Learning-Based Shadow Mitigation For Terahertz Multi-Layer Imaging

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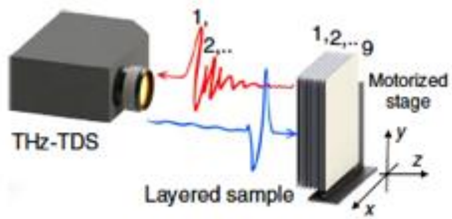
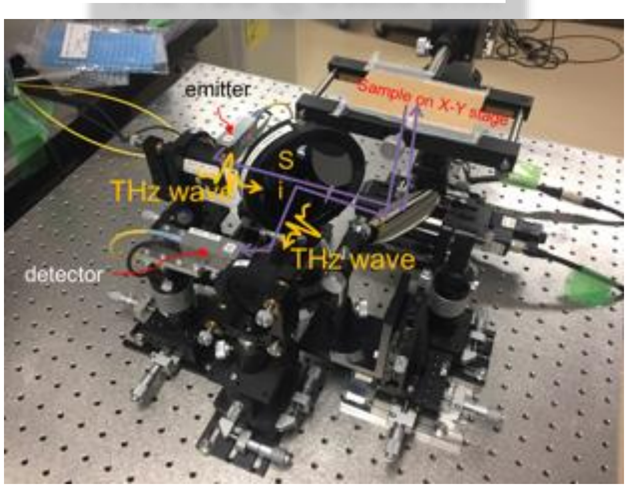
THz-TDS (THz Time-Domain Spectroscopy)

❑ Raster Scanning Mode

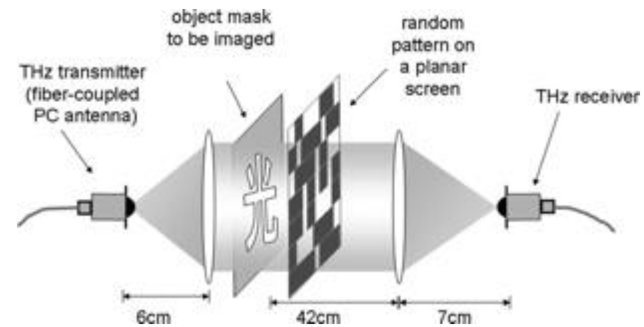


- Normal incident THz beam
- Mechanically move THz transceiver or samples
- Spot size: 1-mm radius at 1 THz
- Pulse width: 1-5 ps
- Sampling frequency: up to 5 THz
- Scanning rate: 100 Hz to 1000 Hz

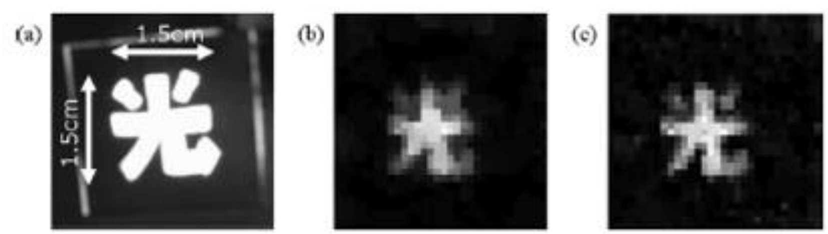
THz-TDS @ Osaka Univ.



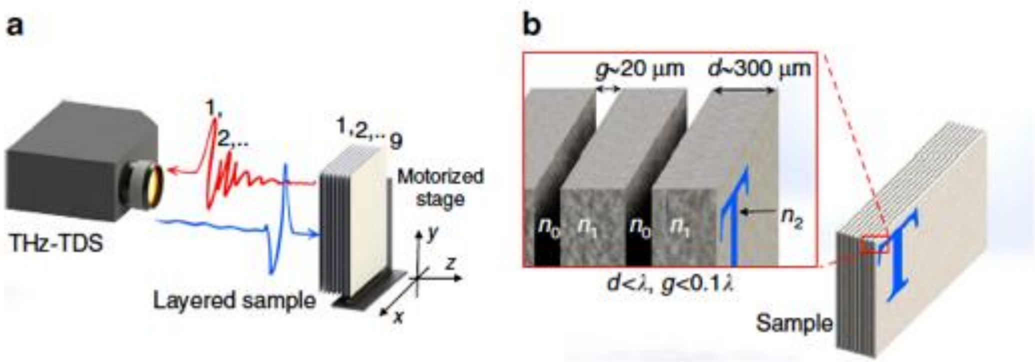
❑ Compressed Scanning Mode



- Collimated THz beam
- Spatial light modulator (SLM) at THz band
- Focusing lens before THz detector
- No mechanical scanning
- Need random masks



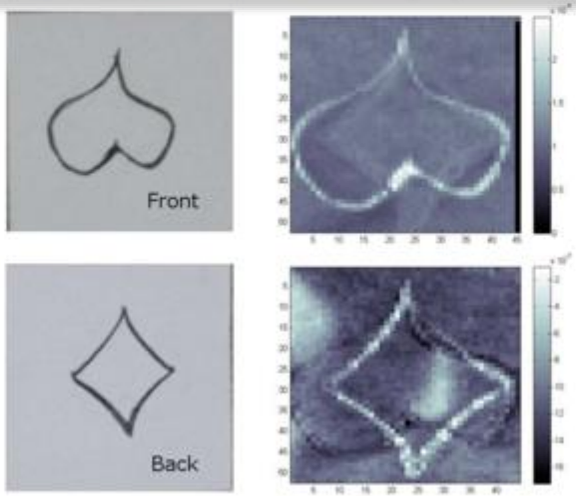
THz Multi-Layer Imaging



Images from https://www.extremetech.com/extreme/252289-2019-audi-a8-will-self-driving-37-mph

Shadow Effect (I)

Ref. [1]: THz images of the front and back of the first sheet of paper



Ref. [2]: THz image (c) of the painting *La oracion en el huerto*

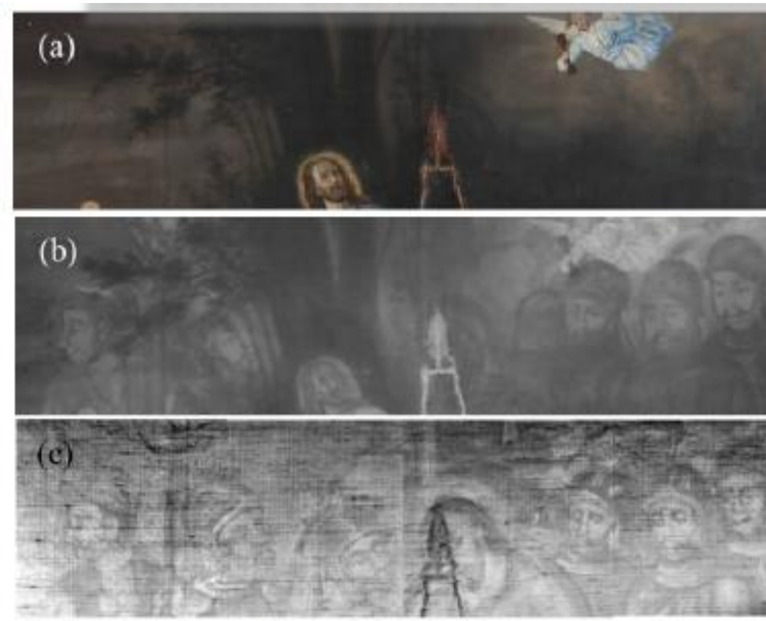
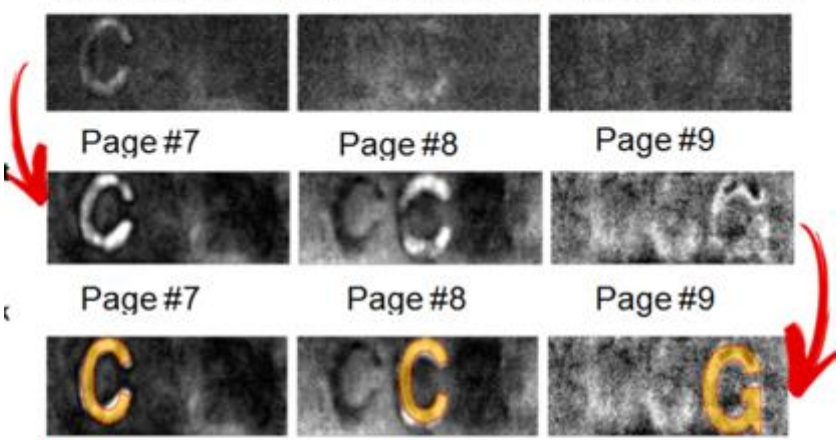


Fig. 3. a. Second detail of the painting *La oración en el huerto*. **b.** the infrared image of the detail. **c.** the THz record of the detail

Ref. [3]: MIT THz See-Through Book

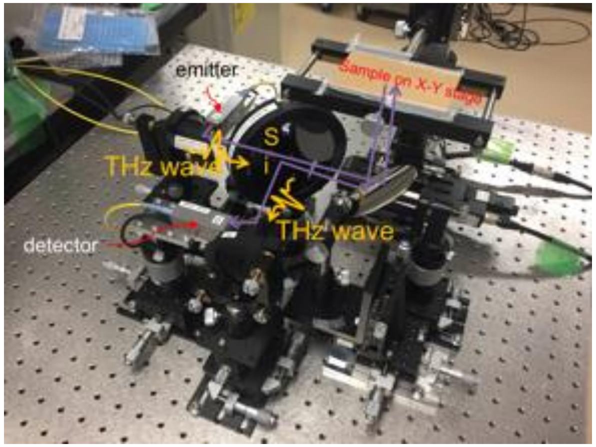
Measured time-domain E-field amplitude on page 7-9

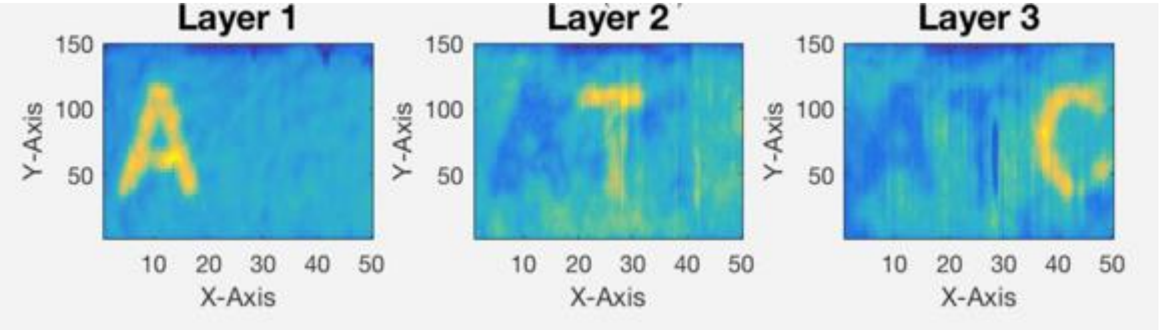


[1] G. C. Walker, et al., "Terahertz deconvolution," Optics Express, vol. 20, no. 25, pp. 27230–27241, Dec. 2012.
[2] C. L. K. Dandolo et al., "Contribution of terahertz time-domain analysis to art history: The case of the paintings of the Santo Entierro de Nuestro Señor Jesucristo altarpiece," 42nd IRMMW-THz, Cancun, Mexico, 2017
[3] A. Redo-Sanchez, et al., "Terahertz time-gated spectral imaging for content extraction through layered structures," Nature Communications, vol. 7, pp. 1–7, Sept. 2016.

Shadow Effect (II)

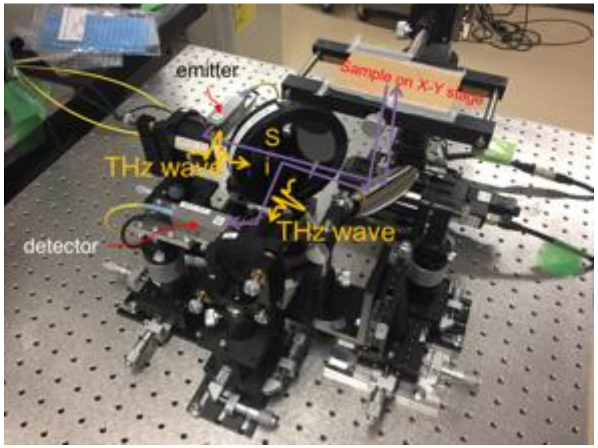
Our own experiment at Osaka University

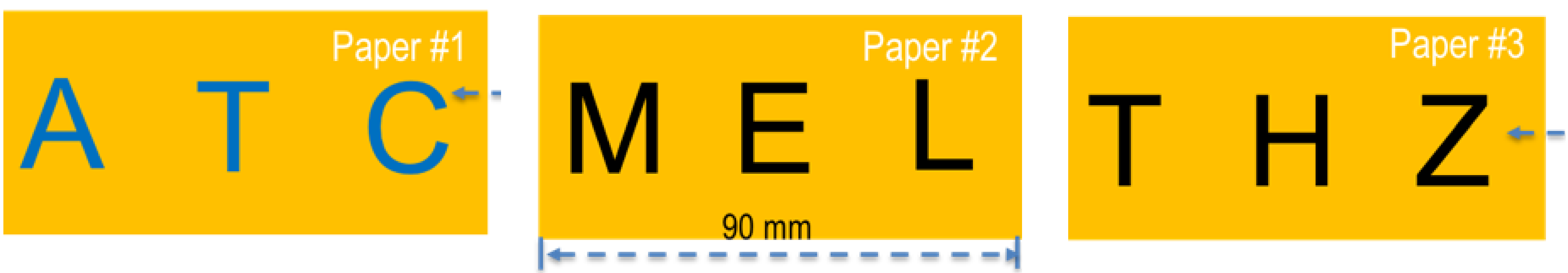




Shadow Effect (III)

Our own experiment at Osaka University

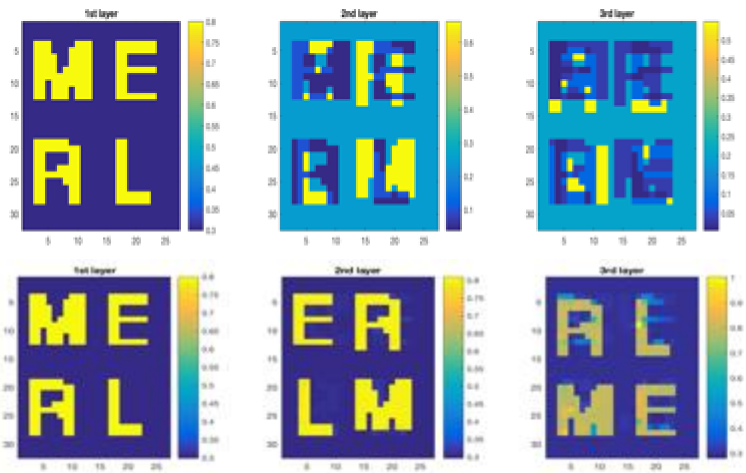


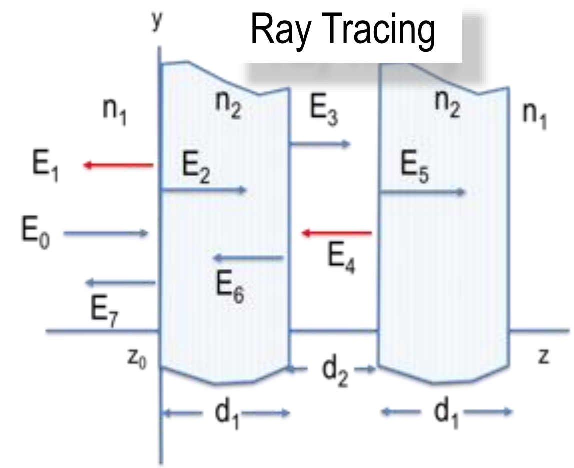


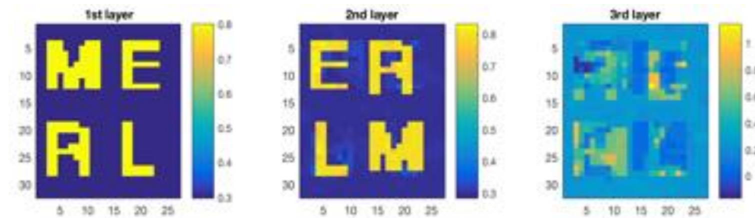
Model-based Approaches

Ray-tracing model

$$x(t) = \rho_1 s\left(t - 2\frac{z_0}{c}\right) + \rho_2(1-\rho_1^2)^2 s\left(t - 2\frac{z_0}{c} - 2\frac{n_2 d_1}{c} - 2\frac{d_2}{c}\right)$$



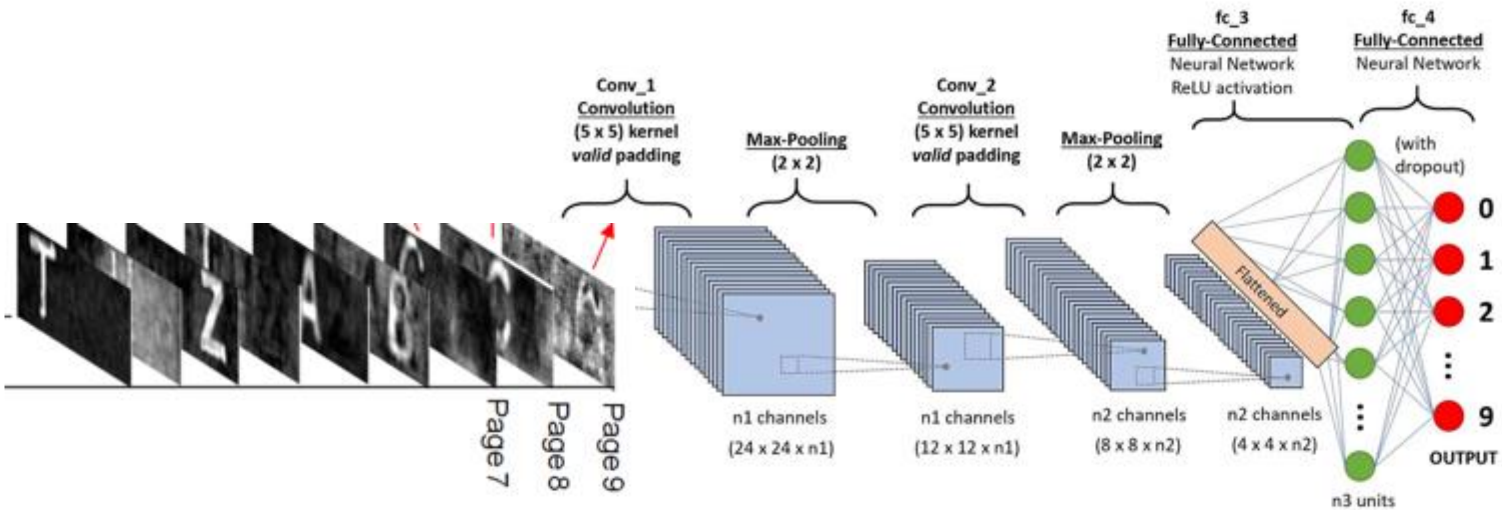




Nonlinear scattering model

Learning-based Approaches

Image-domain learning approaches



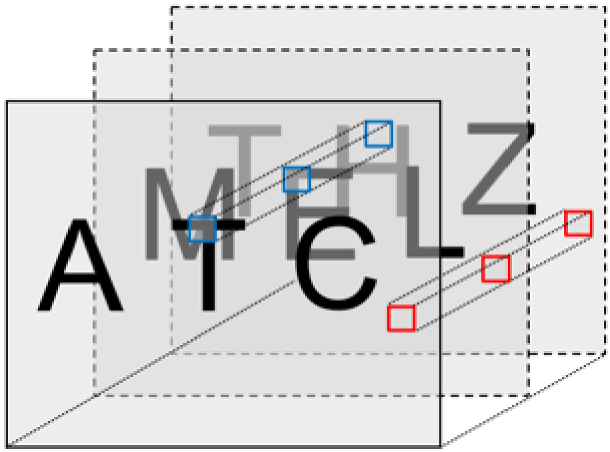
- Inputs: multi-layer THz images with shadow effects
- Labels: ground truth
- Convolutional neural networks (CNN) with multi-dimensional local convolution
- May work well with sufficient multi-layer THz images
- Challenges: multi-layer THz images are limited.

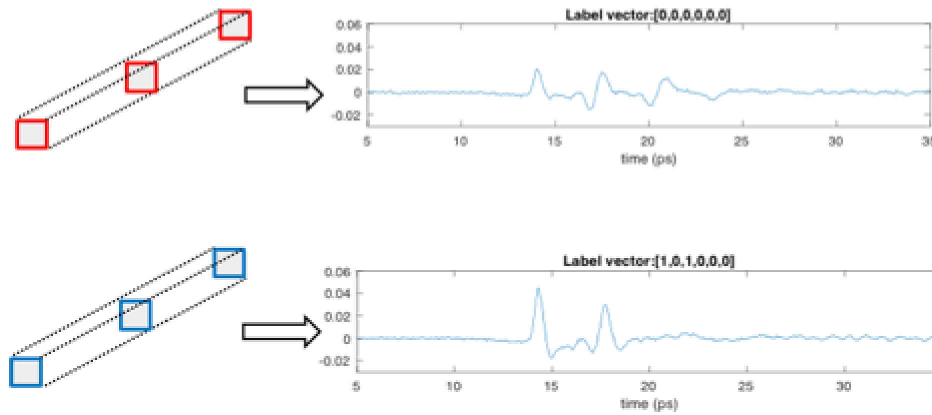
Voxel-domain learning approaches

Learning-based Approaches

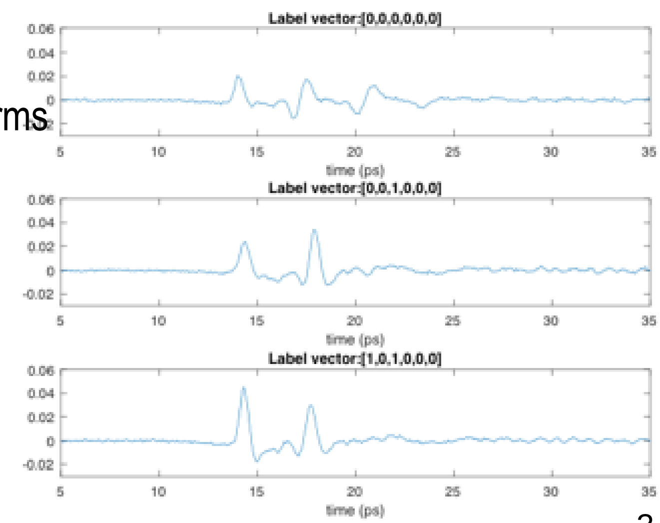
Voxel-domain learning approaches

- Decompose multi-layer images into voxels
- Voxels are labeled by binary vectors (0/1): 0 denotes no content while 1 means there is a content
- The dimension of binary vectors is 2L, where N is the number of layers



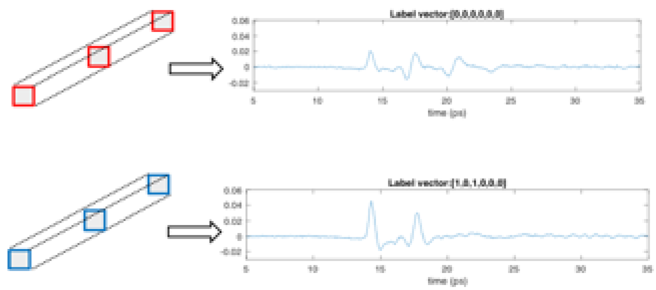


- Each voxel is attached to corresponding THz-TDS time-domain waveforms

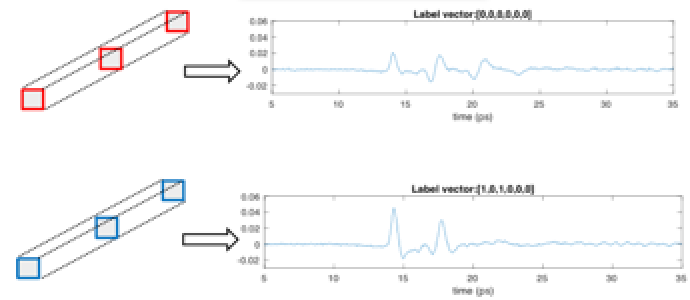


Learning-based Approaches

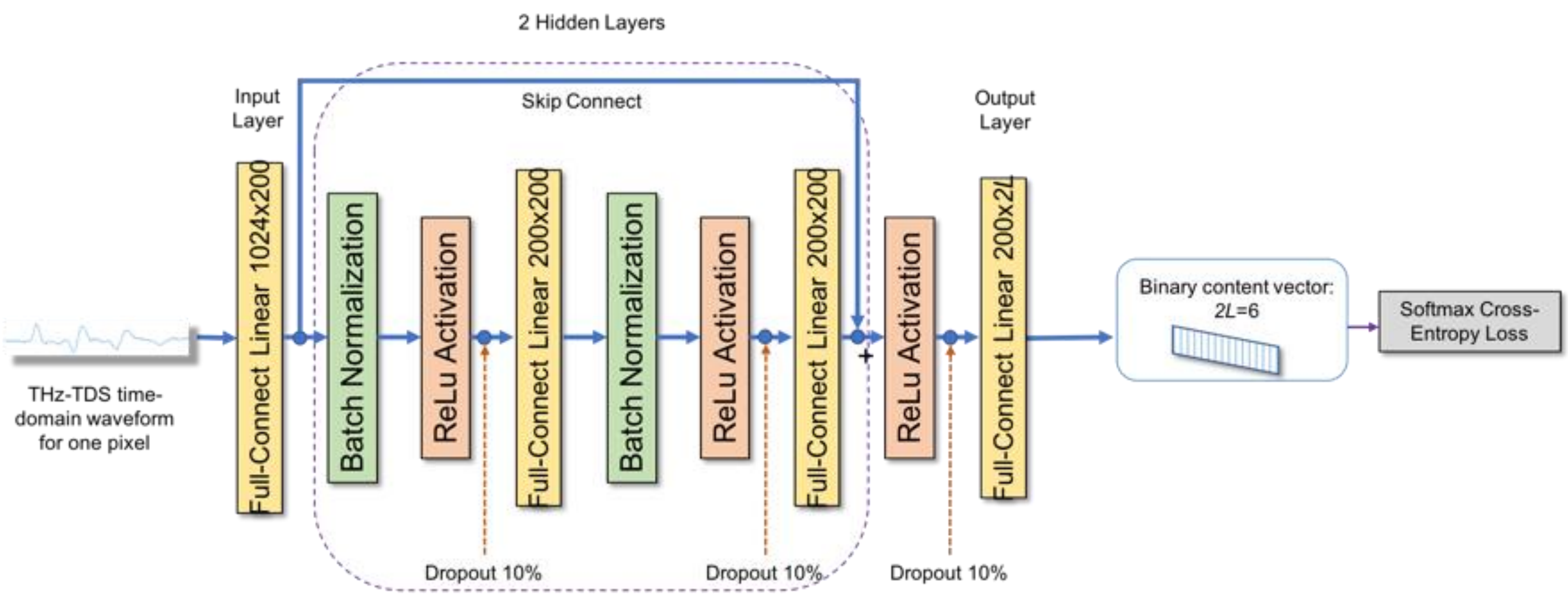
Training



Testing

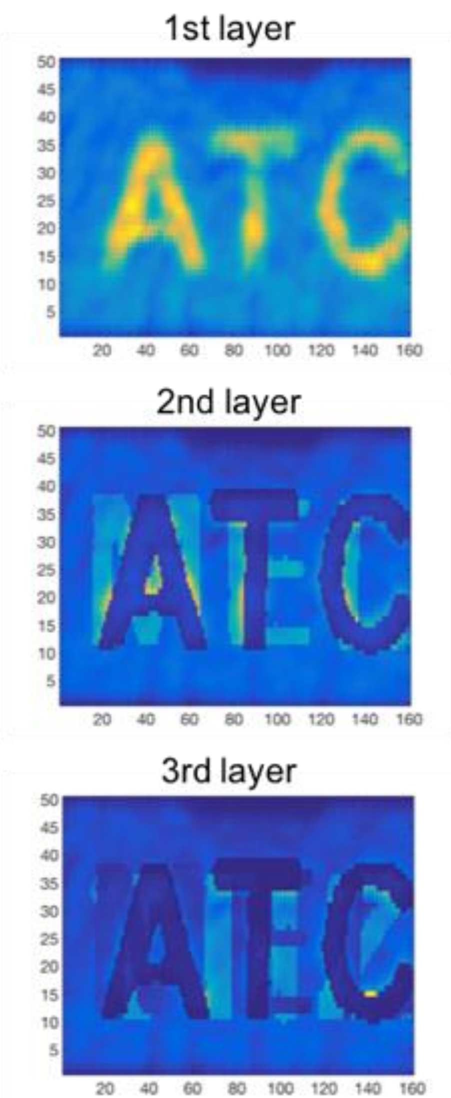


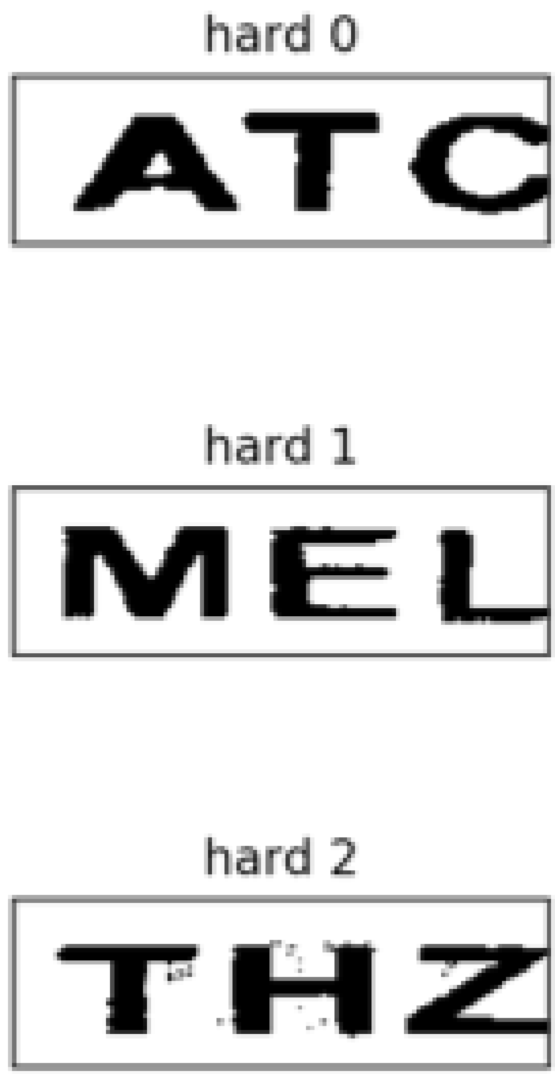
Deep Residual Network (ResNet)

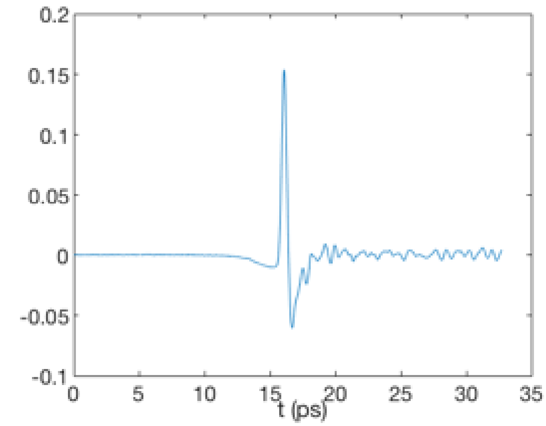


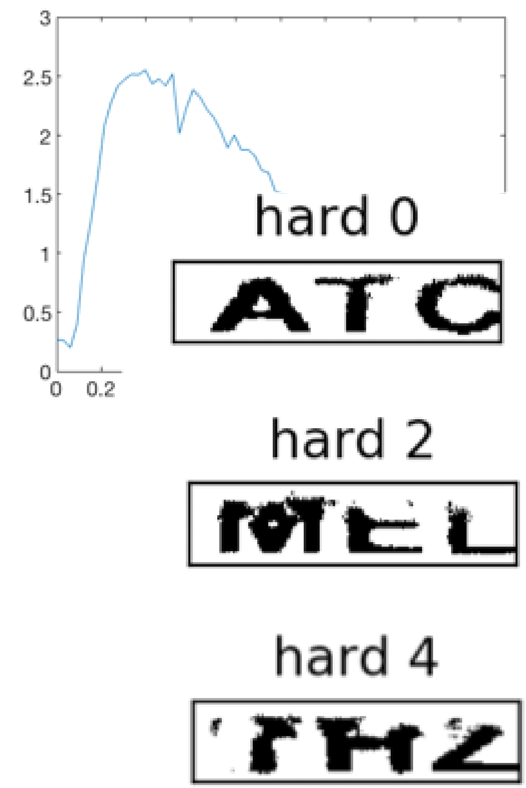
Validations

Synthesized Dataset with Sweep Distortion









Summary