Seeing Around the Corner with Passive Non-Line-of-Sight Imaging

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Abstract

We consider the scenario of a person standing in a hallway, with possible danger hiding around the corner. The person may be able to see the danger directly if there were a window or other specular surface in the hallway. However, we pose the question: is it possible to see around the corner by looking at reflections in a diffusive painted wall when no visible shadow is present? This has been done using active means, for example through the use of lasers. Here, we passively image using only natural light already present in the scene. A diffusive wall scatters incident light such that a lens cannot be used to form a useful image. Measuring the spatial coherence, which describes correlation in the random light field, provides extra information that can help counteract the detrimental effects of the wall.

This poster summarizes the author's research, which constitutes one part of the DARPA REVEAL (Revolutionary Enhancement of Visibility by Exploiting Active Light-fields) project. It was performed under the direction of the author's advisor and mentors, who served as Principal Investigators on the project. Experimental results were collected by CREOL, as noted in the figures.

Model

Coherence and Intensity

The partially coherent light found in a room consists of random fields. Coherence describes the nature of these random fields in the form of a correlation between two spatial points. Intensity appears as a slice of the coherence. For convenience, we use transformed coordinates $\mathbf{r}$ and $\boldsymbol{\rho}$.

Ensemble average of two-point field correlation: $\langle E(\mathbf{r}_1)E^*(\mathbf{r}_2)\rangle$

Spatial coherence: $G(\mathbf{r},\boldsymbol{\rho}) = \langle E(\mathbf{r}+\boldsymbol{\rho}/2)E^*(\mathbf{r}-\boldsymbol{\rho}/2)\rangle$

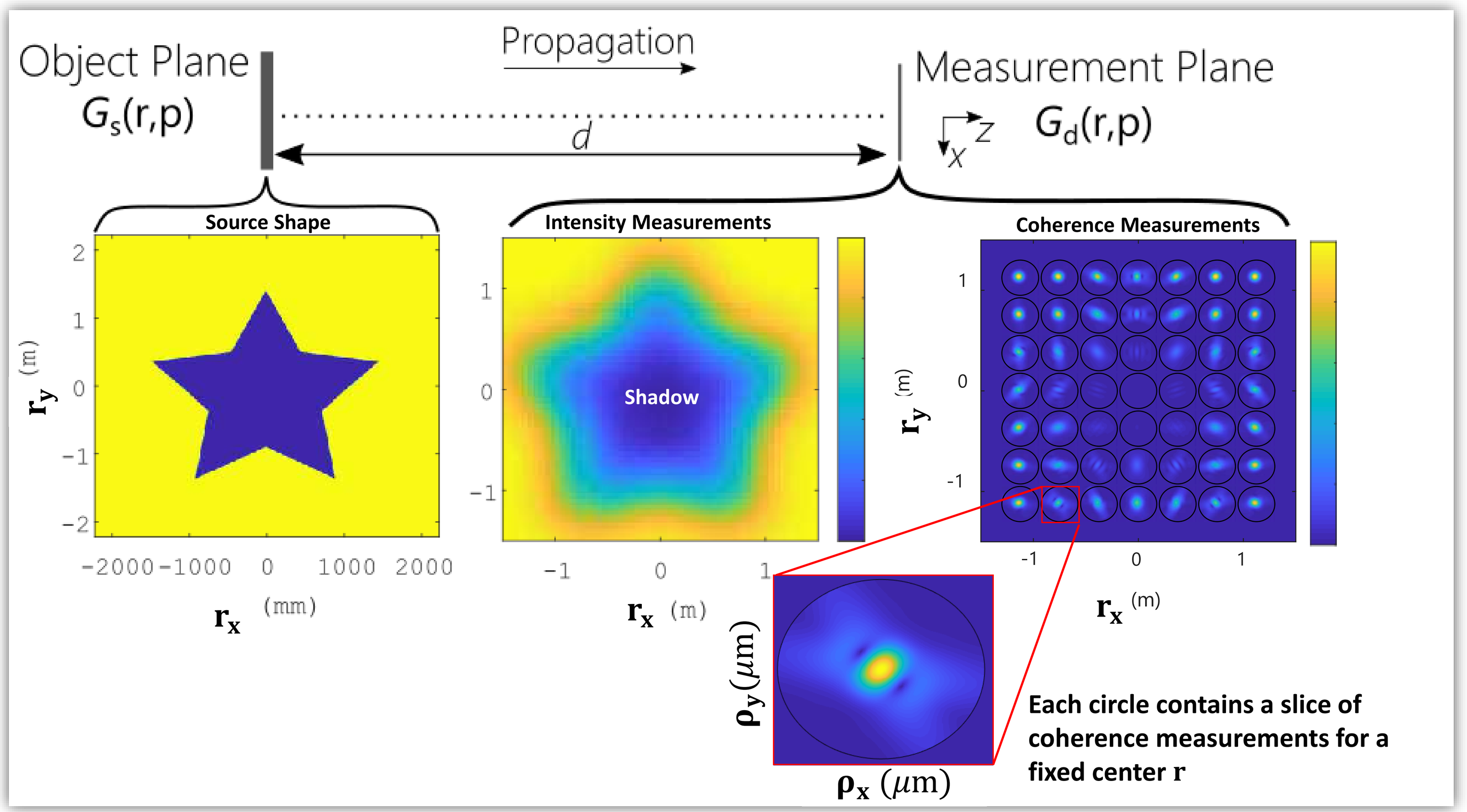
Intensity: $I(\mathbf{r}) = G(\mathbf{r},\mathbf{0})$

Center between points: $\mathbf{r} = (\mathbf{r}_1+\mathbf{r}_2)/2$

Separation between points: $\boldsymbol{\rho} = \mathbf{r}_1 - \mathbf{r}_2$

Propagation by distance d using Fresnel transform (paraxial approx.): $G_d(\mathbf{r},\boldsymbol{\rho}) = \iint d\mathbf{r}\, d\boldsymbol{\rho} \exp\{ik(\mathbf{r}-\mathbf{r}')\cdot(\boldsymbol{\rho}-\boldsymbol{\rho}')/d\}\, G_{source}(\mathbf{r},\boldsymbol{\rho})$

Numerical Example – Propagating coherence to obtain simulated intensity and coherence measurements

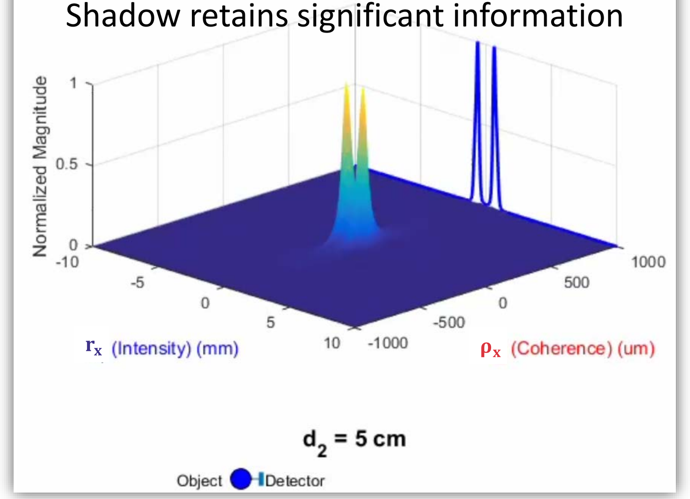


Why is coherence useful?

Coherence adds two extra dimensions of information over intensity alone. This helps in lensless imaging (as shown below). It also allows for 3D scene reconstruction as with holography.

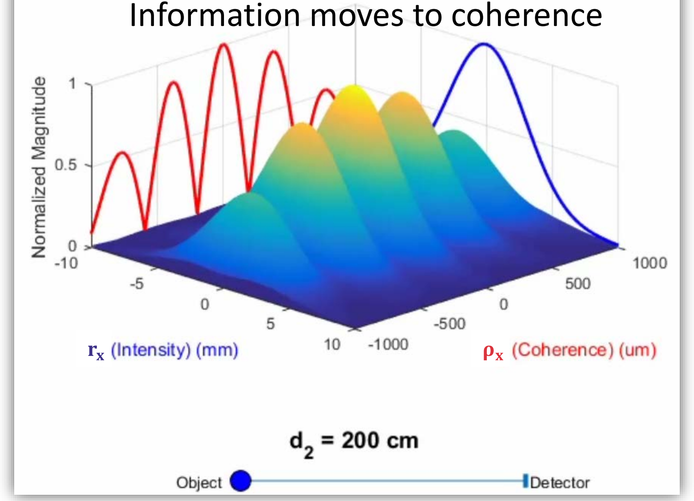
Large Object / Small Distance

Shadow retains significant information



Small Object / Large Distance

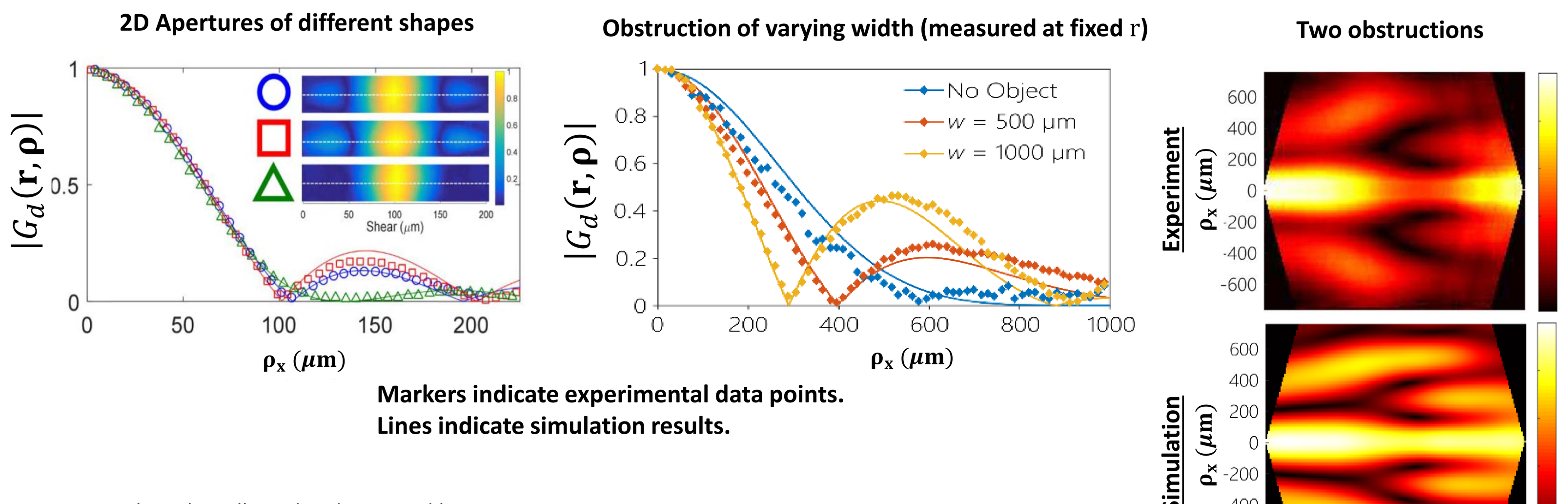
Information moves to coherence



Comparison with Experiments

Simulations were shown to match experimental results

Some discrepancies exist, due for example to measurement artifacts and approximations in the model.



Markers indicate experimental data points.
Lines indicate simulation results.

Experimental results collected and prepared by

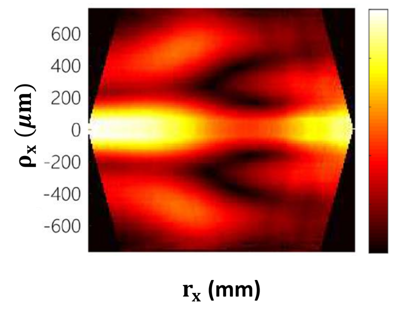
- A. El Halawany, H. E. Kondakci, M. Monroe, N. Mohammadian, A. F. Abouraddy [3]
- H. E. Kondakci, A. El Halawany, N. Mohammadian, A. F. Abouraddy [4]
- R. R. Naraghi, H. E. Gemar, M. Batarseh, S. Sukhov, A. Dogariu [5]

Inverse Problem using Coherence

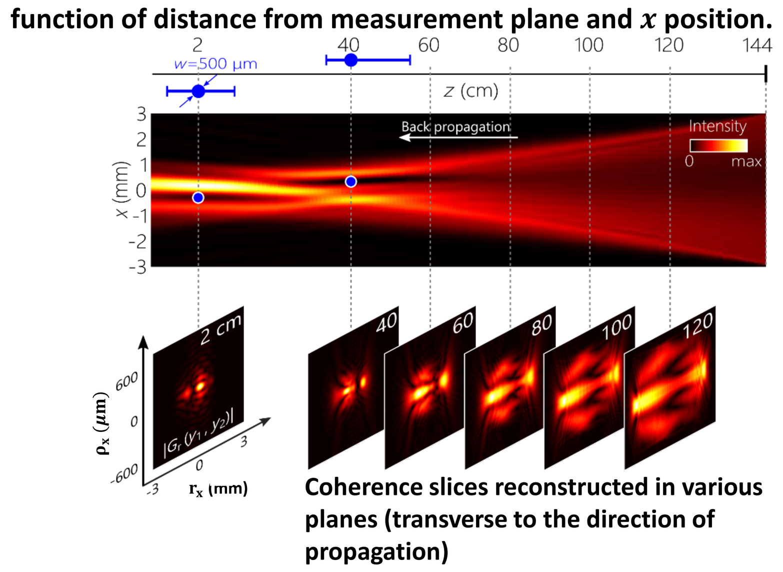
Back propagation

One way to locate objects using coherence measurements is to use the inverse Fresnel transform. This approach works well provided sufficient samples are taken.

1) **Obtain coherence measurement**



2) **Perform back propagation. Intensity is "reconstructed" as a function of distance from measurement plane and x position.**



3) **Make estimates (manually obtained). The two objects can be seen as dark areas.**

Object 1 z position:	Actual = 22 cm	Estimated = 40 cm	**Error = 15 %**
Object 2 z position:	Actual = 7 cm	Estimated = 2 cm	**Error = 3.6 %**
Object 1&2 width:	Actual = 500 um	Estimated = 400 um	**Error = 20 %**
Object 1 x position:	Actual = 375 um	Estimated = 309 um	**Error = 17 %**
Object 2 x position:	Actual = -375 um	Estimated = -321um	**Error = 14 %**

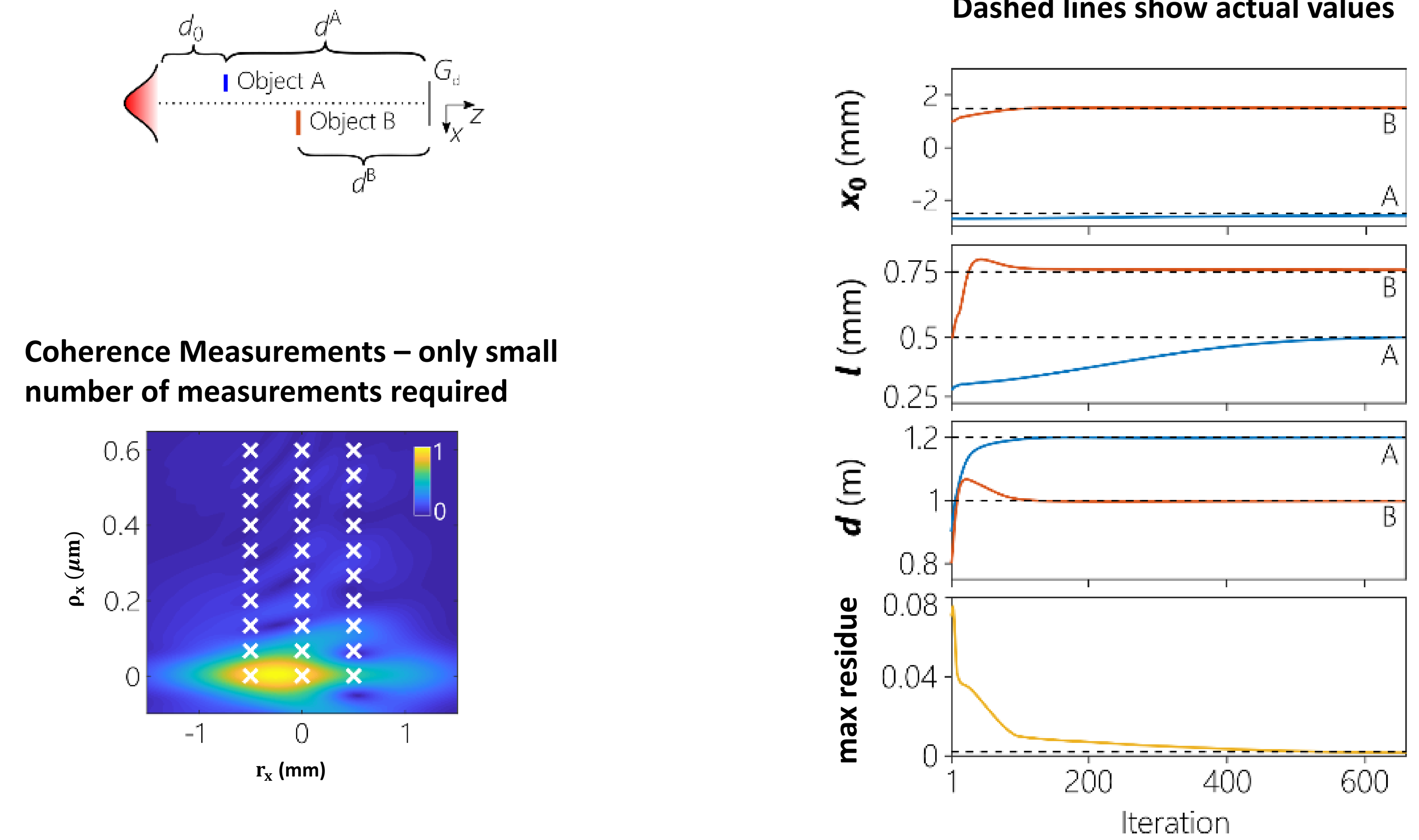
Gradient Descent Optimization

We have derived a simpler approximation to the Fresnel propagation integral (defined in terms of a Hilbert transform and / or complex error function). This can be used to derive analytic gradients for the position and width of objects with regard to coherence samples.

Scenario – two objects in different planes

Iterations of gradient descent. Dashed lines show actual values

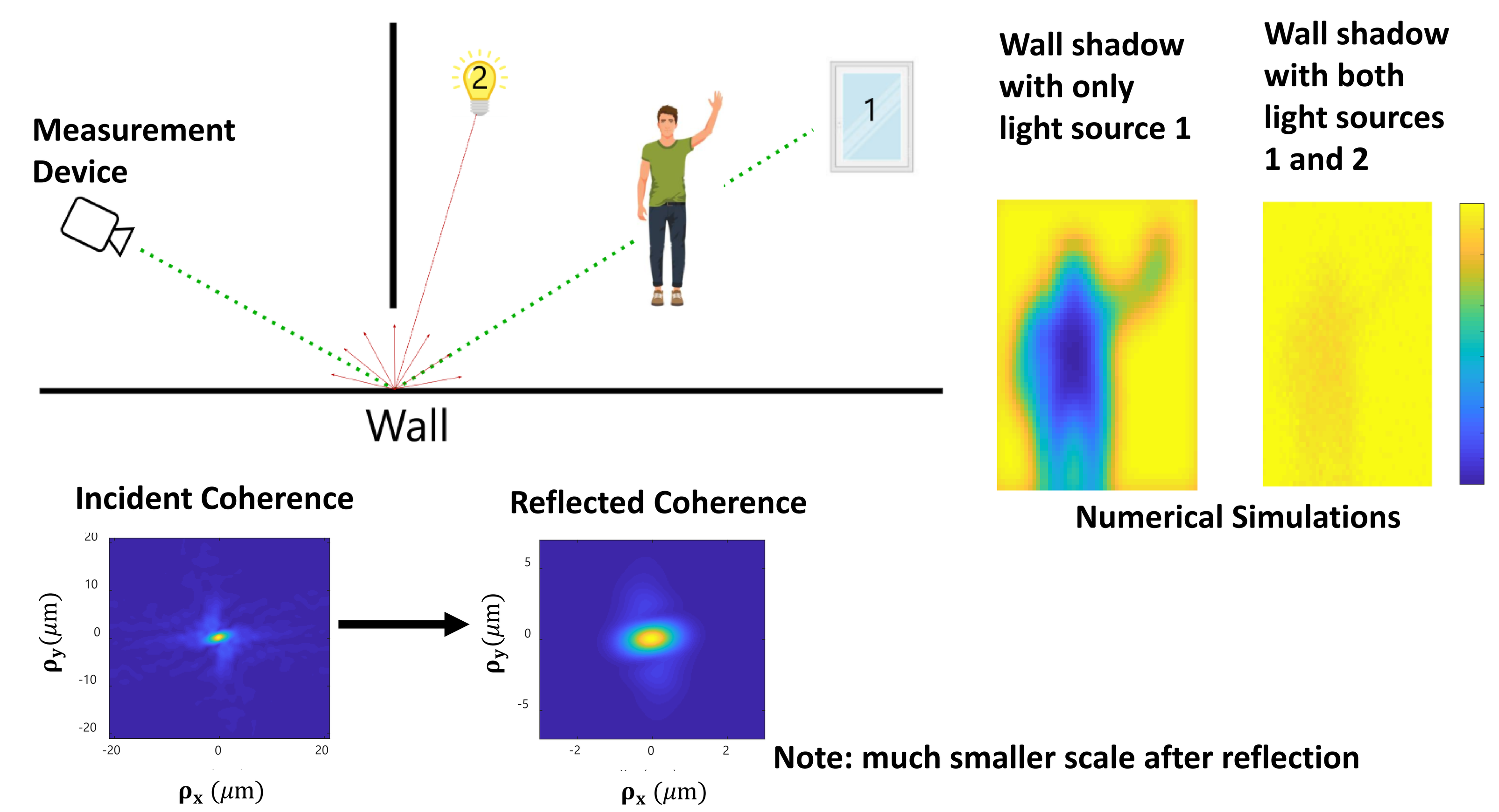
Coherence Measurements – only small number of measurements required



The Wall

Hypothetical Scenario

We have a person standing in a room. This person stands in front of a window (1), thus casting a shadow on the wall. However, there is a light source (2) which serves to "wash out" the shadow. The effect of the wall on coherence is assumed to be a Gaussian multiplier (based on convolution with a Gaussian spread function).



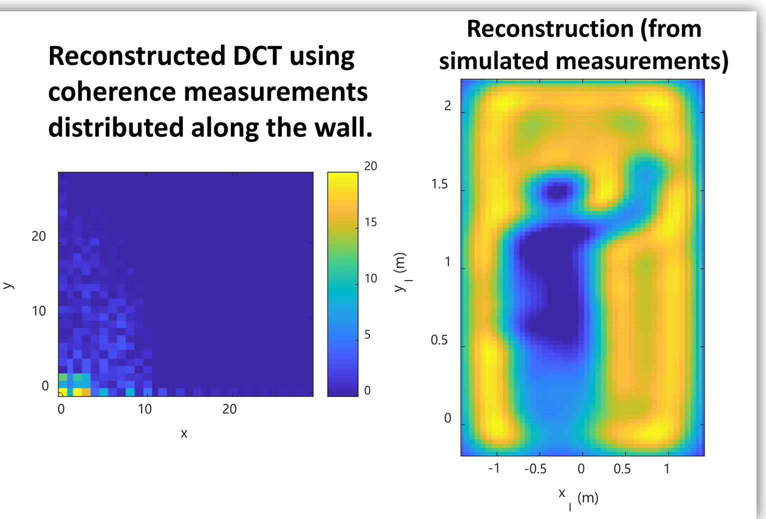
Inversion

Multiple measurements are collected. We represent the image in a sparse basis, then an optimization problem is solved using Alternating Directions Method of Multipliers (ADMM).

Goal: $\min \|x\|_1$ subject to $\Phi_i \Psi \mathrm{x} - y_i, \quad 1 \le i \le N$

N Measurements: y_i
N Propagation functions: Φ_i
Discrete Cosine Transform (DCT): Ψ
Sparse representation: x

See: Andre Beckus, Alexandru Tamasan, George K. Atia. "Multi-modal Non-line-of-sight Passive Imaging". IEEE Trans. Image Process. (2019)



Conclusion

In this work, we demonstrate not only that simulated coherence closely matches experimental data, but also that this data allows a scene to be reconstructed in line-of-sight scenarios. Then, we show that when a wall is present, coherence measurements may still be used to estimate source images. The techniques are extendable to other measurements as well. For example, intensity measurements of a shadow may be incorporated. Light-field measurements from a plenoptic camera could also be used.

Publications

This research is published in the following works. The author thanks the co-authors on these works for discussions and suggestions, and for providing valuable insights into the experiments and physical models.

1. Andre Beckus, Alexandru Tamasan, Aristide Dogariu, Ayman F. Abouraddy, and George K. Atia, "**On the inverse problem of source reconstruction from coherence measurements**," ArXiv e-prints (2017)
2. Andre Beckus, Alexandru Tamasan, Aristide Dogariu, Ayman F. Abouraddy, and George K. Atia, "**Spatial coherence of fields from generalized sources in the Fresnel regime**," J. Opt. Soc. Am. A 34, 2213-2221 (2017)
3. Ahmed El-Halawany, Andre Beckus, H. Esat Kondakci, Morgan Monroe, Nafiseh Mohammadian, George K. Atia, and Ayman F. Abouraddy, "**Incoherent lensless imaging via coherency back-propagation**," Opt. Lett. 42, 3089-3092 (2017)
4. H. Esat Kondakci, Andre Beckus, Ahmed El Halawany, Nafiseh Mohammadian, George K. Atia, and Ayman F. Abouraddy, "**Coherence measurements of scattered incoherent light for lensless identification of an object's location and size**," Opt. Express 25, 13087-13100 (2017)
5. Roxana Rezvani Naraghi, Heath Gemar, Mahed Batarseh, Andre Beckus, George K. Atia, Sergey Sukhov, and Aristide Dogariu, **"Wide-field interferometric measurement of a nonstationary complex coherence function",** Optics Lett. 42, 4929-4932 (2017)

This work was supported by DARPA (contract HR0011-16-C-0029)