Seeing and listening when common sense says it shouldn't be possible

Ilya Starshynov

UDRC Themed Meeting on Imaging through Obscure Media, 22 July 2020

Outline

- Imaging through dynamic scattering media using artificial neural networks
- Spatial imaging from temporal data
- NLOS laser microphone

Outline

- Imaging through dynamic scattering media using artificial neural networks
- Spatial imaging from temporal data
- NLOS laser microphone

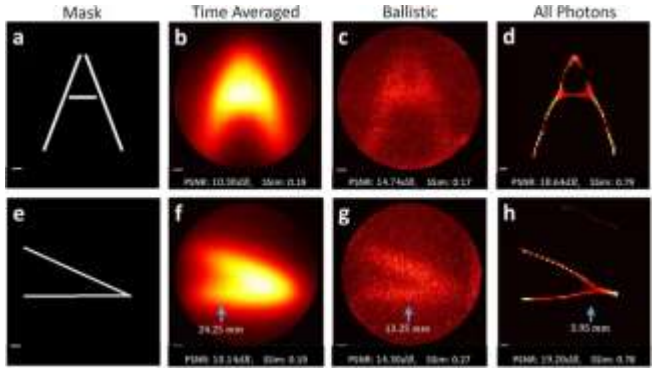
Imaging through scattering

Scattering strength

Ballistic light

Optical coherence tomography

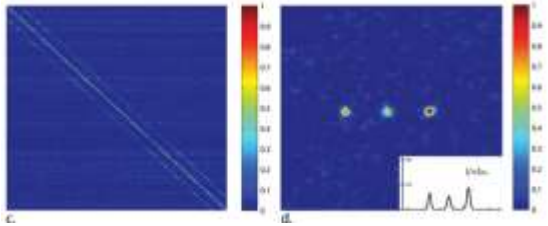
Time gated imaging



Satat, Guy, et al. Scientific reports **6** (2016): 1-8.

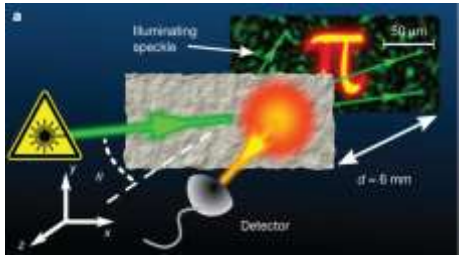
Multiply scattered light

Transmission matrix

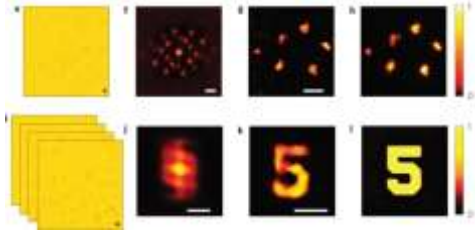


Popoff, S. M., et al. Phys. Rev. lett. **104** (2010): 100601.

Memory effect

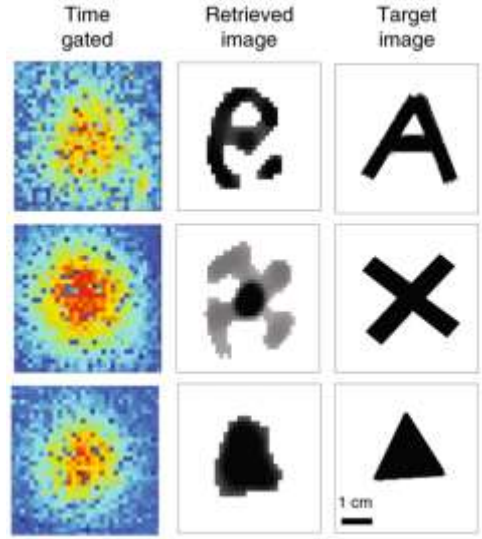


Bertolotti, J. et al. Nature **491**, 232–234 (2012).



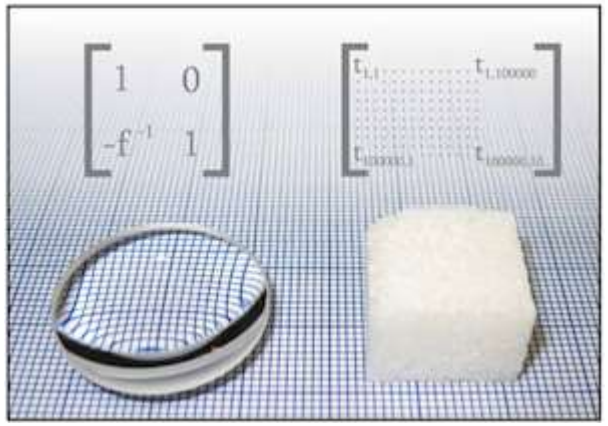
Katz, O., et al. Nat. phot. **8** (2014): 784.

Diffused light

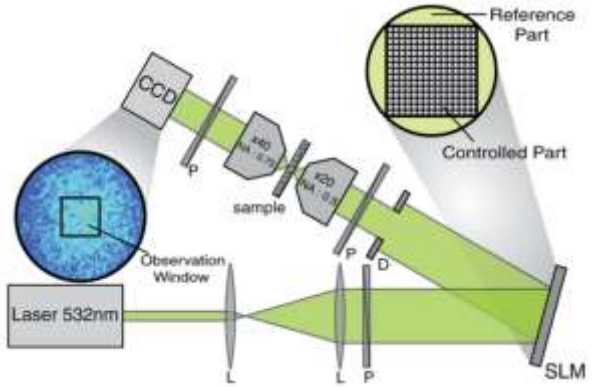


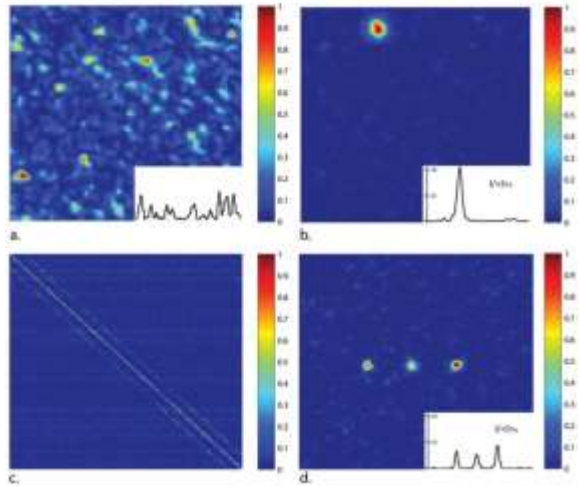
Lyons, A., Tonolini, F., Boccolini, A. *et al. Nat. Photonics* **13,** 575–579 (2019)

Transmission matrix

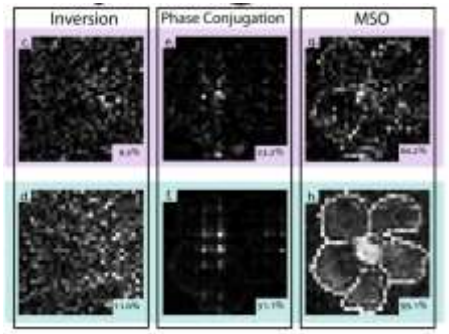


E. G. van Putten and A. P. Mosk,
Physics **3**, 22 (2010)





Popoff, S. M., et al., Phys. rev. lett., **104**, 100601 (2010)
Popoff, S. M., et al., New J. Phys. **13**, 123021 (2011)
Kim, M., Choi, W., Choi, Y., Yoon, C., & Choi, W. Opt. exp., **23**, 12648-12668 (2015)

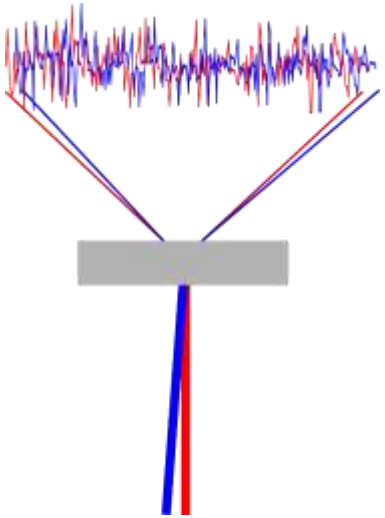


Popoff, S., Lerosey, G., Fink, M., Boccara,
A. C., Gigan, S. Nat. comm., **1**, 1-5 (2010)

- Difficult to measure
- Never measured completely
- Noise => errors (regularization)
- Changes when the medium is changed

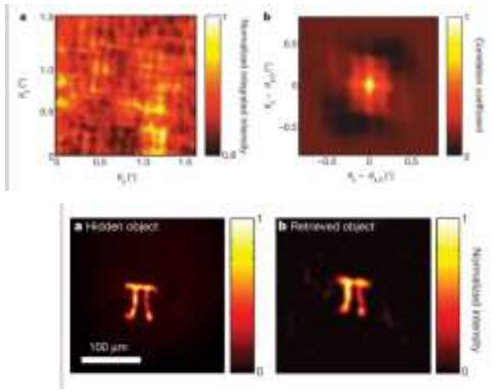
Memory effect

Speckle memory effect ==> autocorrelation of the scattered light = autocorrelation of the object

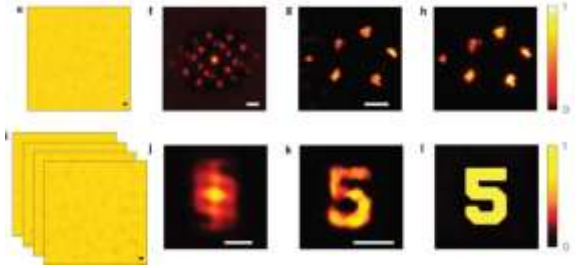


Changing the incidence angle of the incoming wave causes displacement of the output speckle without changing its shape (if the tilt is not too large)

S. Feng, C. Kane, P. A. Lee, and A. D. Stone, Phys. Rev. Lett. **61**, 834 (1988)



Bertolotti, J. et al. Nature **491**, 232–234 (2012).



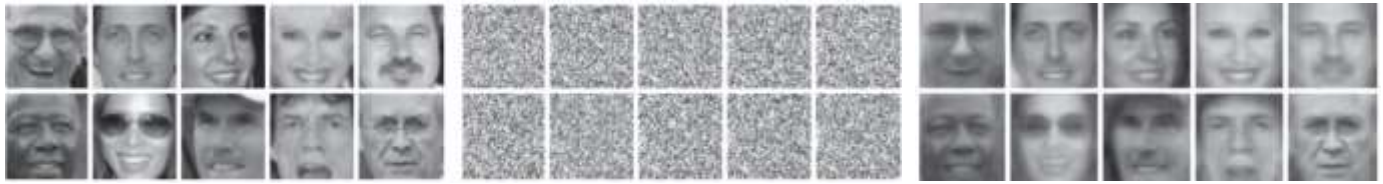
Katz, O., et al. Nat. phot. **8** (2014): 784.

ML based methods

Speckle-learning-based object recognition through scattering media

Takamasa Ando, Ryoichi Horisaki, and Jun Tanida

Optics Express Vol. 23, Issue 26, pp. 33902-33910 (2015)



Object classification through scattering media with deep learning on time resolved measurement

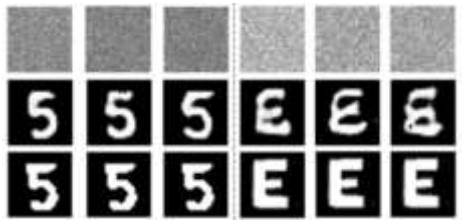
Guy Satat, Matthew Tancik, Otkrist Gupta, Barmak Heshmat, and Ramesh Raskar

Optics Express Vol. 25, Issue 15, pp. 17466-17479 (2017)

Learning-based lensless imaging through optically thick scattering media

Meng Lyu; Hao Wang; Guowei Li; Shanshan Zheng; Guohai Situ

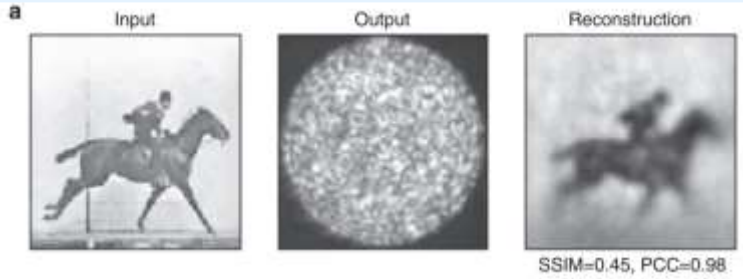
Advanced Photonics, 1(3), 036002 (2019).



Transmission of natural scene images through a multimode fibre

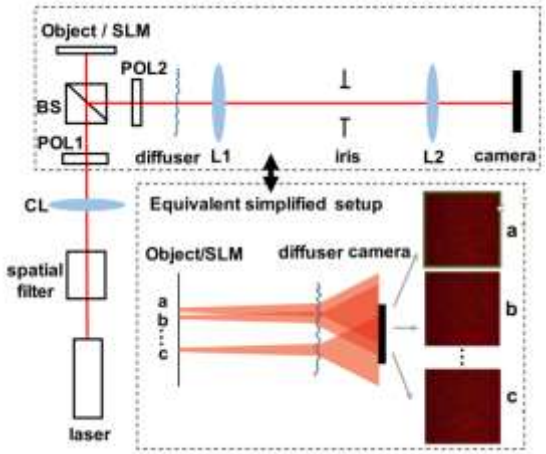
Piergiorgio Caramazza, Oisín Moran, Roderick Murray-Smith & Daniele Faccio

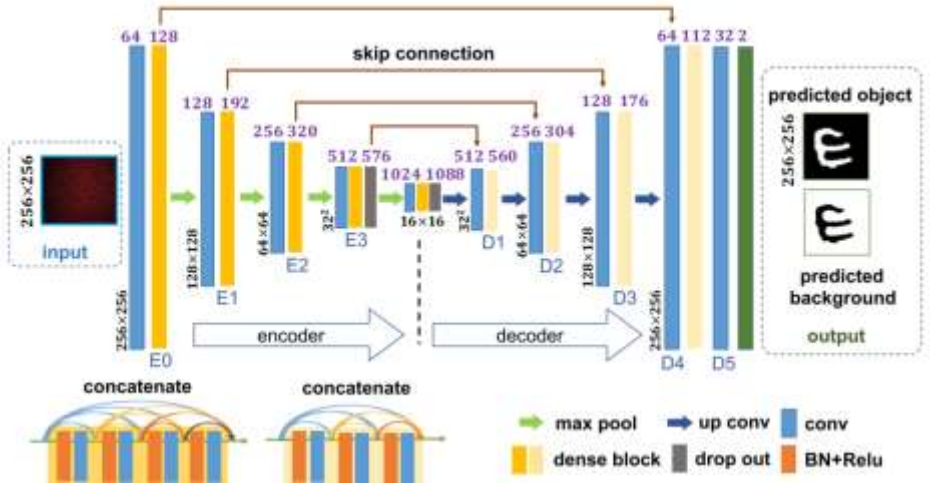
Nature Communications **10**, Article number: 2029 (2019)

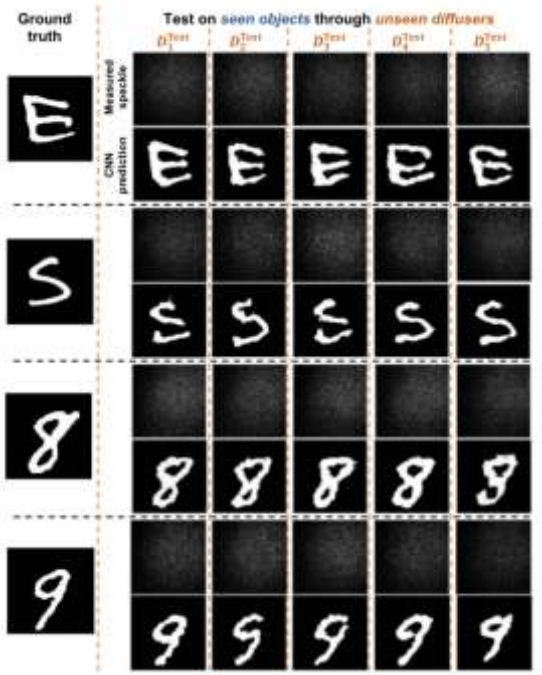


Barbastathis, G., Ozcan, A., & Situ, G. Optica, **6**, 921-943 (2019) **Review**

Deep speckle correlations

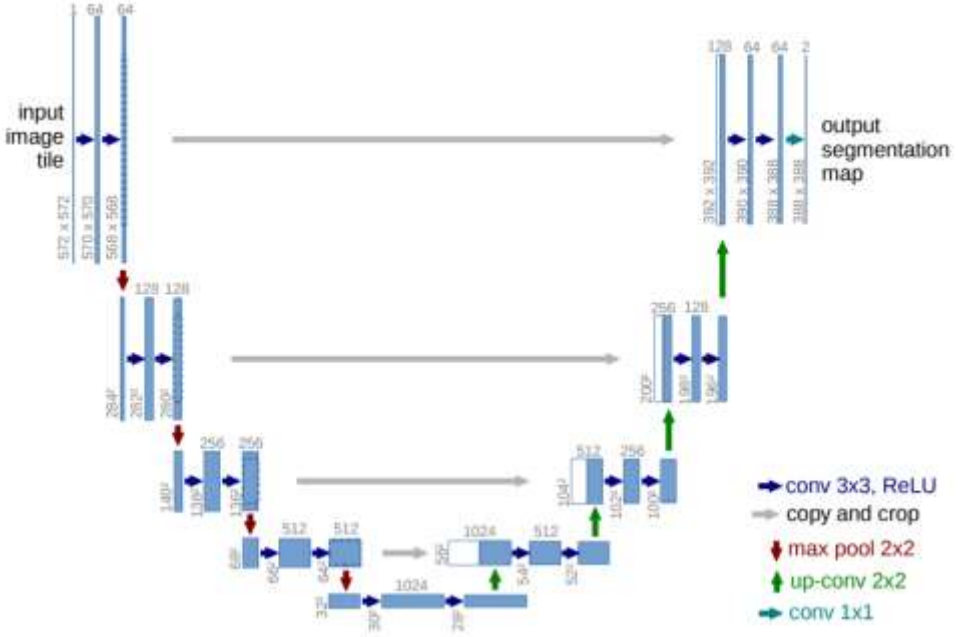


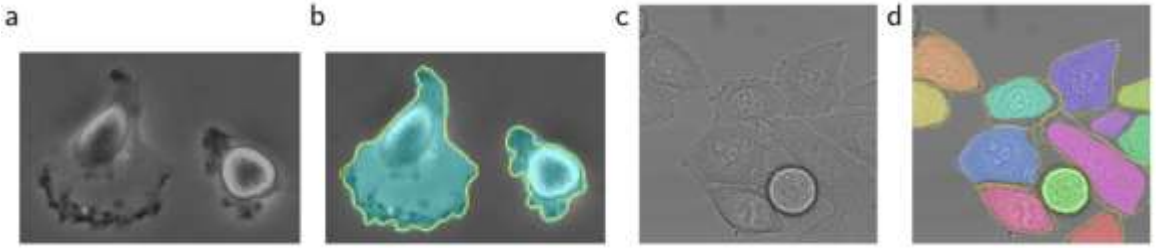




Li, Y., Xue, Y., & Tian, L. Deep speckle correlation: a deep learning approach toward scalable imaging through scattering media. Optica, **5**, 1181-1190 (2018).

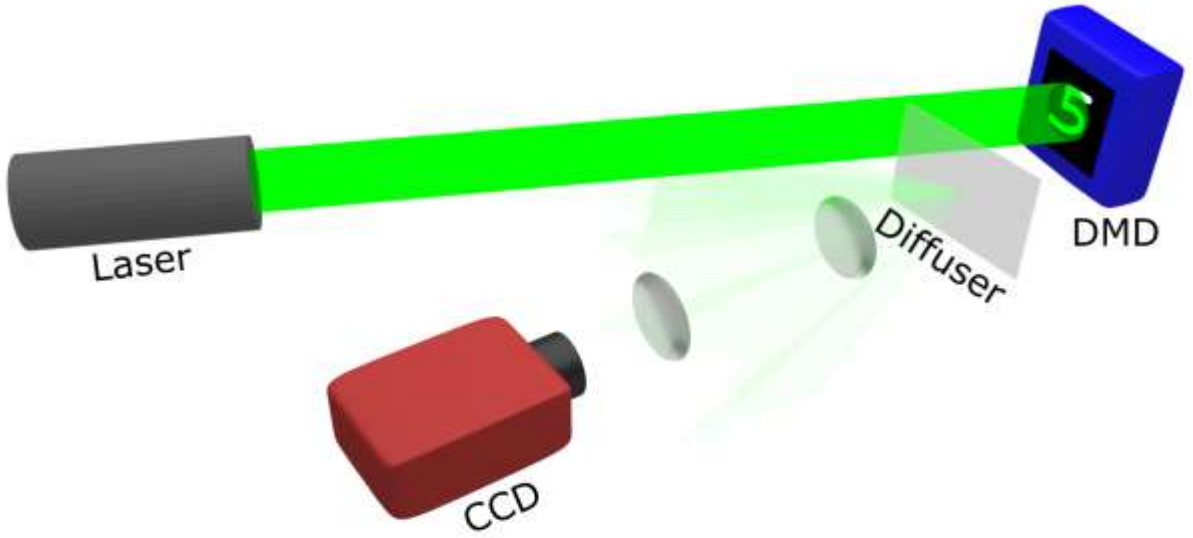
U-net autoencoder





Ronneberger, O., Fischer, P., & Brox, T. International Conference on Medical image computing and computer-assisted intervention (pp. 234-241). Springer, Cham. (2015)

Imaging through one diffuser



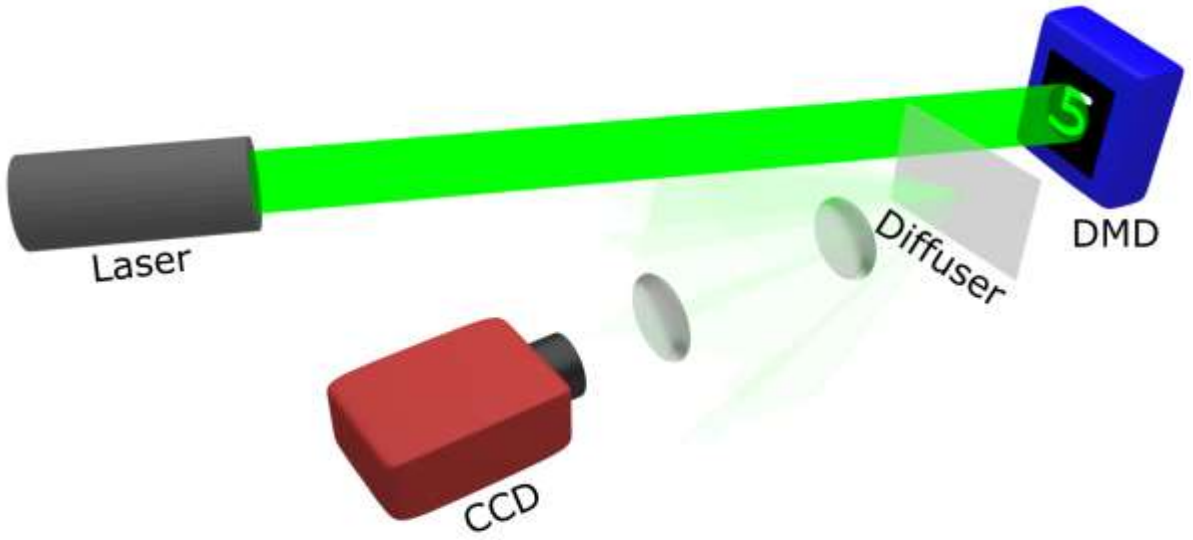
Seen spot

MSE = 0.07

Unseen spot

MSE = 0.09

Imaging through one diffuser



Could it be memory effect?

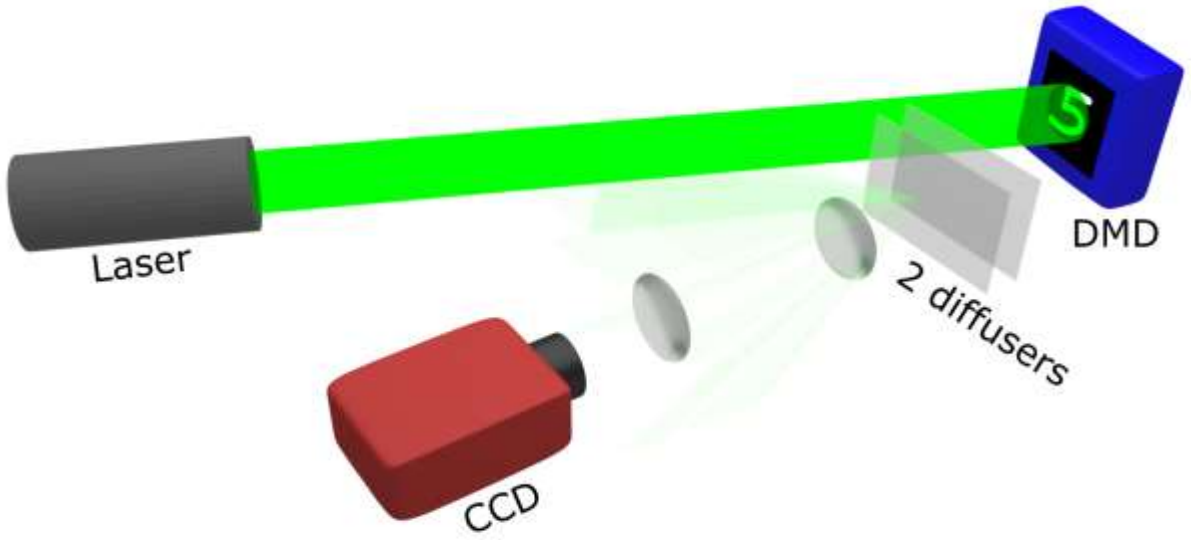
Seen spot

MSE = 0.07

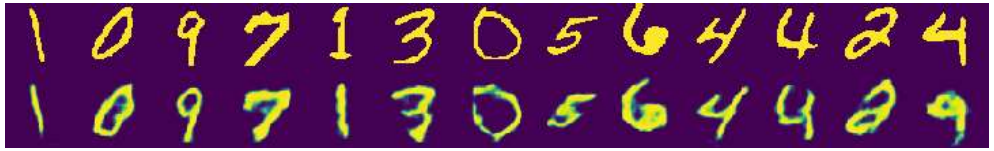
Unseen spot

MSE = 0.09

Two diffusers



Seen spot

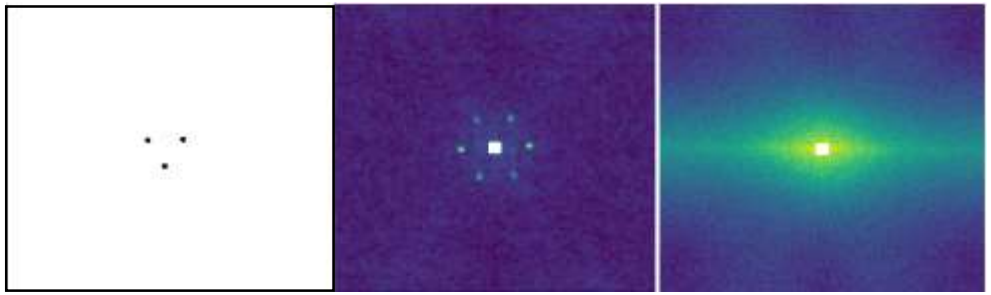


Unseen spot

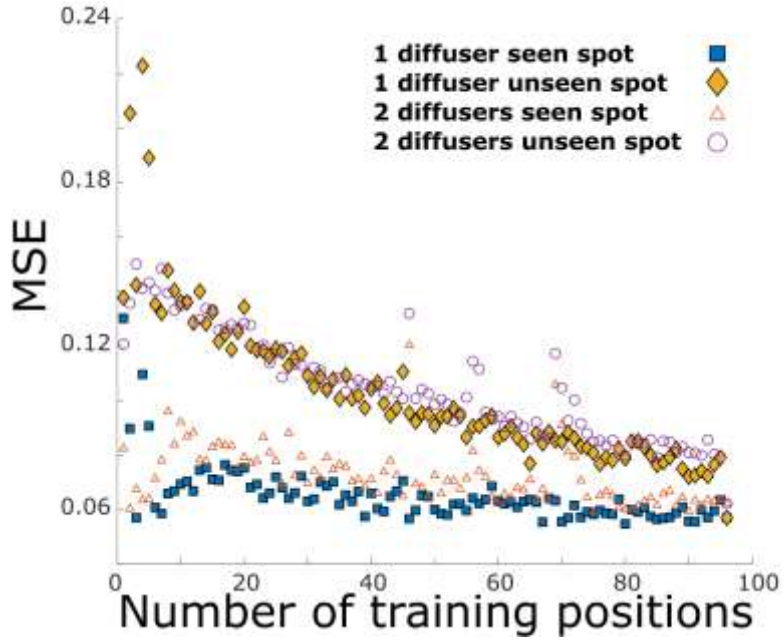
DMD image

Average speckle autocorrelation (one diffuser)

Average speckle autocorrelation (**two** diffusers)

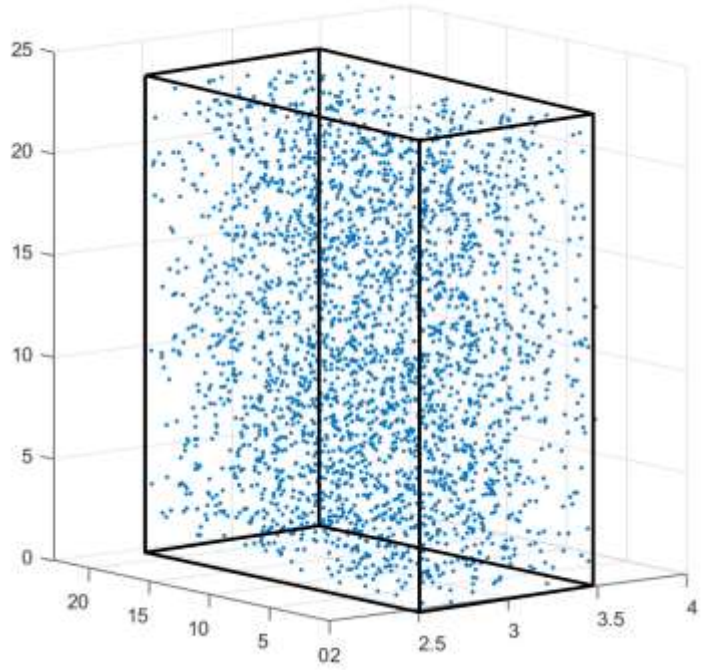


no memory effect



Simulations

Coupled dipoles approximation



Effective field at each scatterer

$$E_j = E_0(\mathbf{r}_j) + \alpha(\omega)k_0^2 \sum_{\substack{k=1 \\ k\neq j}}^{N} G_0(\mathbf{r}_j - \mathbf{r}_k)E_k,$$

Input field

$$G_0(\mathbf{r}) = \frac{e^{-ik\mathbf{r}}}{4\pi\mathbf{r}}$$

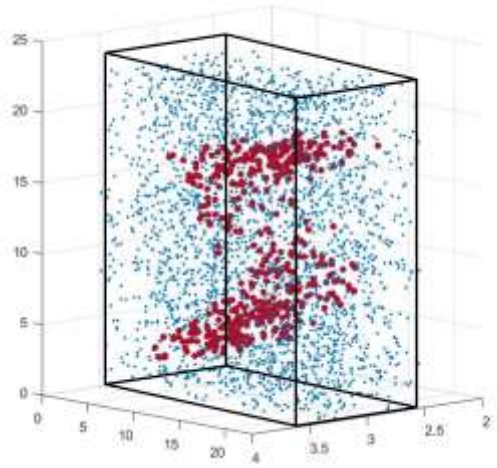
Free space Green's function

$$E(\mathbf{r}) = E_0(\mathbf{r}) + \alpha(\omega)k_0^2 \sum_{j=1}^{N} G_0(\mathbf{r} - \mathbf{r}_j)E_j.$$

Output field

M. Lax, Phys. Rev. **85**, 621

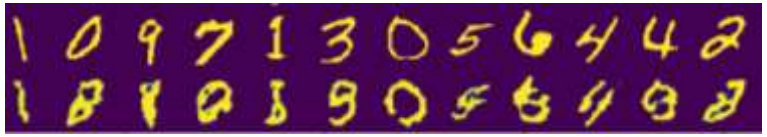
Structured disorder



Fully uniform distribution

MSE = 0.095

10% scatterers fixed

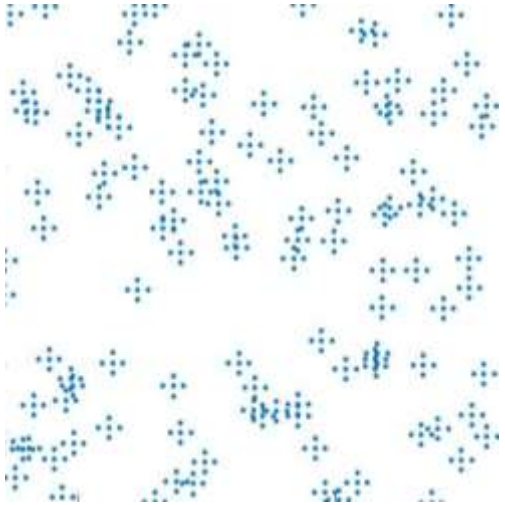


MSE = 0.11

30% scatterers fixed

MSE = 0.12

Clustered disorder



MSE = 0.091

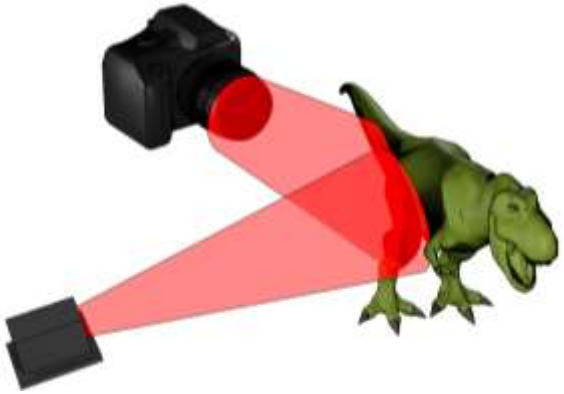
30 Disorder realizations

Outline

- Imaging through dynamic scattering media using artificial neural networks
- Spatial imaging from temporal data
- NLOS laser microphone

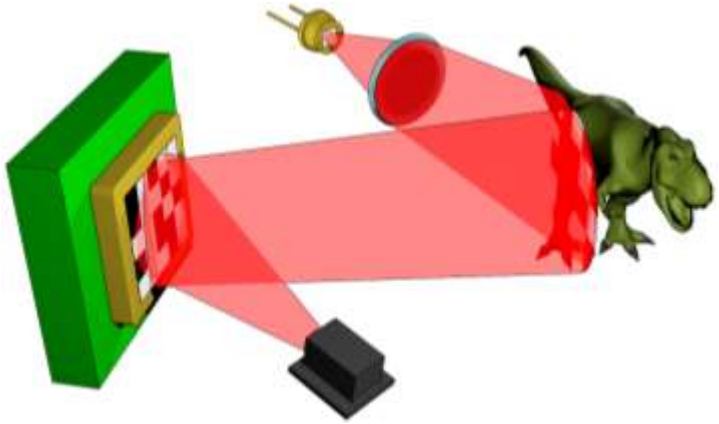
Single-pixel imaging

Conventional imaging



- Single point illumination
- Multi pixel camera

Single-pixel imaging



- Single point detector
- Mutlipixel illumination

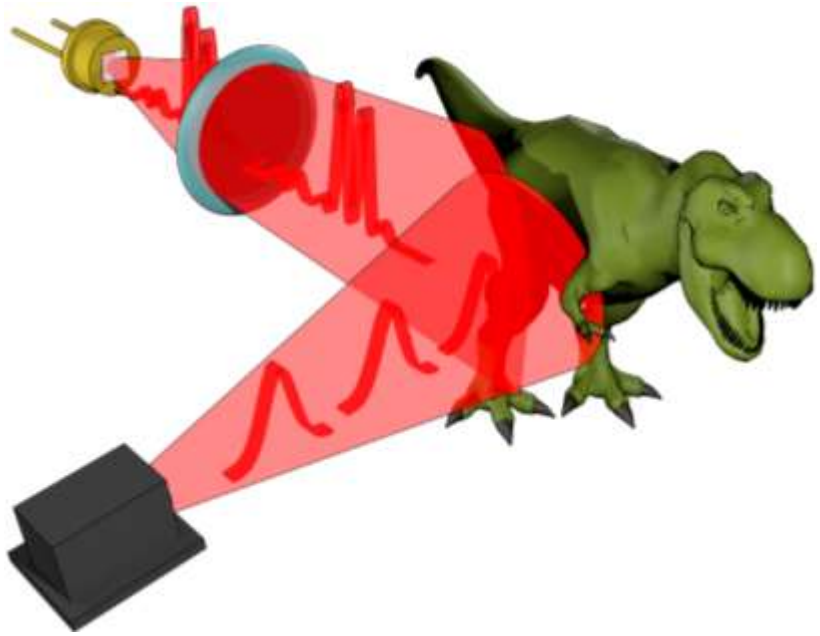
Galvo (or other way) scanning

LIDAR

https://www.lasershop.de/en/ctiset-2d-galvo-motor-kit-high-end.html

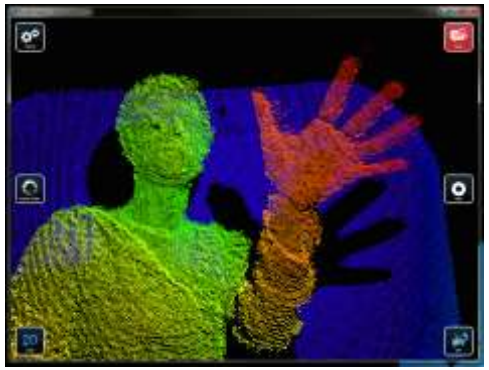
Single-pixel LIDAR

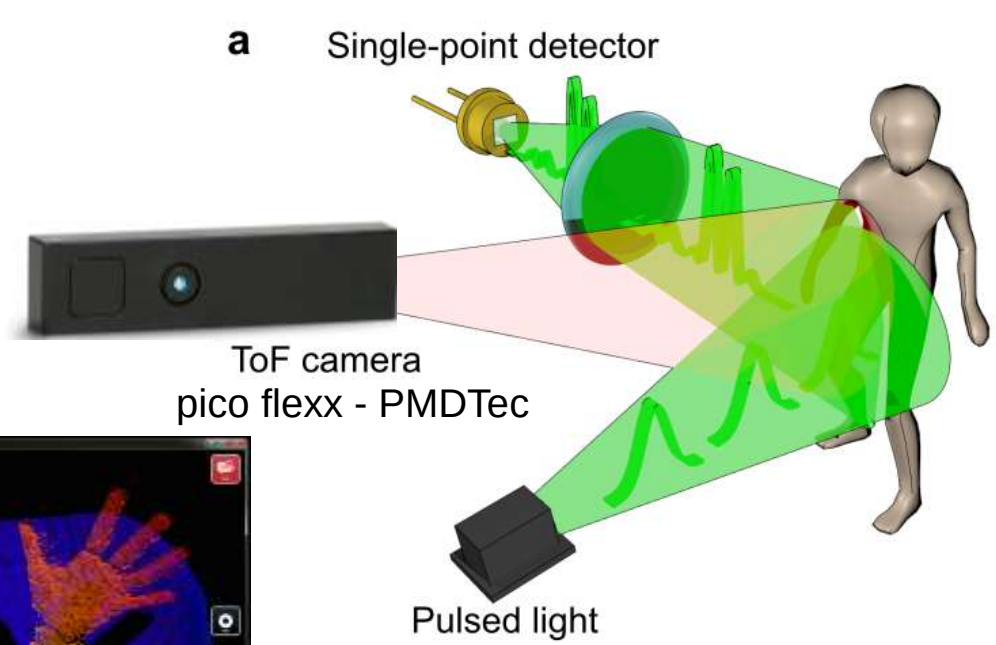
Can we image with a single-point sensor alone using only temporal information?

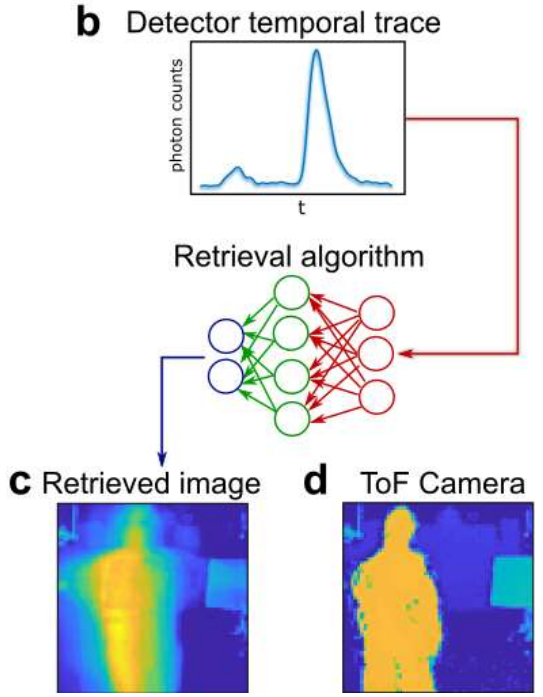


Single-pixel LIDAR

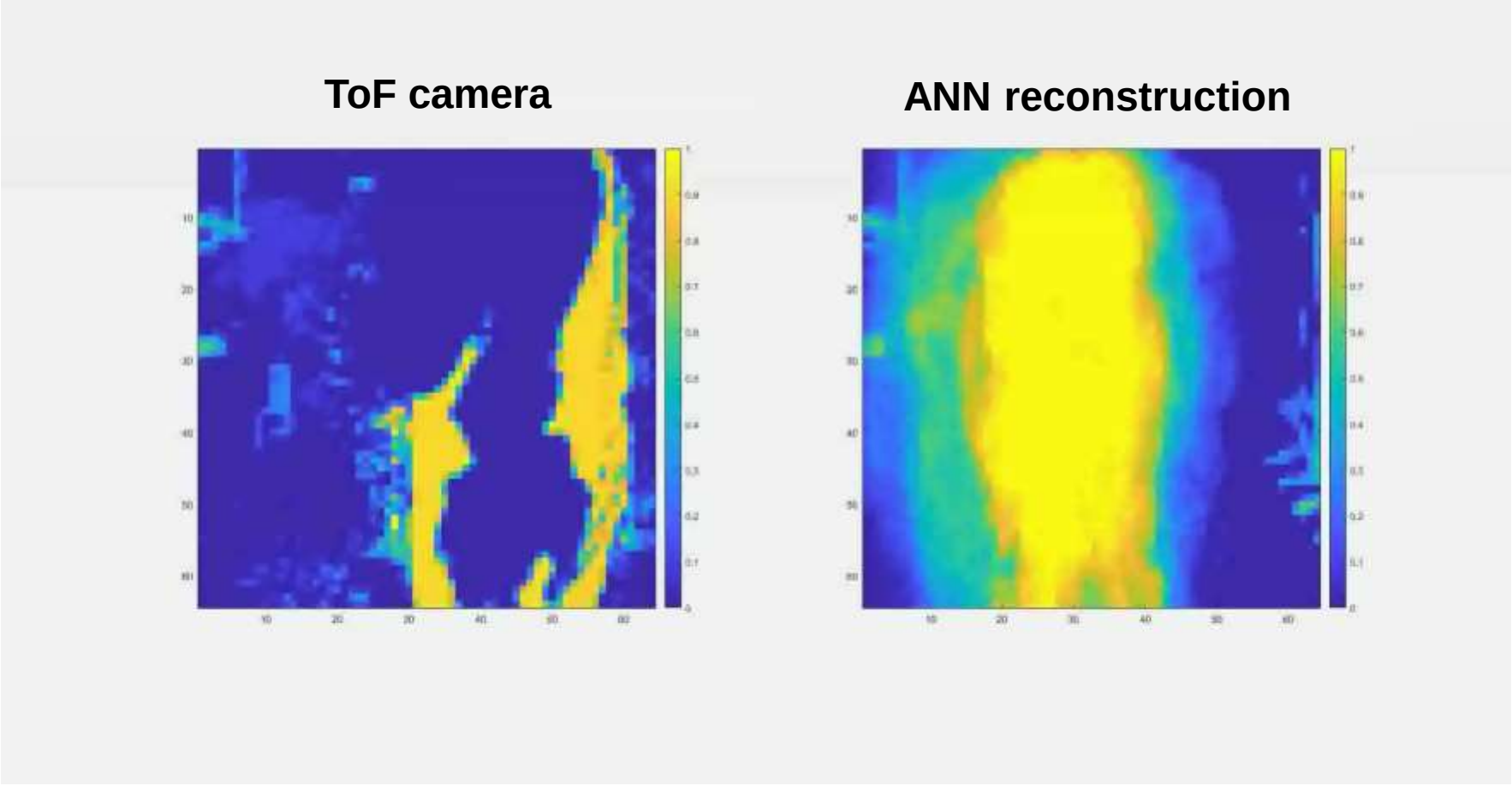
Our approach: ANNs reconstruct 3D information in a scene from a single time trace







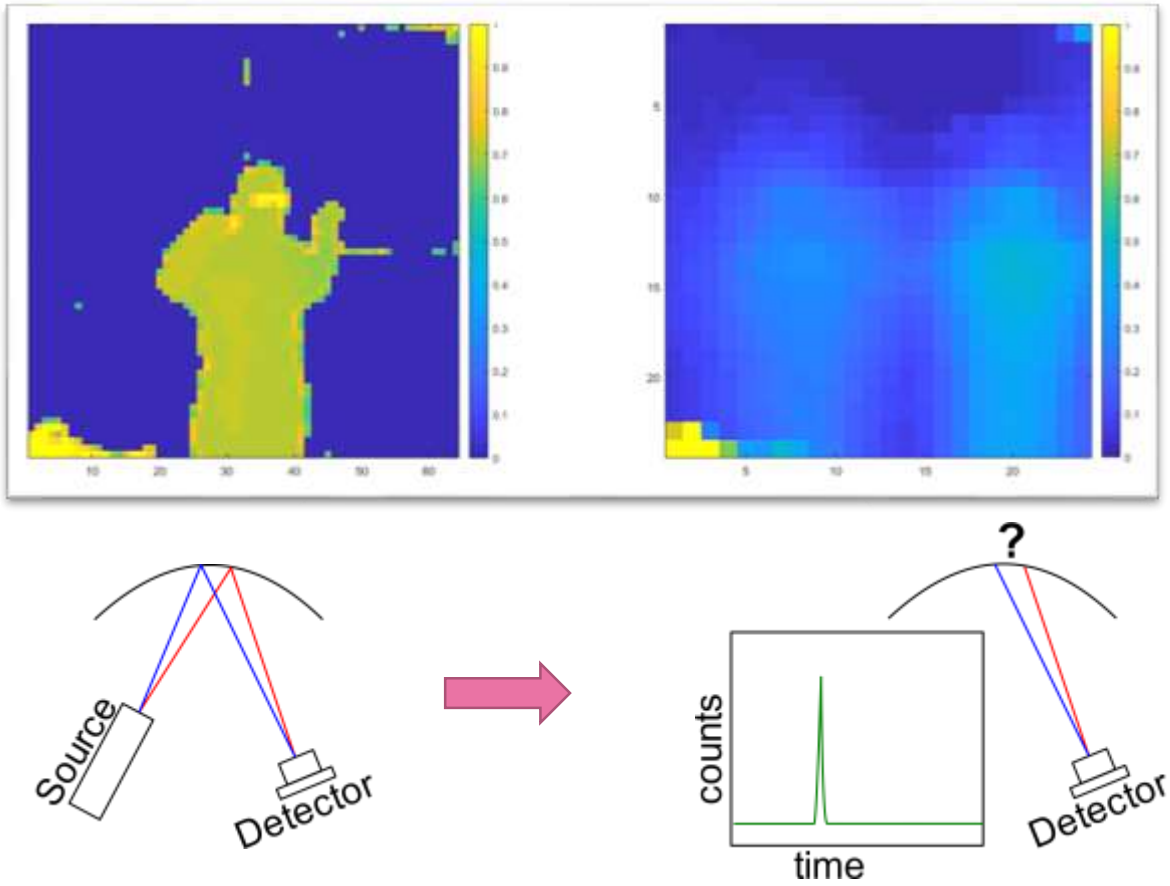
Results



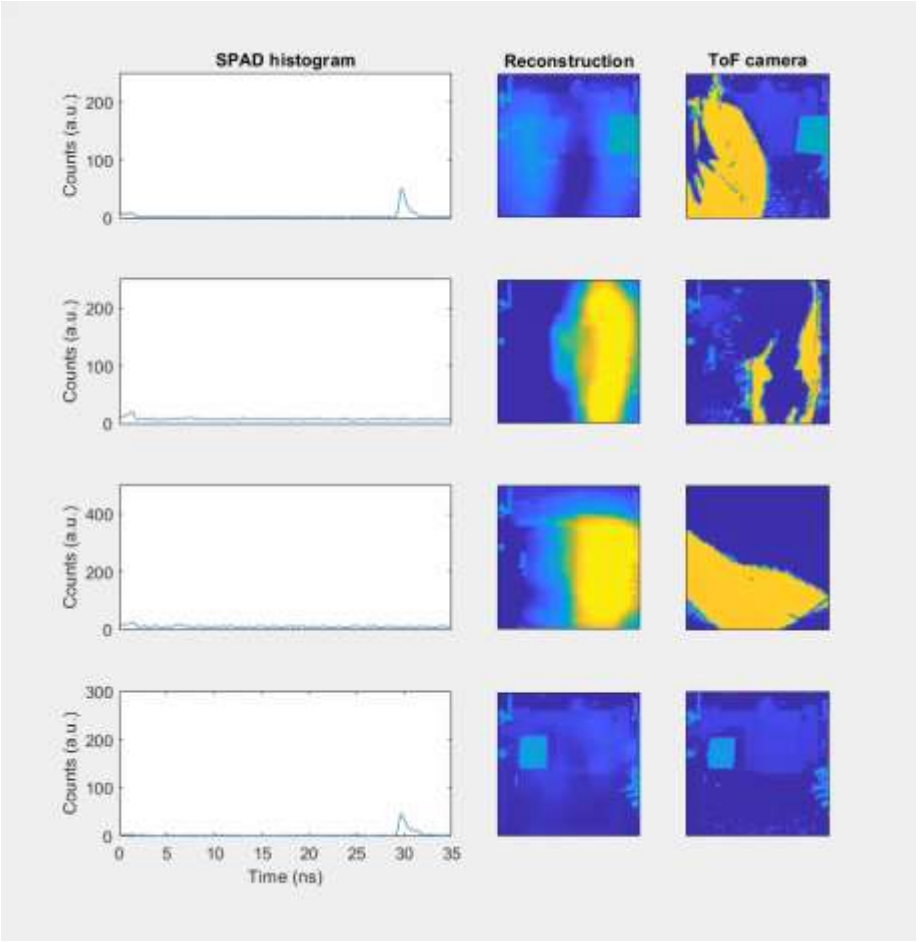
A. Turpin, G. Musarra, V. Kapitany, et al., Optica, to be published

Single-pixel LIDAR caveats

Symmetry degeneracy

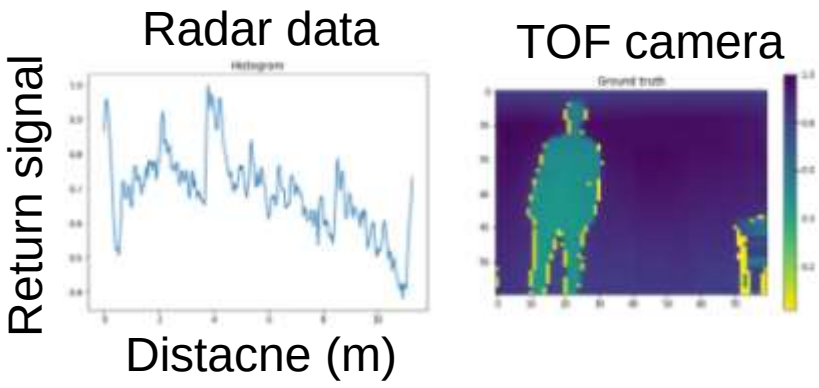


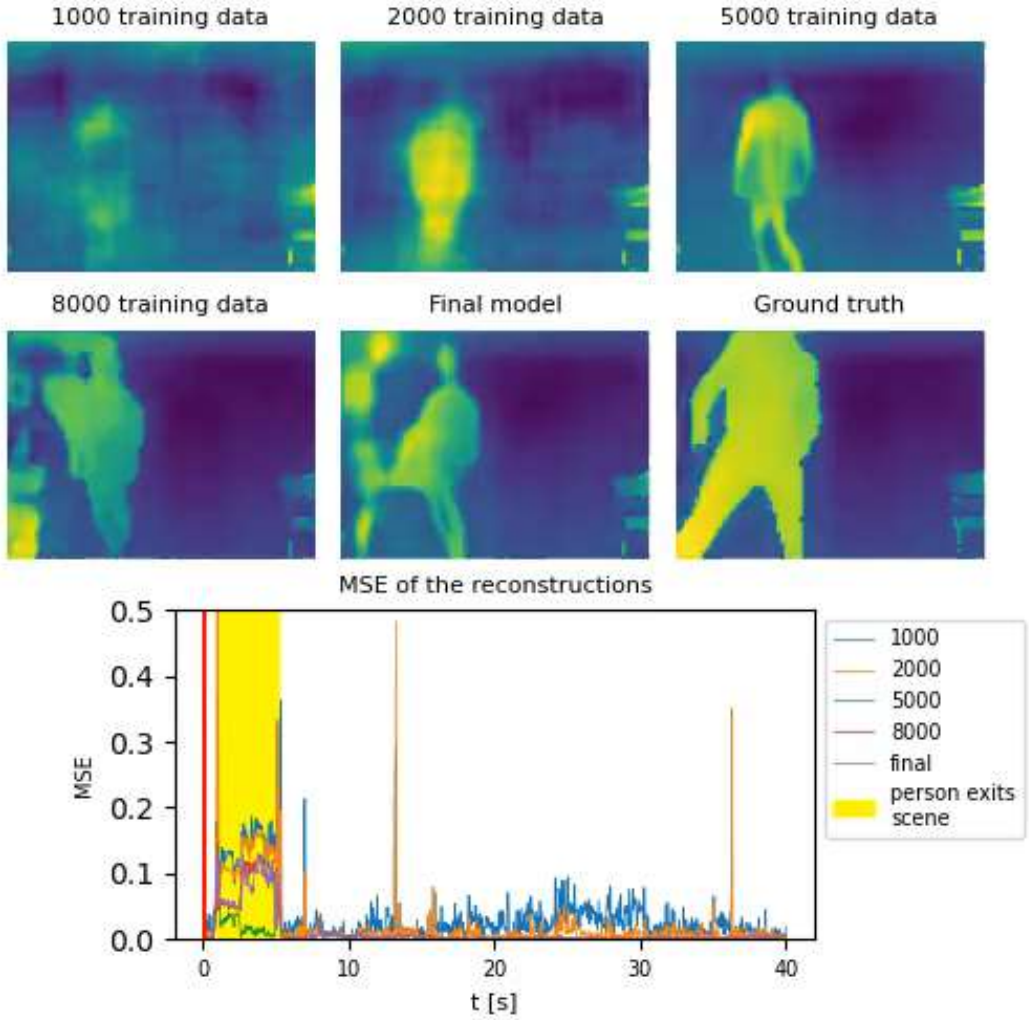
Imaging different types of objects



Radar imaging

AWR1642 single-chip 76-GHz to 81-GHz automotive radar sensor evaluation module





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Photophone

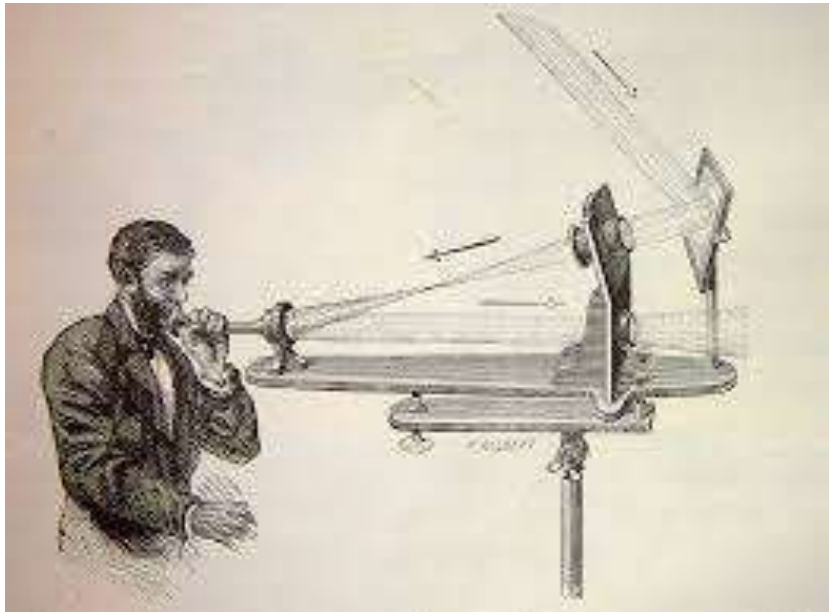


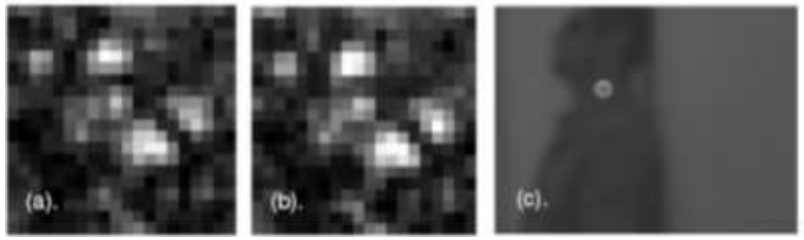
Image: Wikimedia Commons

We have found that the simplest form of apparatus for producing the effect consists of a plane mirror of flexible material against the back of which the speaker's voice is directed. Under the action of the voice the mirror becomes alternately convex and concave and thus alternately scatters and condenses the light.

J. Bell U.S. Patent 235,199

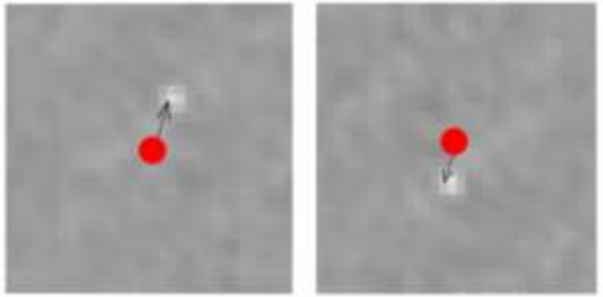
Laser speckle microphone

Speckle pattern shifts with sound



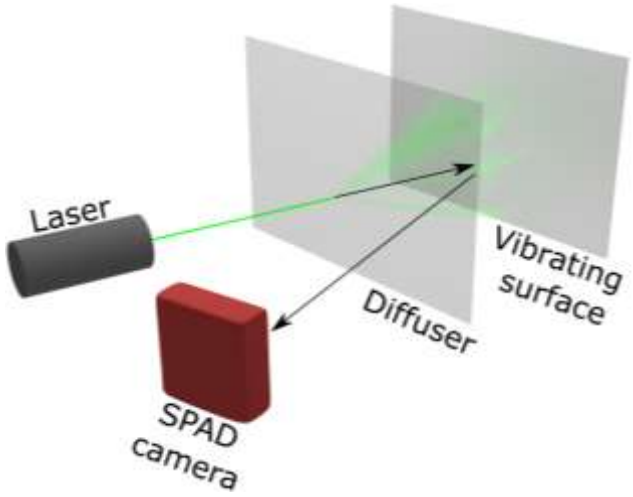
Zalevsky et al., 2009, 'Simultaneous remote extraction of multiple speech sources and heart beats from secondary speckles pattern', *Optics express,* Vol. 17, Issue 27, page 21566.

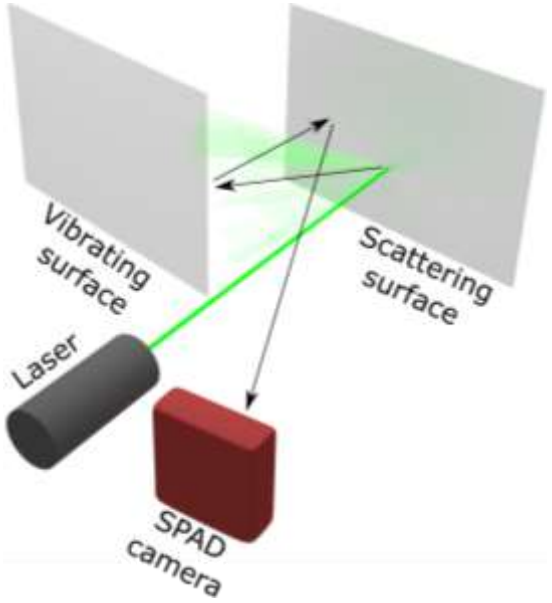
Correlation and peak tracking

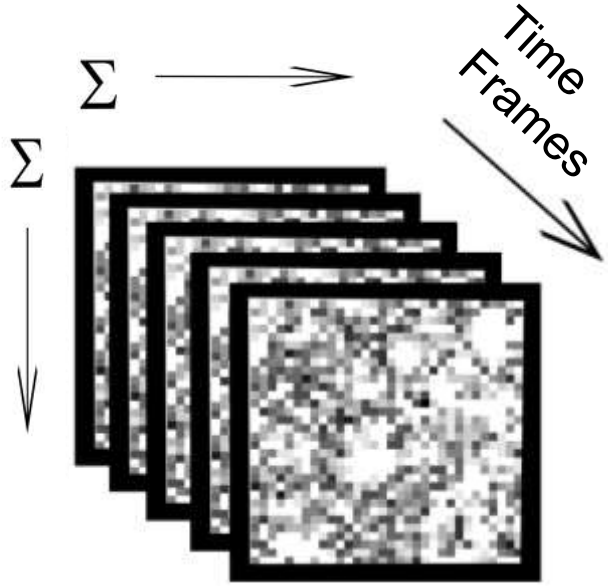


Peak displacement => sound

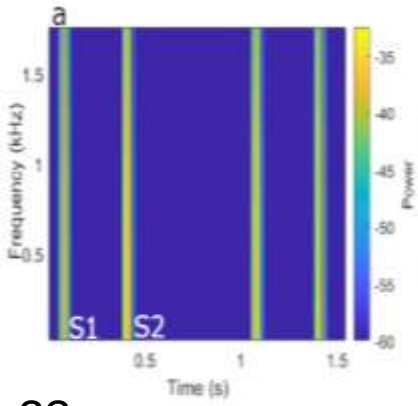
Laser speckle microphone



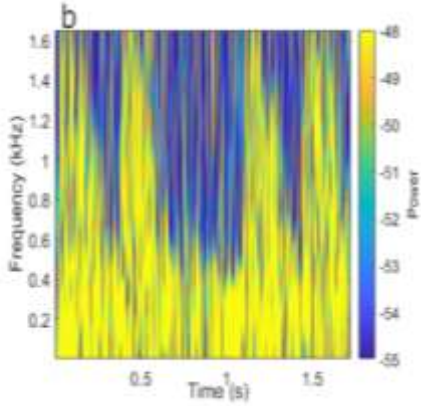




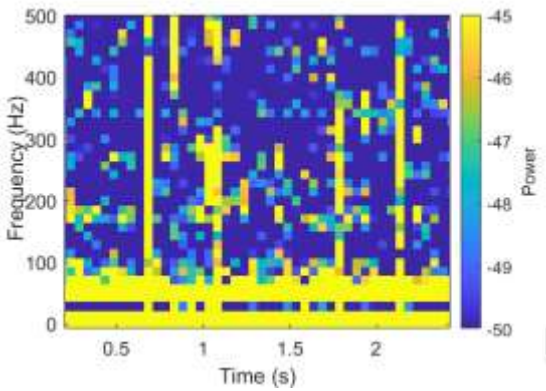
Input sound

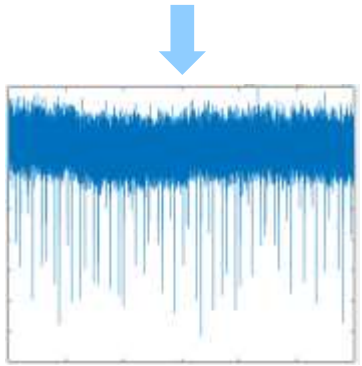


Transmission

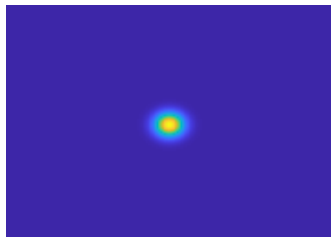


Reflection

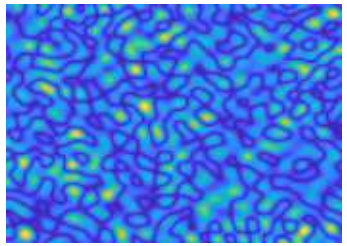




Simulations

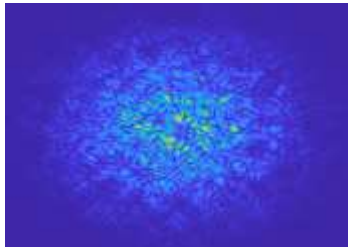


Laser Beam

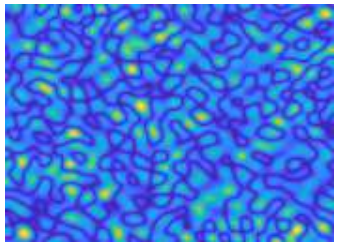


Stationary Surface

Fresnel propagation

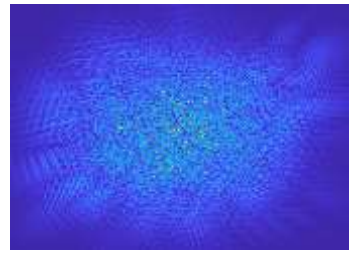


First speckle pattern seen at the vibrating surface

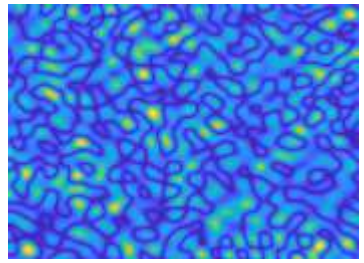


Vibrating Surface

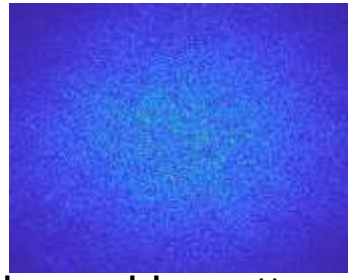
Fresnel propagation



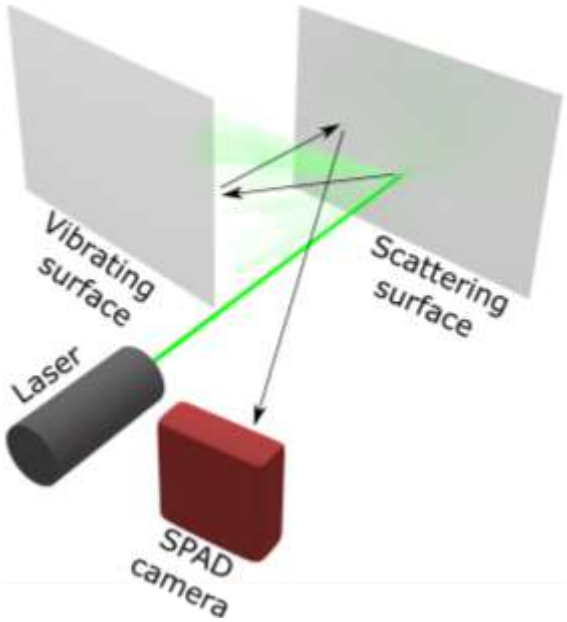
Second speckle pattern seen at the stationary surface



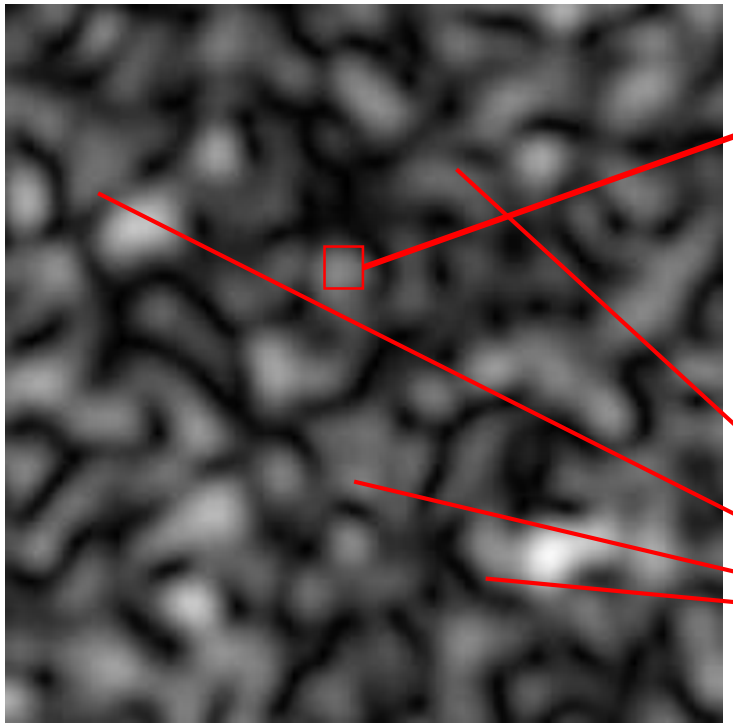
Stationary Surface



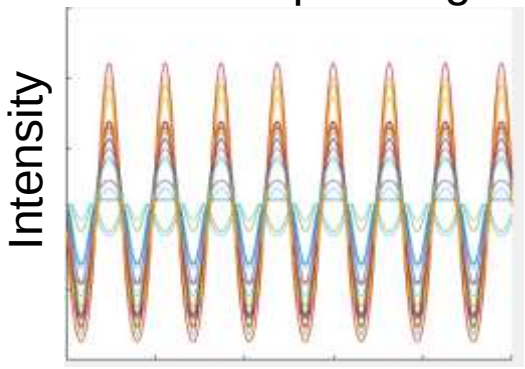
Third speckle pattern seen at the camera



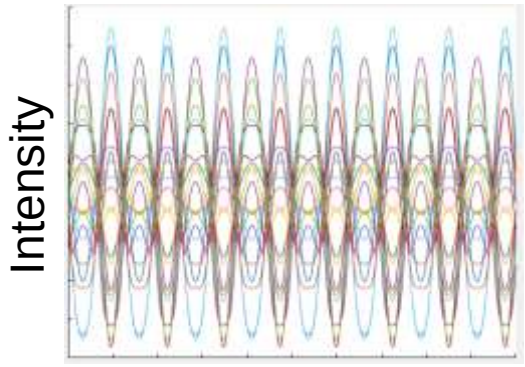
Simulations



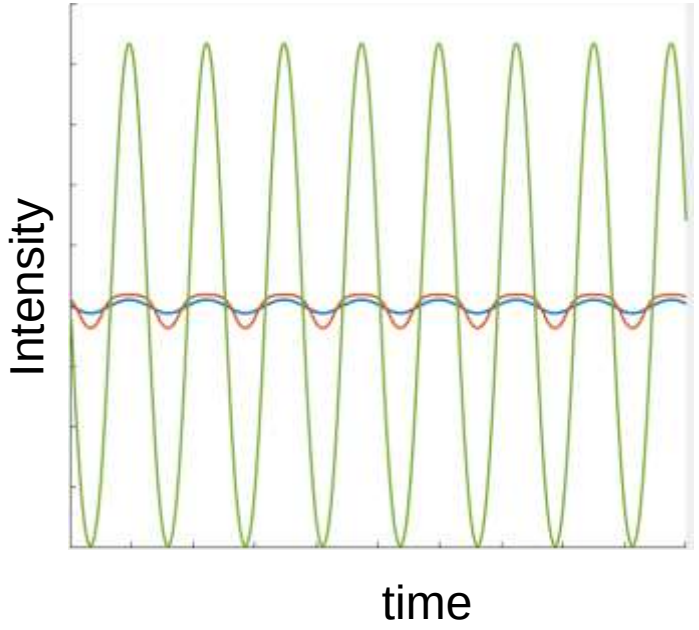
Within one speckle grain



Random choice



One speckle grain
Large area
Large area + Align phases



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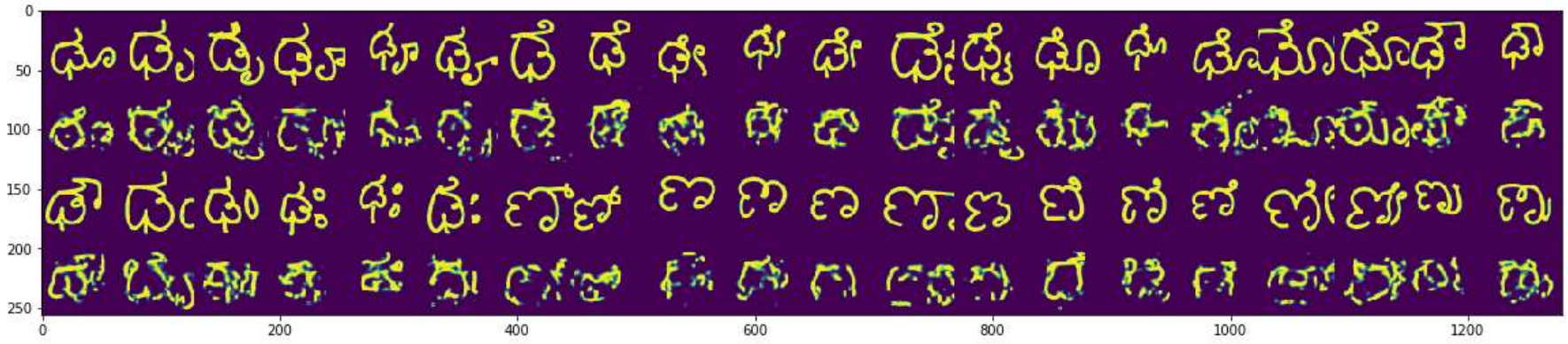
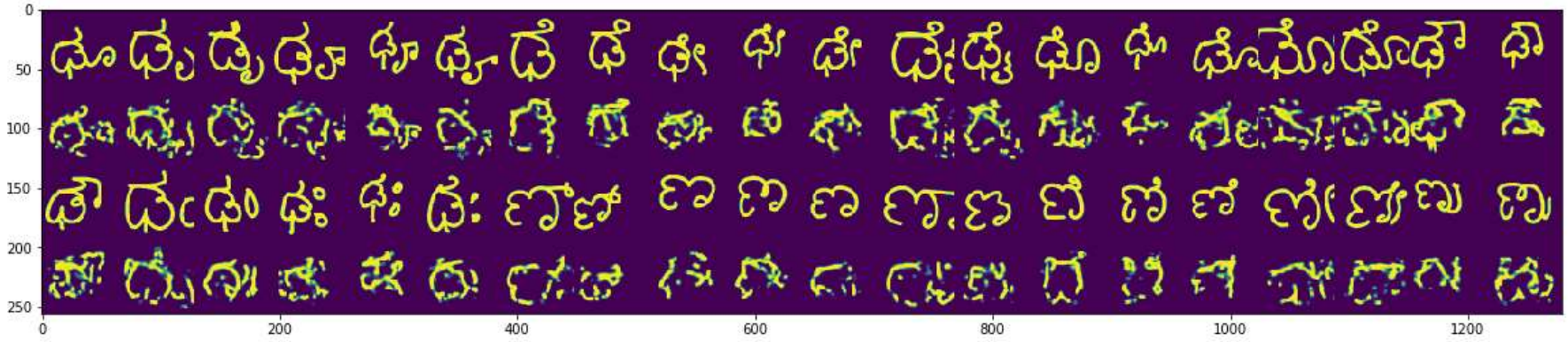
Thank you!

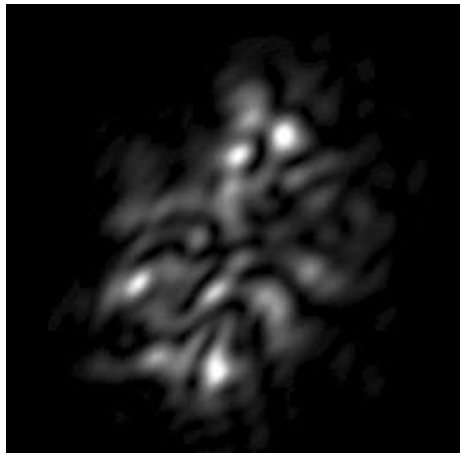
Is it imaging?

Seen spot



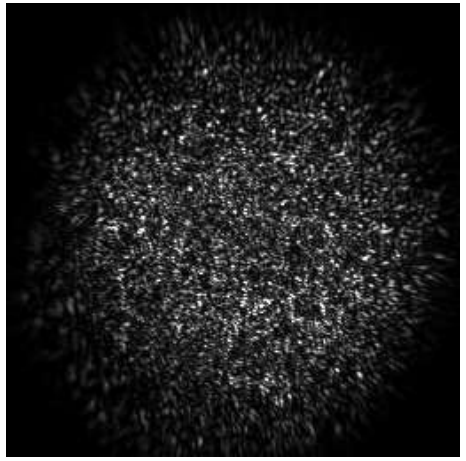
Unseen spot





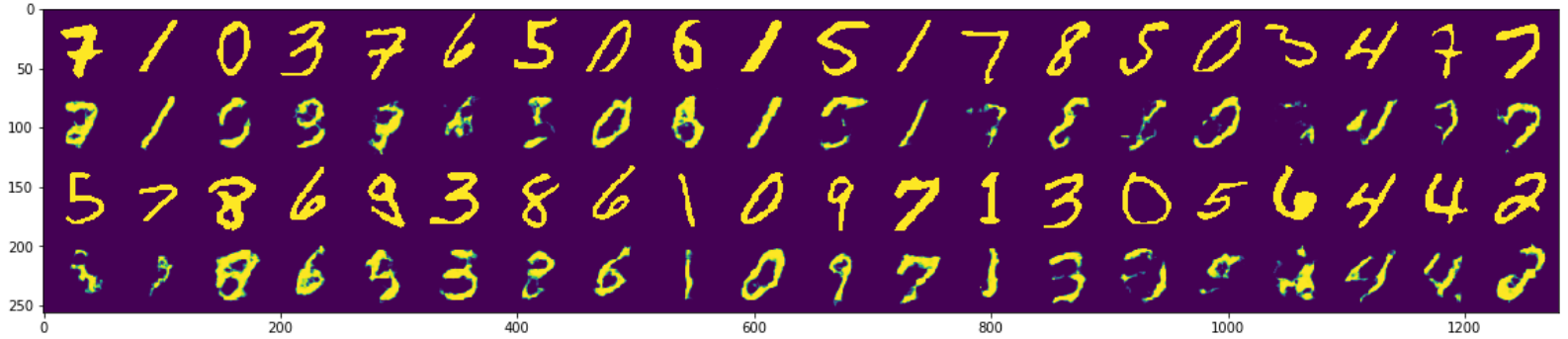
Seen spot

Unseen spot

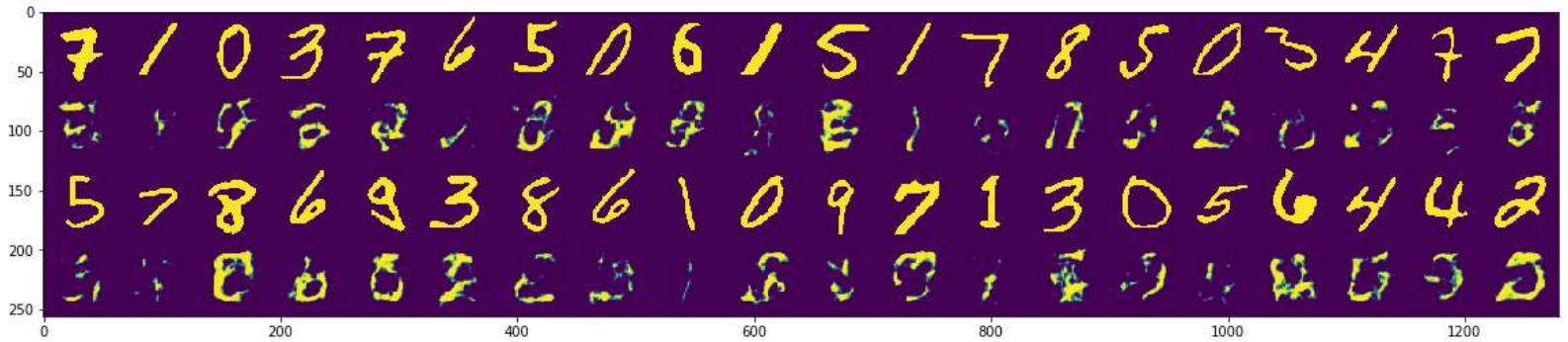


Three layers

Seen spot



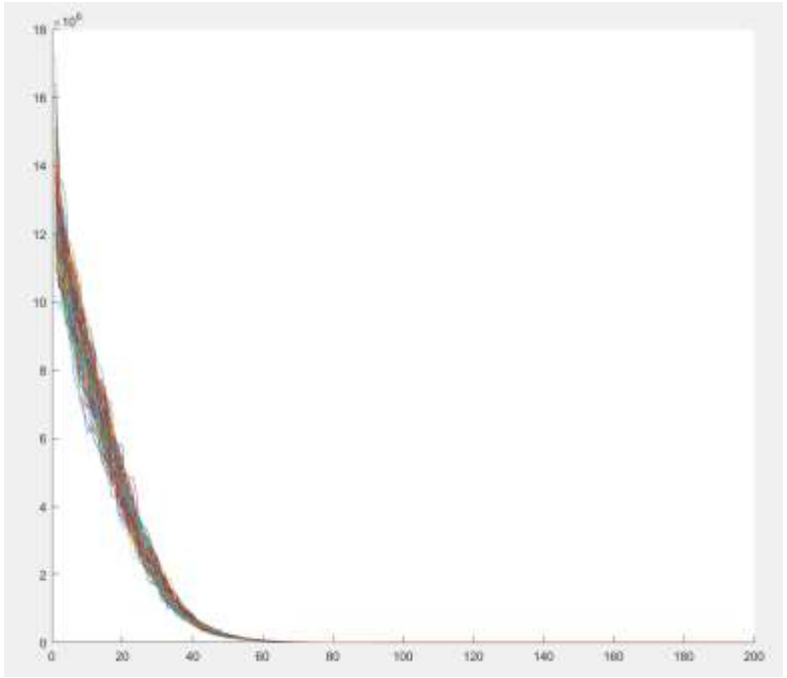
Unseen spot



SVD

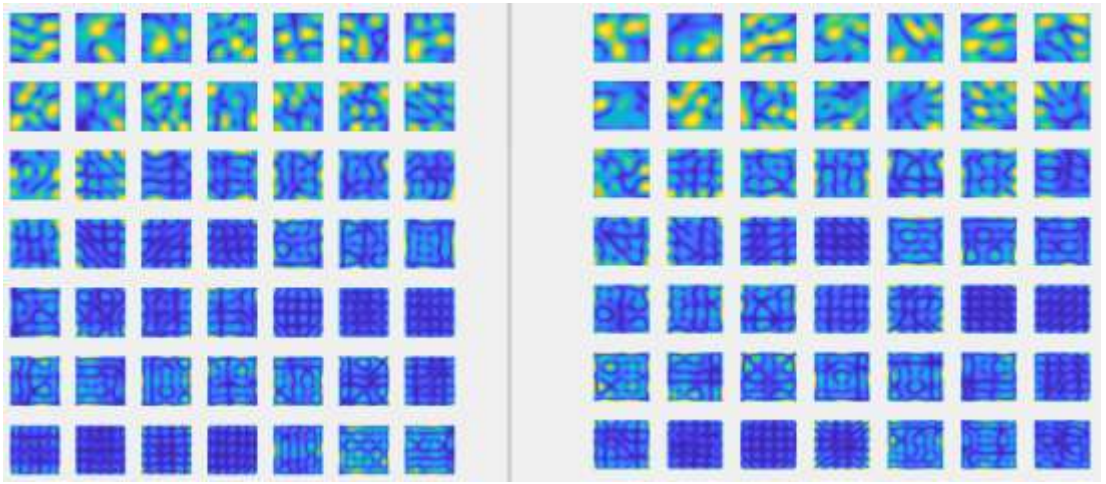
$S = UZV^{+}$

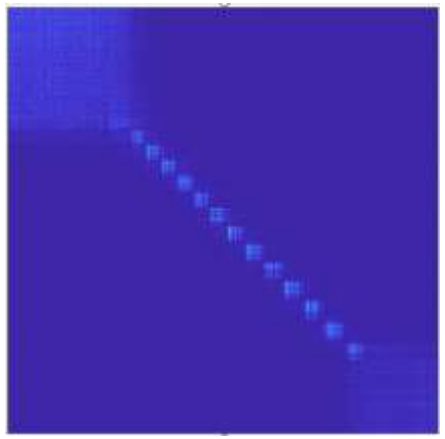
Two scattering matrices



Z

U





V