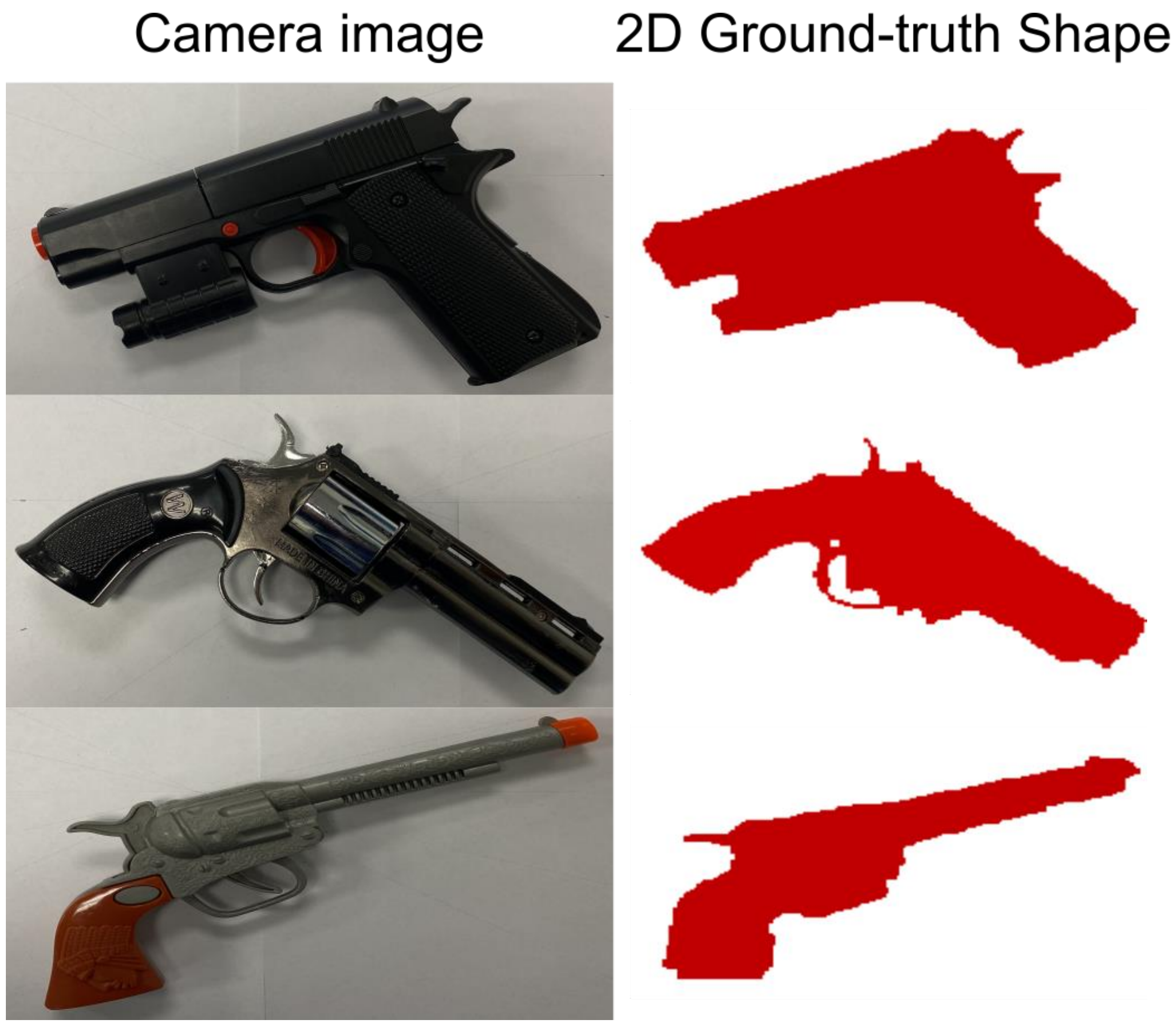
Scan Requirement Reduced by 30 times

Evaluation

Hand-Held Imaging

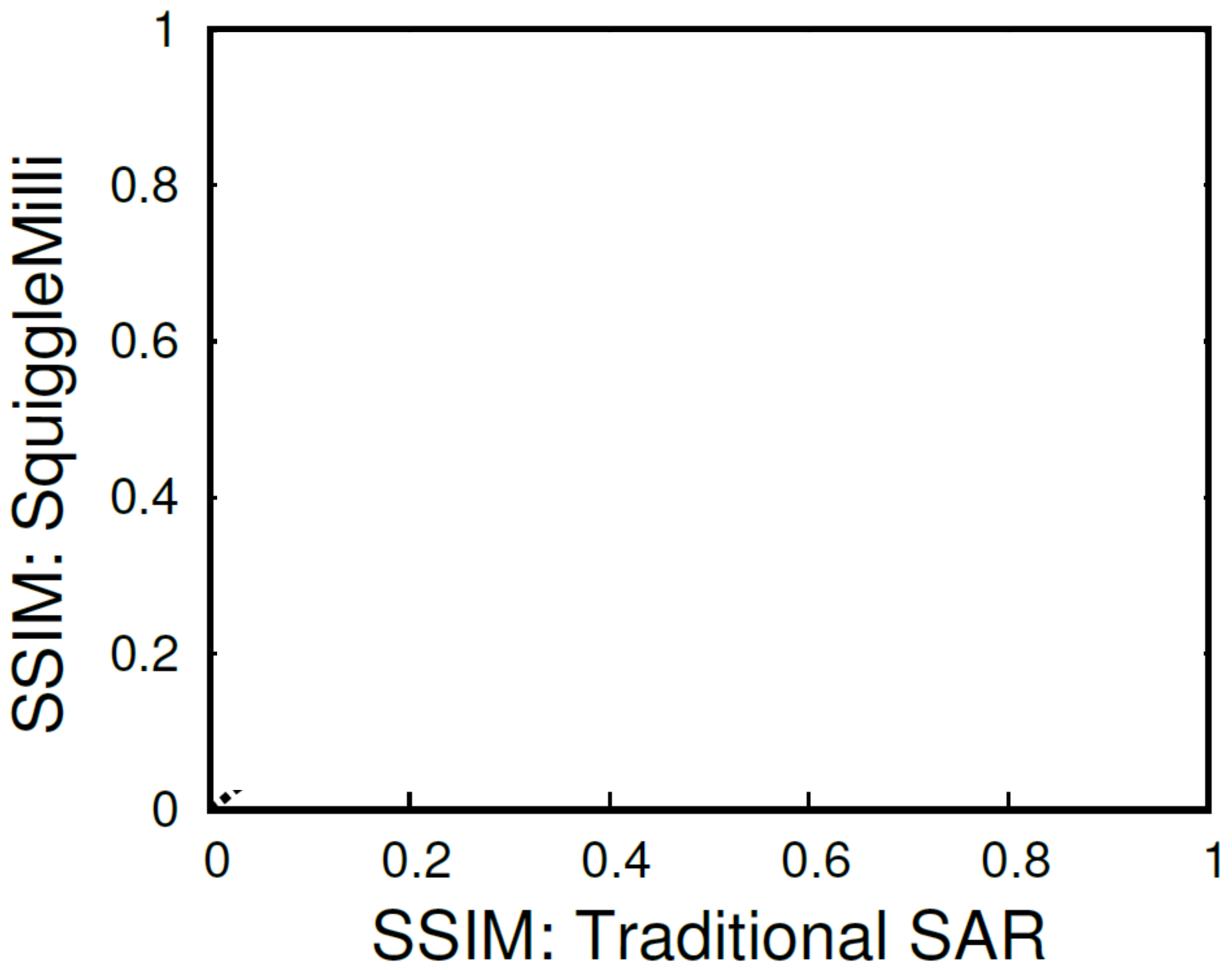
Specularity and Weak Reflectivity

Full Shape Recovery With SquiggleMilli



Human perceptible shape generated by Generator

Full Shape Recovery With SquiggleMilli



LOS: Line of Sight
NLOS: None Line of Sight
Unseen: Objects not included in Training but looks like the Category of objects trained

Median similarity to ground-truth is 90% for NLOS

Object Classification

Actual/Predicted	Boxcutter	Cellphone	Explosive	Hammer	Knife	Pistol	Scissor	Screw	Other
Boxcutter	**94**	0	0	0	0	0	1	0	5
Cellphone	0	**69**	0	4	0	2	0	0	25
Explosive	0	0	**85**	8	0	0	0	0	7
Hammer	0	0	0	**93**	0	0	3	0	4
Knife	5	0	0	0	**67**	0	8	0	20
Pistol	2	0	0	0	0	**87**	2	1	8
Scissor	0	0	0	0	0	0	**100**	0	0
Screw	0	0	0	3	0	0	19	**45**	33
Other	0	0	19	6	0	21	2	0	**52**

Objects are selected which are use used in TSA Screening

Objects are correctly classified to respective classes

Field Trials

Camera image

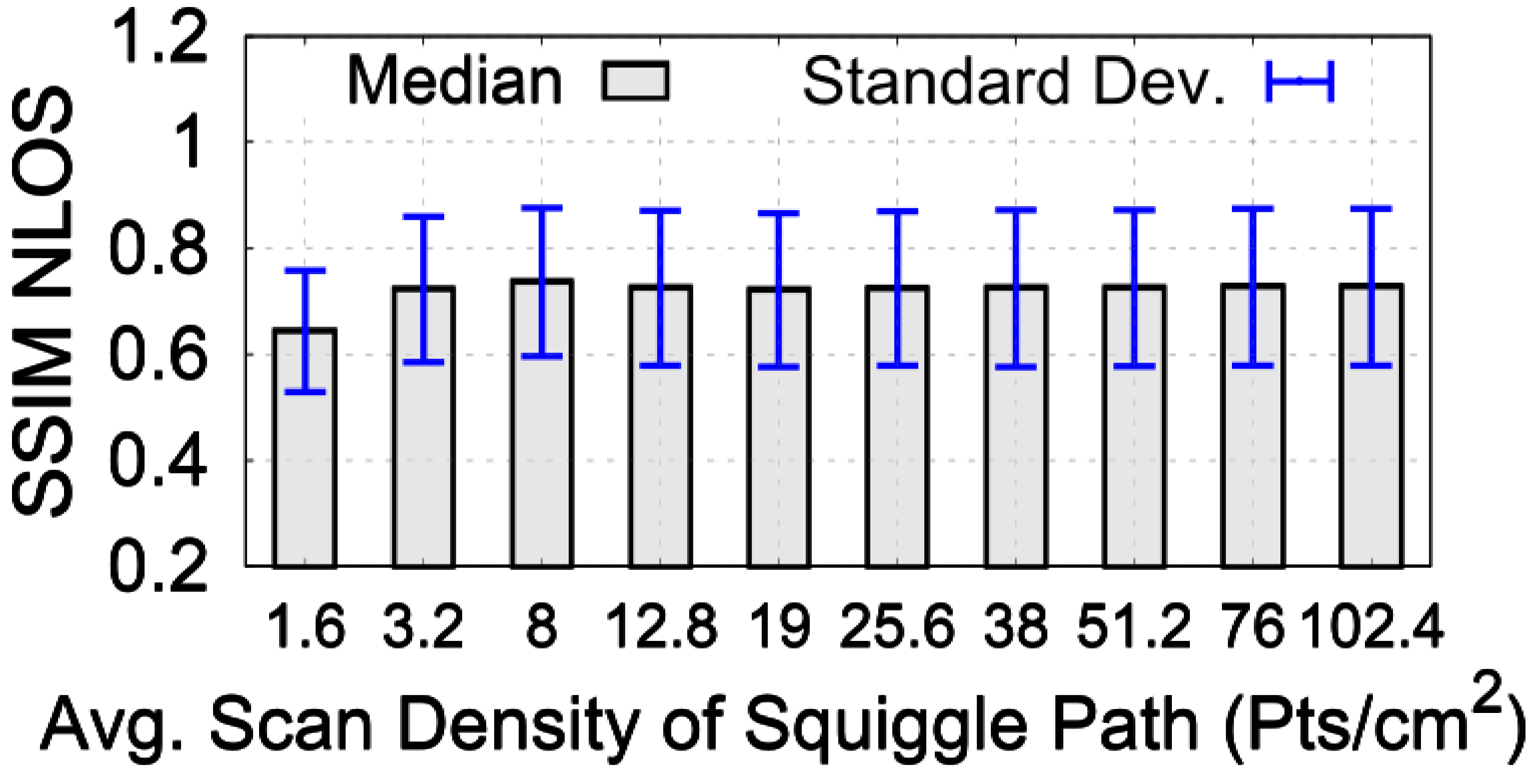
Pistol semi-occluded

Pistol fully-occluded

Scissors semi-occluded

Human perceptible shape even when object is occluded

Field Trials



Achieved 72% shape similarity with just 3.2 pts/cm^2 scan density

Conclusion

- SquiggleMilli brings **high-resolution**, through-obstruction imaging into cheap, **ubiquitous mobile devices**

Thank you!

Please check out our paper for more results:
https://github.com/hregmi77/SquiggleMilli

Any Questions: Please email to hregmi@email.sc.edu