Large-Scale Inverse Multiple-Scattering Imaging on GPU Supercomputers with Real Data

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In courtesy of Weng Cho Chew, Michael Oelze, and Wen-mei Hwu
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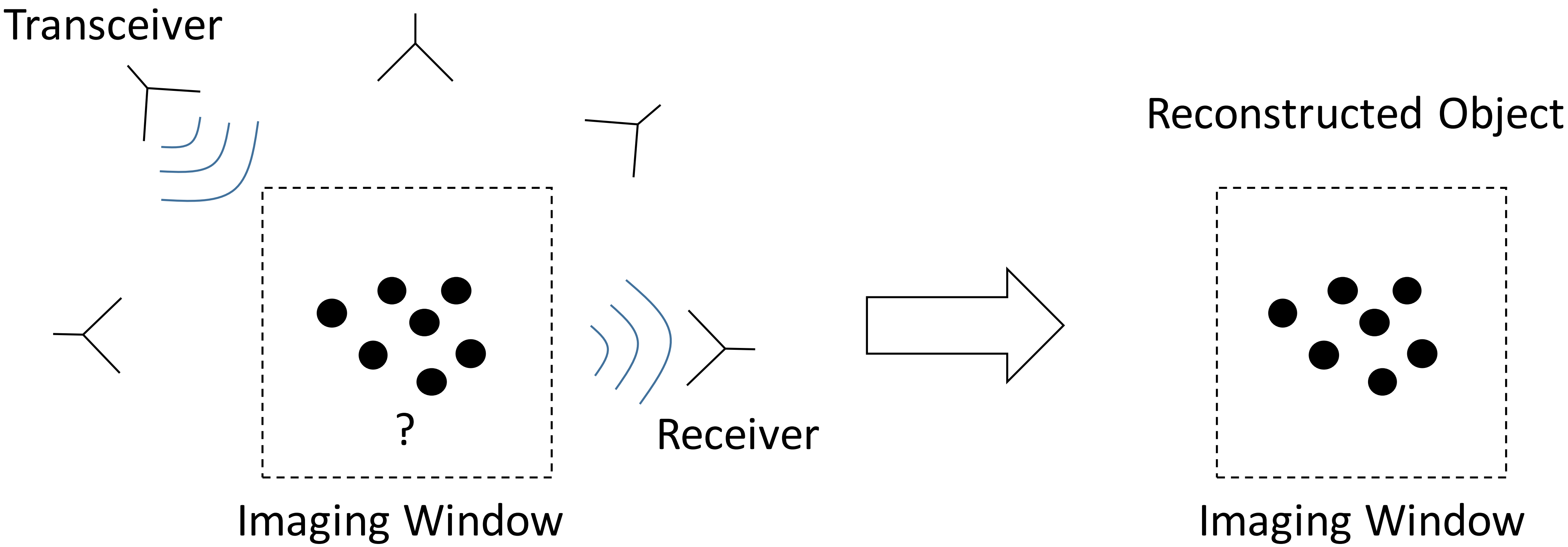
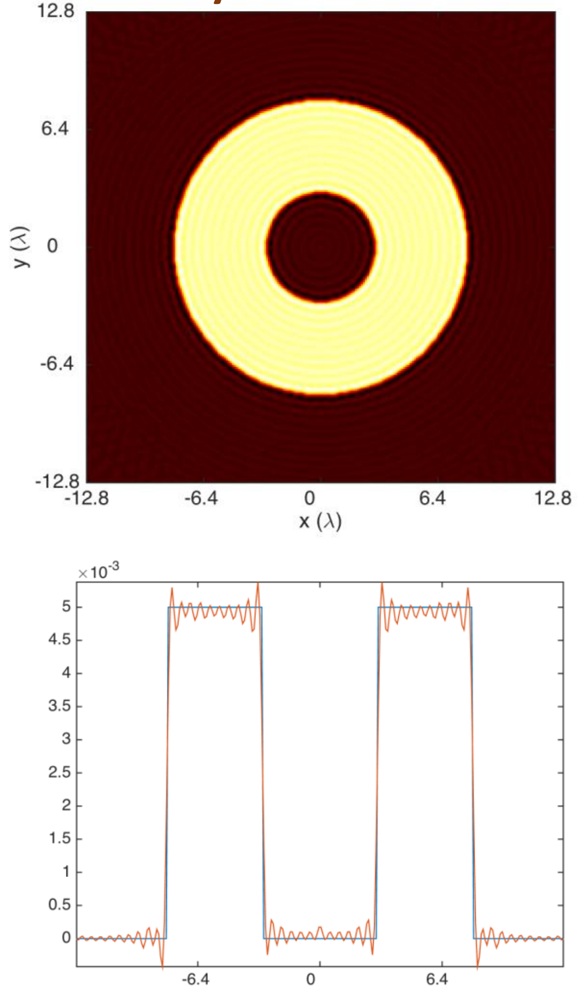
Imaging with Inverse-Scattering

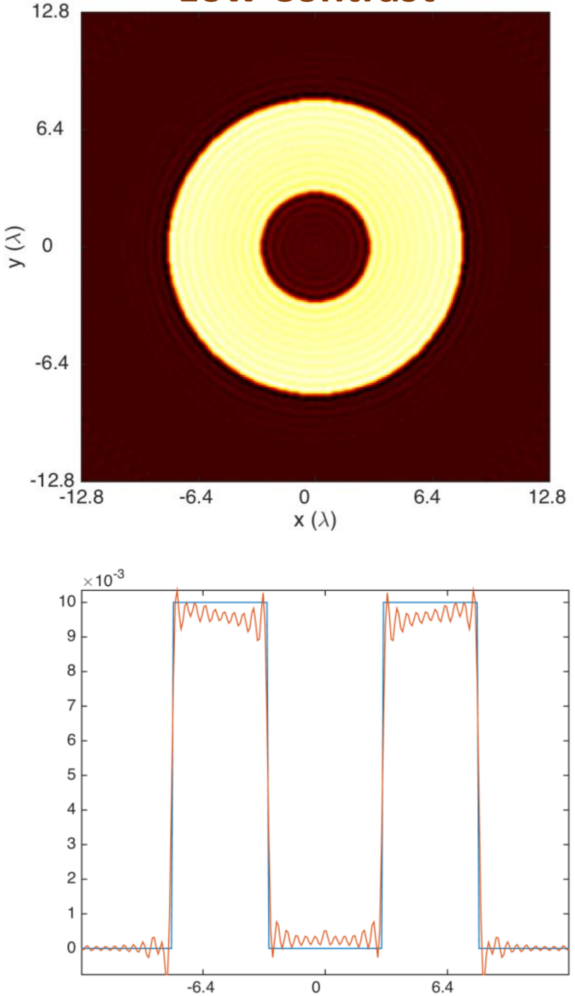


DT Breaks Down with Multiple Scattering

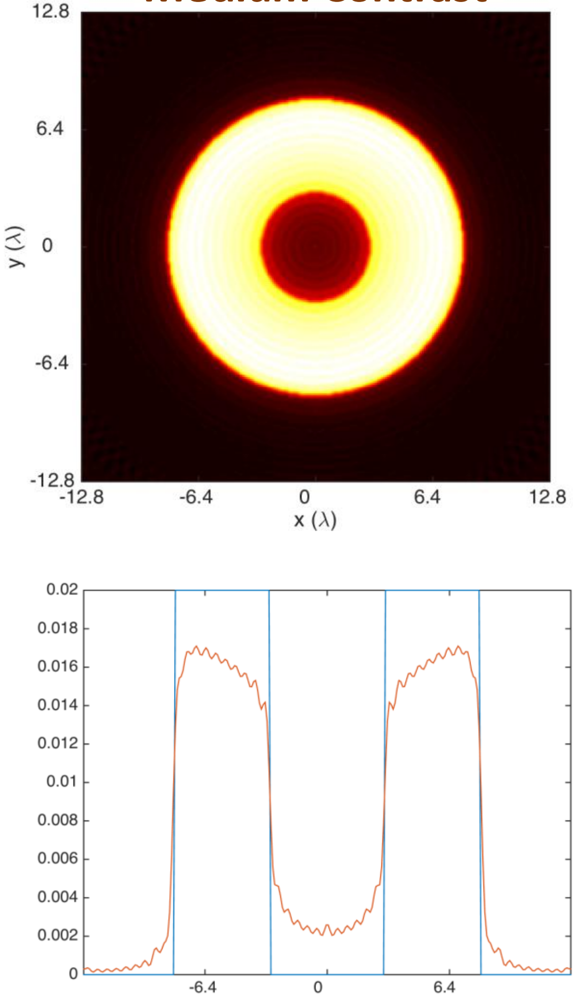
Very Low Contrast



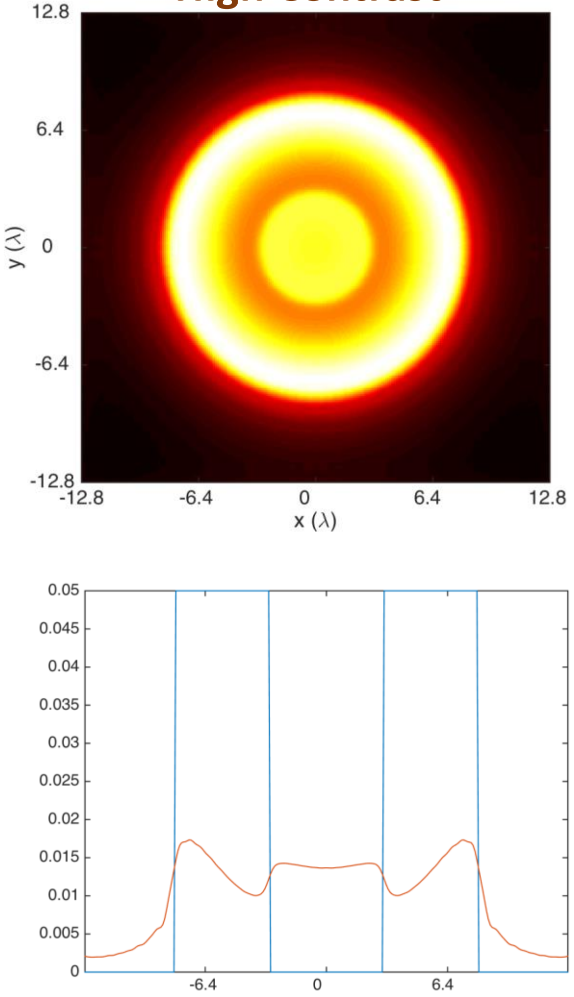
Low Contrast



Medium Contrast



High Contrast

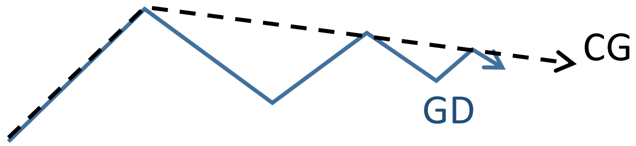


Gradient Search for Nonlinear Optimization

- Gradient-Descent

$$-\nabla\Phi = -\overline{\boldsymbol{F}}^{H}\boldsymbol{r}$$

- Conjugate-Gradient

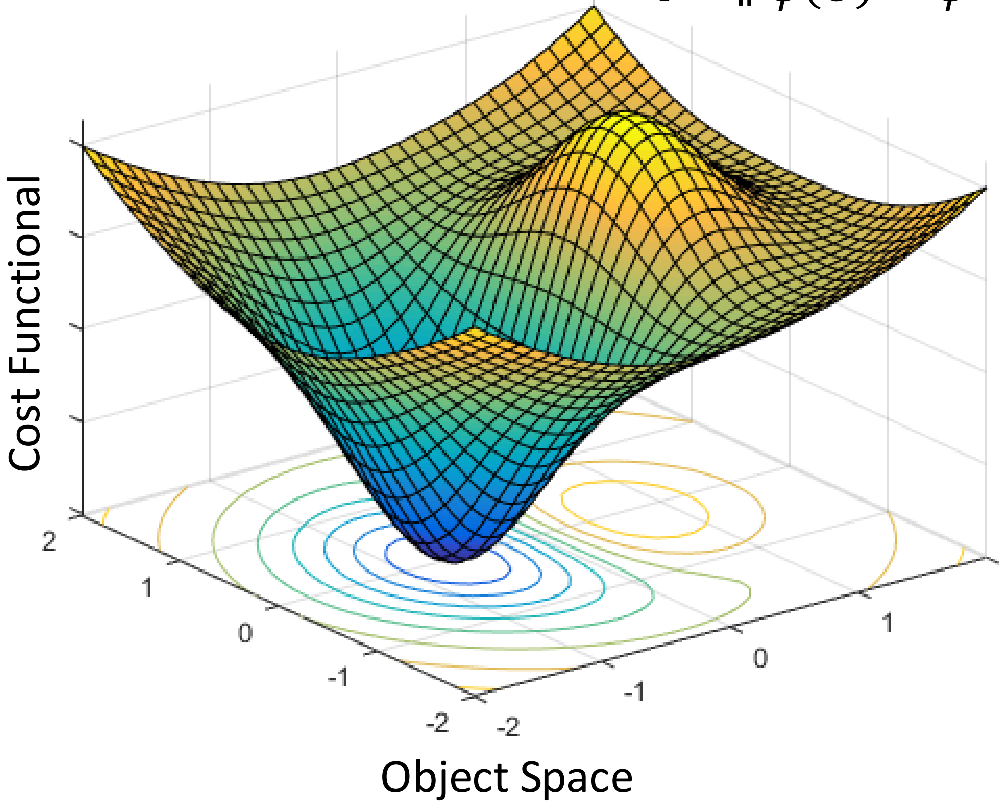


- Newton-Type Methods

$$[\mu^2\overline{\boldsymbol{I}} + \overline{\boldsymbol{F}}^{H}\overline{\boldsymbol{F}}]\delta\boldsymbol{O} = \nabla\Phi$$

$\overline{\boldsymbol{F}}$: Functional Derivative Operator

$$\Phi = \| \phi(\boldsymbol{O}) - \phi^{M} \|^2$$



Finding Derivative with Distorted-Born Approximation

Scattering Equation:

$$\mathcal{G} = \mathcal{G}_0 + \mathcal{G}_0 \mathcal{O} \mathcal{G}$$

Object Perturbation:

$$\mathcal{O} = \mathcal{O}_b + \delta\mathcal{O}$$

$$\delta\mathcal{G} = \mathcal{G}_b \delta\mathcal{O} \mathcal{G}_b + \underbrace{\mathcal{G}_b \delta\mathcal{O} \delta\mathcal{G}}_{\text{Higher-order var.}}$$

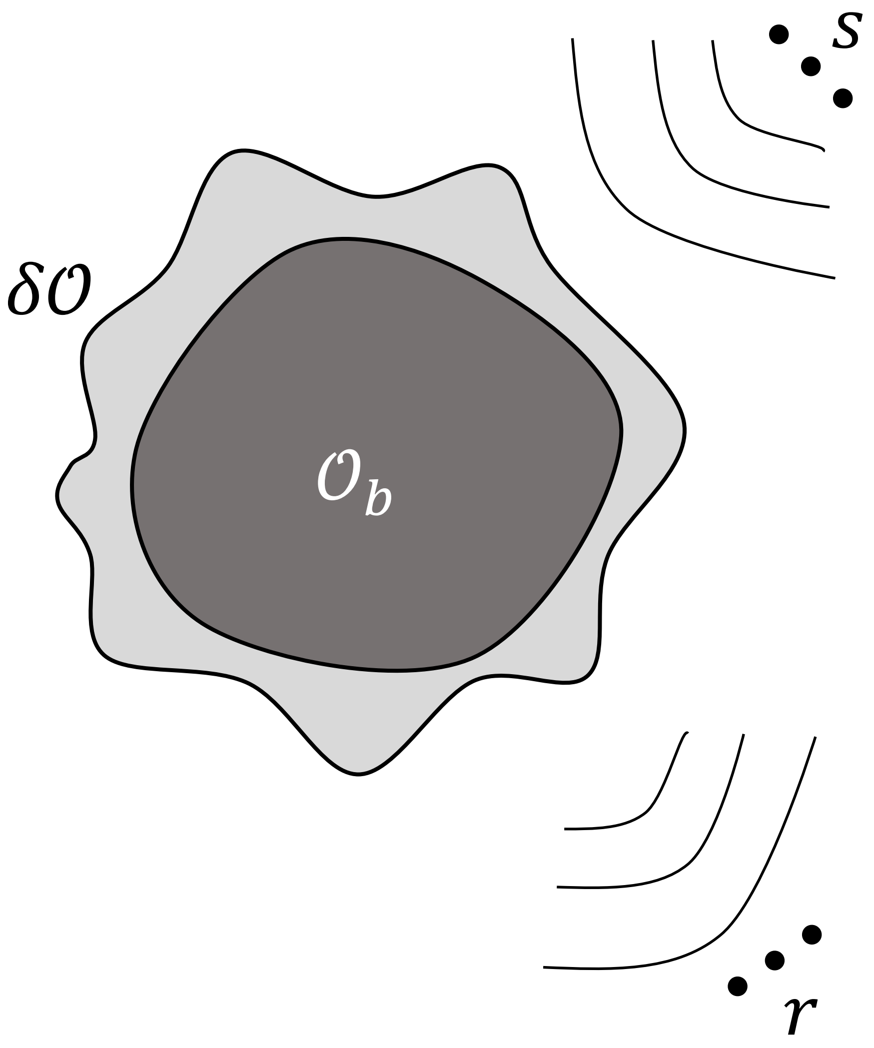
$$\delta\mathcal{G} \approx \delta\mathcal{G}^{(1)} = \mathcal{G}_b \delta\mathcal{O} \mathcal{G}_b$$

Distorted Born Approximation

When operates on a source s:

$$\delta\phi \approx \mathcal{G}_b \delta\mathcal{O} \phi_b = \mathcal{G}_b \phi_b \delta\mathcal{O}$$

$$\delta\phi^{(1)} = \mathcal{F} \delta\mathcal{O}$$



Distorted-Born Approximation Requires two Scattering Solutions

$$-\nabla\Phi = -\mathcal{F}^{\dagger} r$$

$$\mathcal{F} = \mathcal{G}_b \phi_b$$

MoM

$$\overline{\boldsymbol{F}} = \overline{\boldsymbol{G}}_R \left\{ \overline{\boldsymbol{I}} + \overline{\boldsymbol{O}}_b \underbrace{\left[\overline{\boldsymbol{I}} - \overline{\boldsymbol{G}}_0 \overline{\boldsymbol{O}}_b\right]}_{\text{MLFMA}}^{-1} \overline{\boldsymbol{G}}_0 \right\} \mathrm{diag} \left\{ \underbrace{\left[\overline{\boldsymbol{I}} - \overline{\boldsymbol{G}}_0 \overline{\boldsymbol{O}}_b\right]}_{\text{MLFMA}}^{-1} \overline{\boldsymbol{G}}_T \boldsymbol{s} \right\}$$

$\overline{\boldsymbol{G}}_0$: Dense, $N \times N$
$\overline{\boldsymbol{G}}_T$: Dense, $N \times T$
$\overline{\boldsymbol{G}}_R$: Dense, $R \times N$

1 Million Pixels (100λ): 16TB
16 Million Pixels (400λ): 4PB (!)

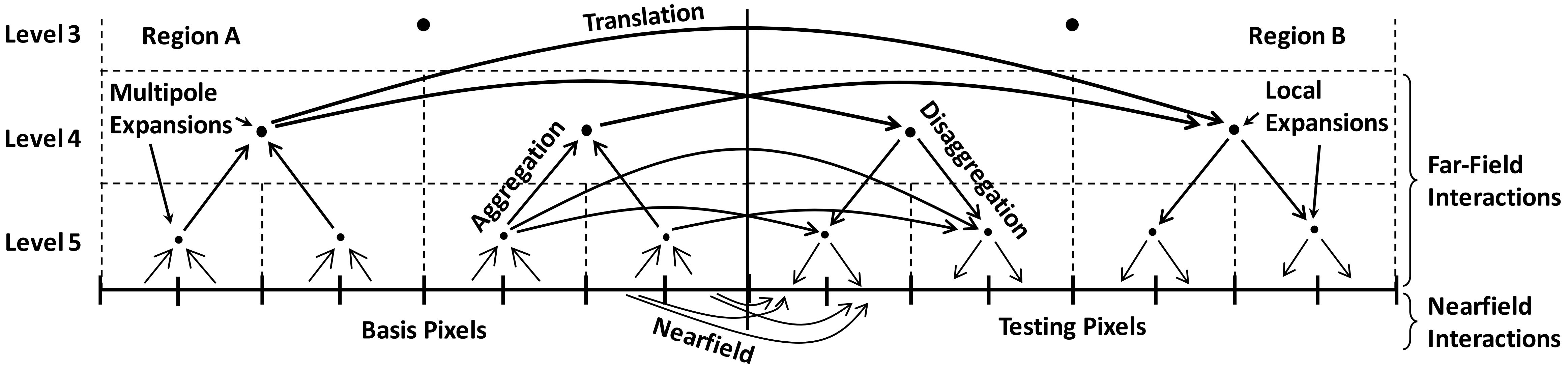
$\overline{\boldsymbol{O}}_b$: Diagonal, $N \times N$
$\overline{\boldsymbol{I}}$: Diagonal, $N \times N$

Algorithmic Speedup with MLFMA

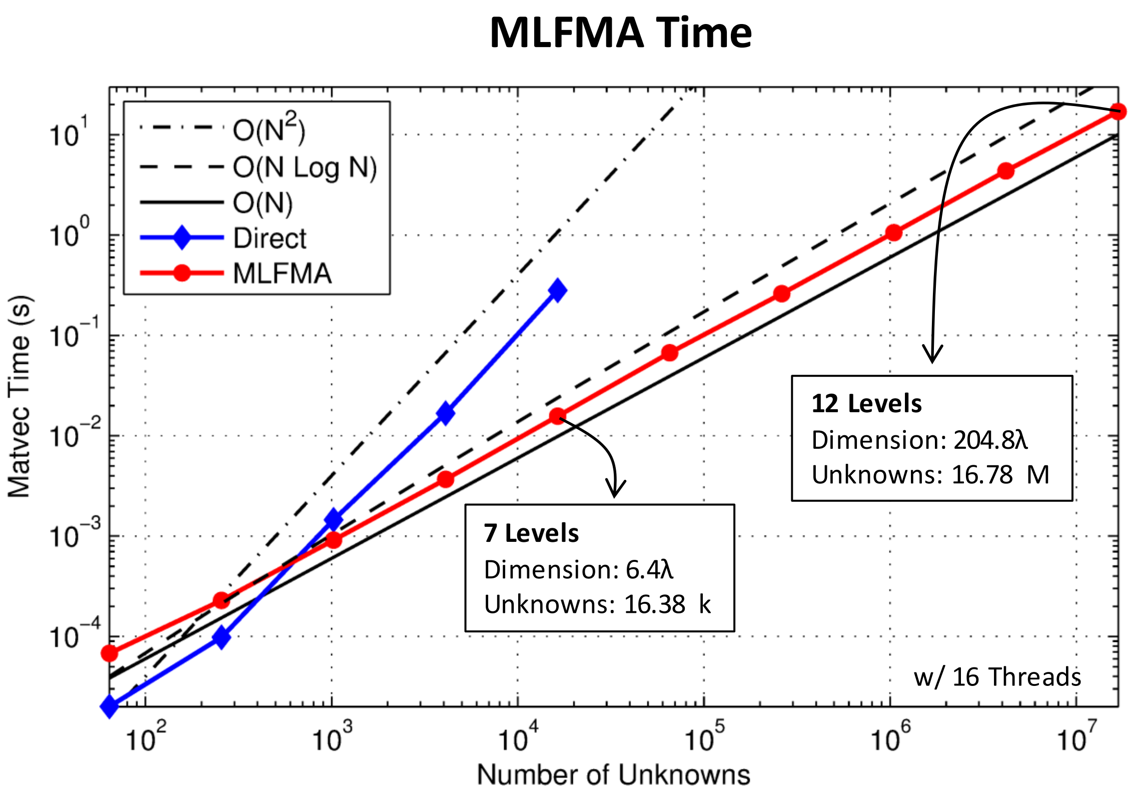
Direct Methods: $\mathcal{O}(N^3)$
Iterative Methods: $\mathcal{O}(N^2)$
Fast Multipole Method: $\mathcal{O}(N^{1.4}) - \mathcal{O}(N^{1.5})$
Multilevel Fast Multipole Algorithm: $\mathcal{O}(N) - \mathcal{O}(N\ \log N)$

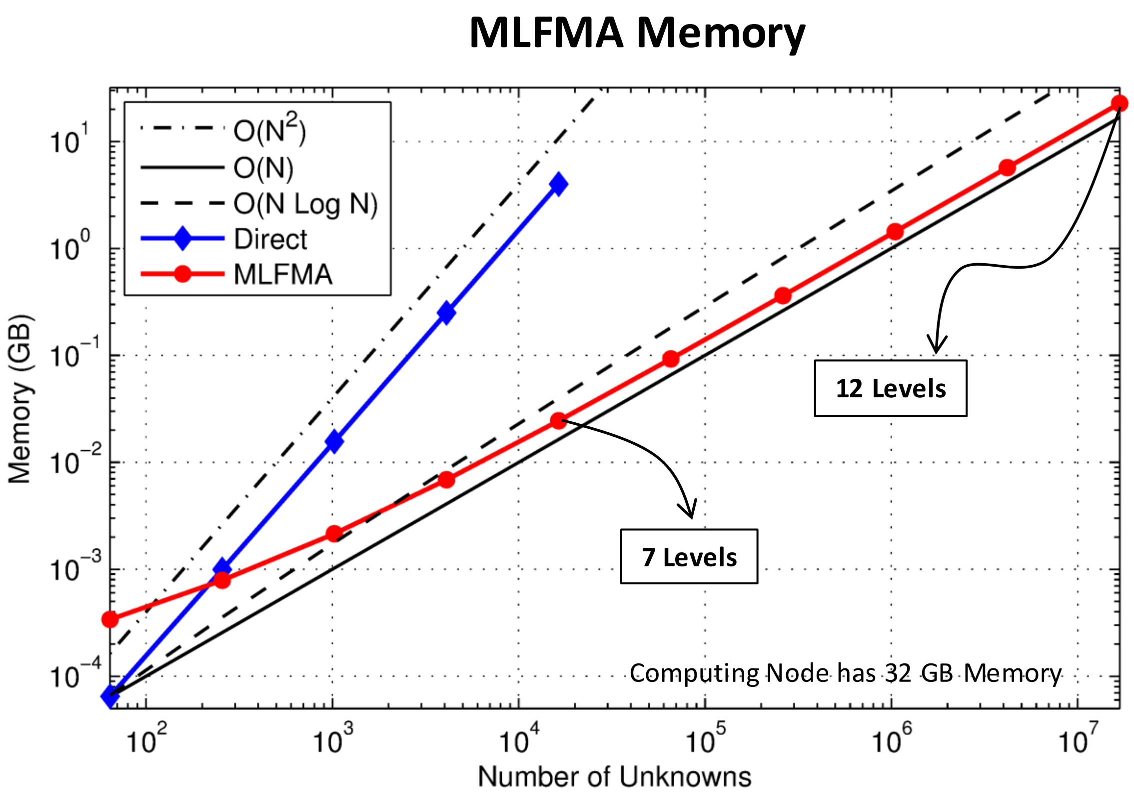
$$\boldsymbol{\phi} = \left[\bar{\boldsymbol{I}} - \underbrace{\bar{\boldsymbol{G}}_0}_{4\ \text{PB}}\bar{\boldsymbol{O}}\right]^{-1}\boldsymbol{\phi}_0$$

MLFMA Schematic

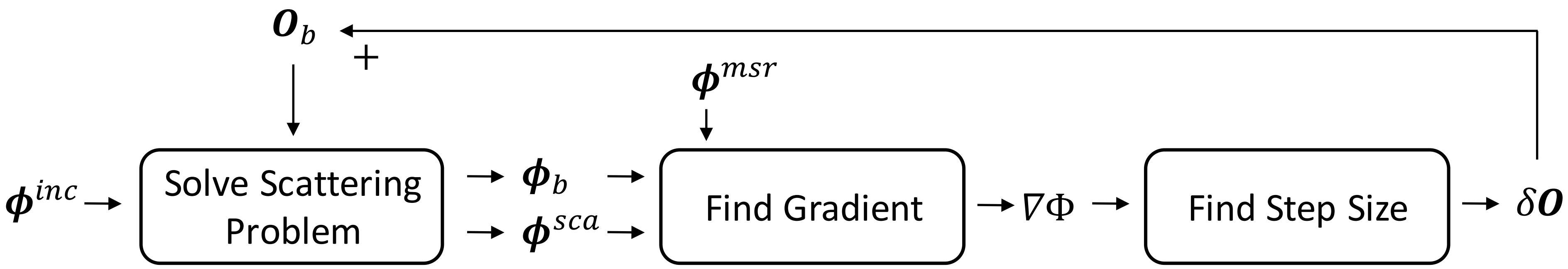


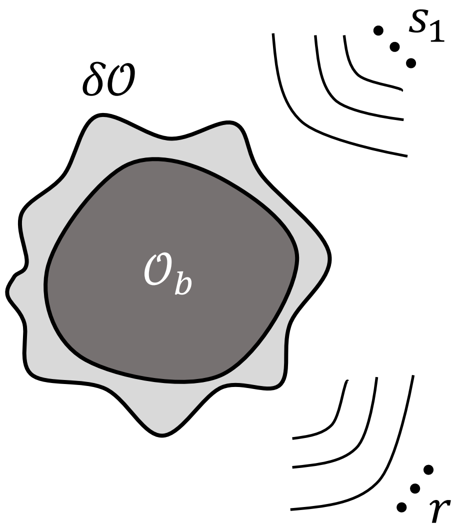
Algorithmic Speedup with MLFMA



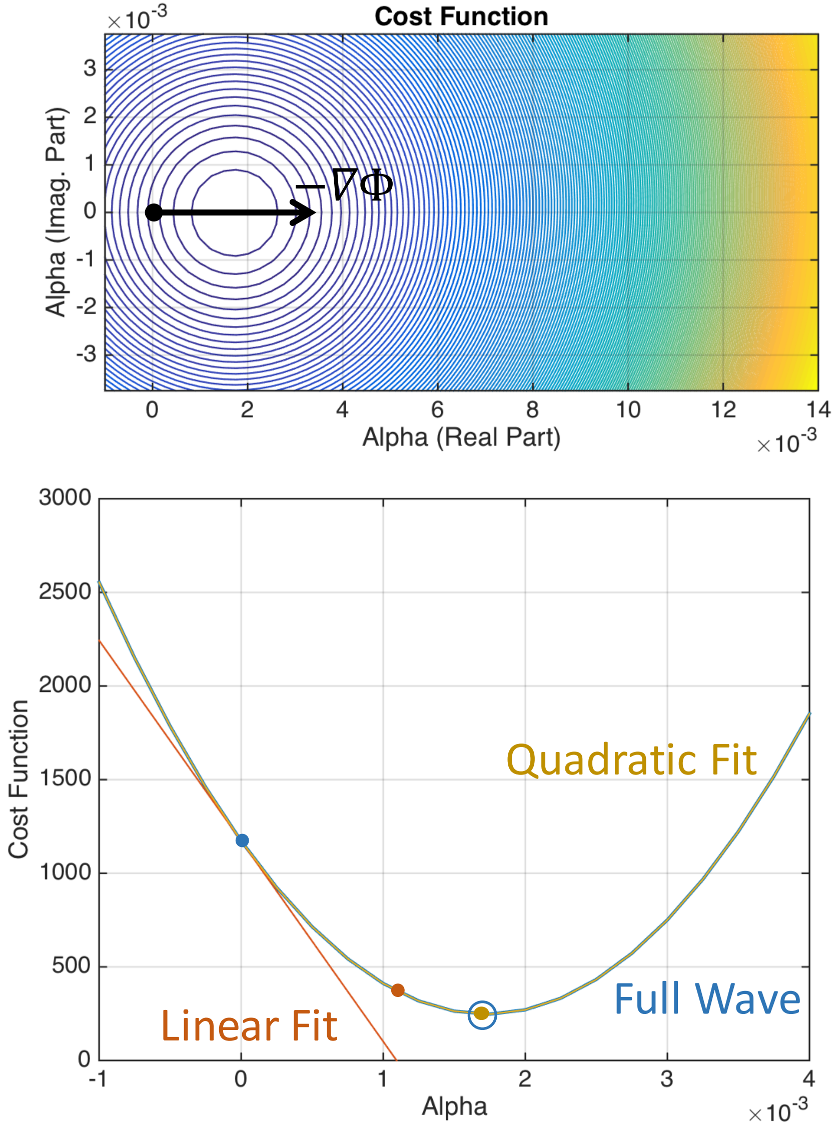


Three MLFMA Solutions per Iteration

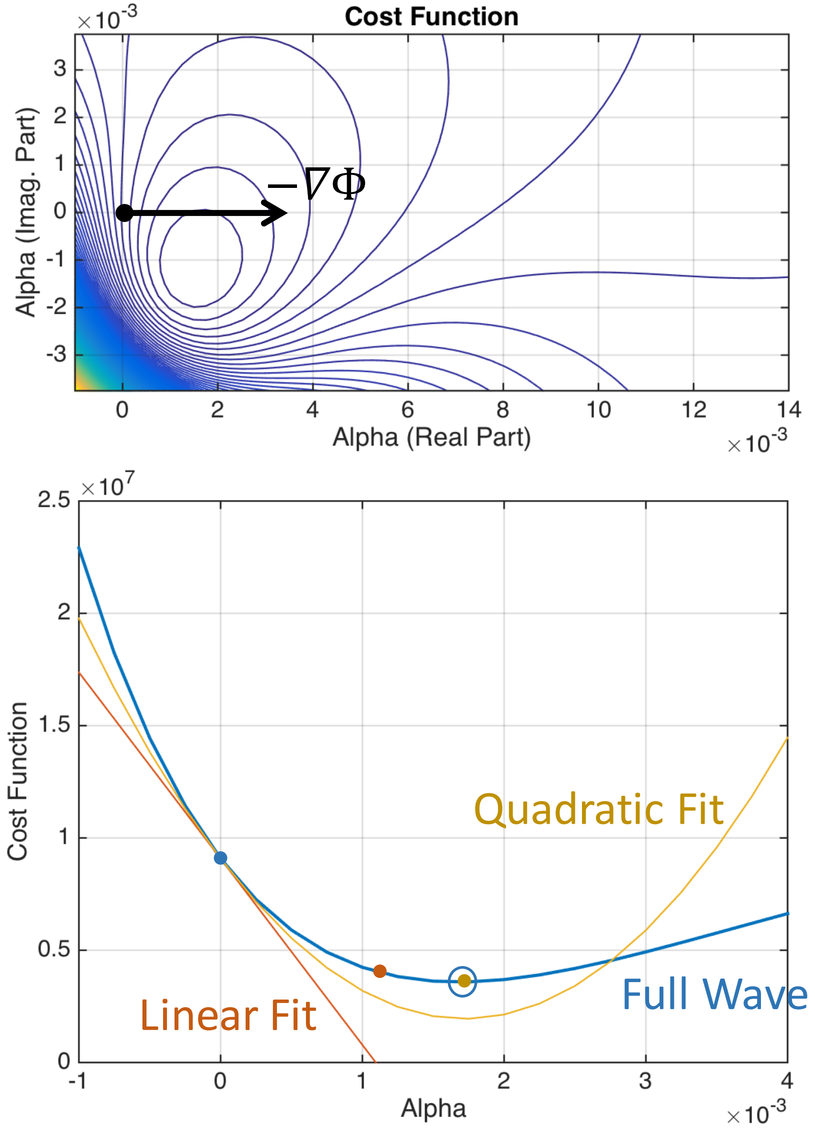




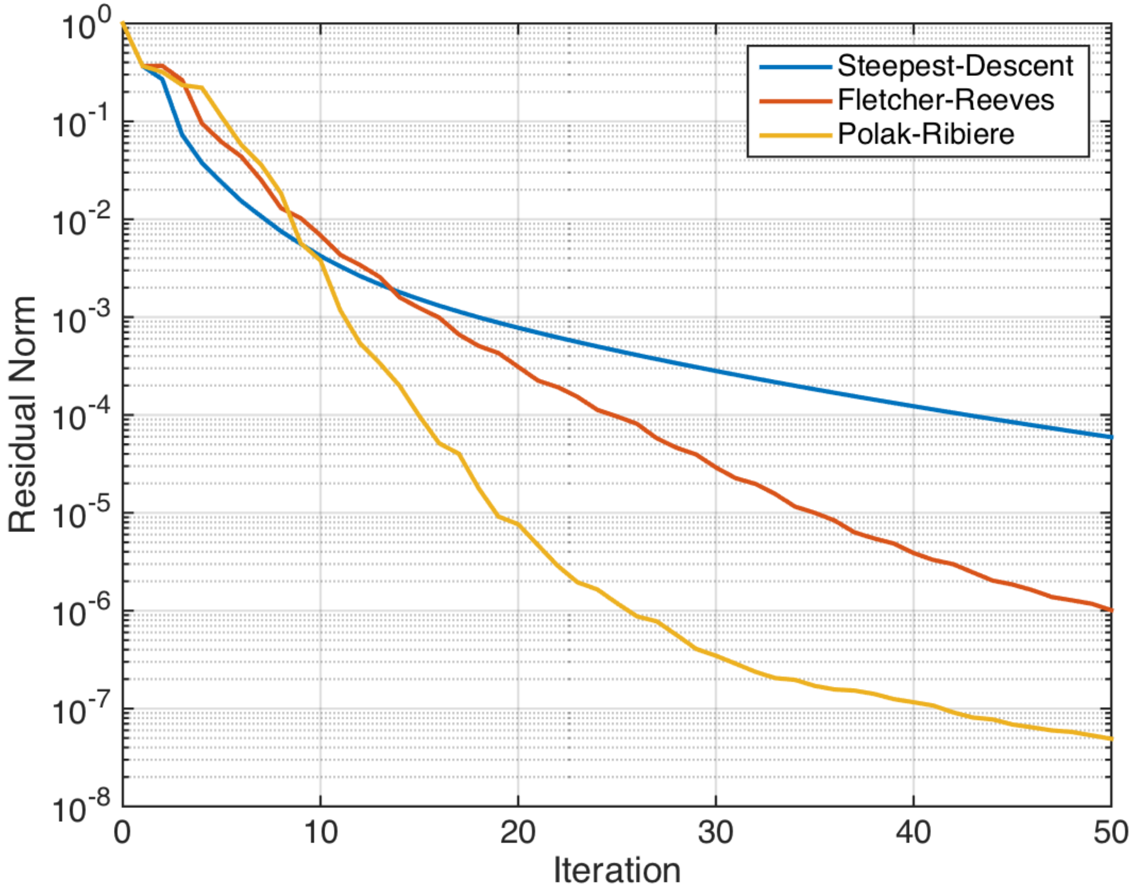
Weak Scatterer



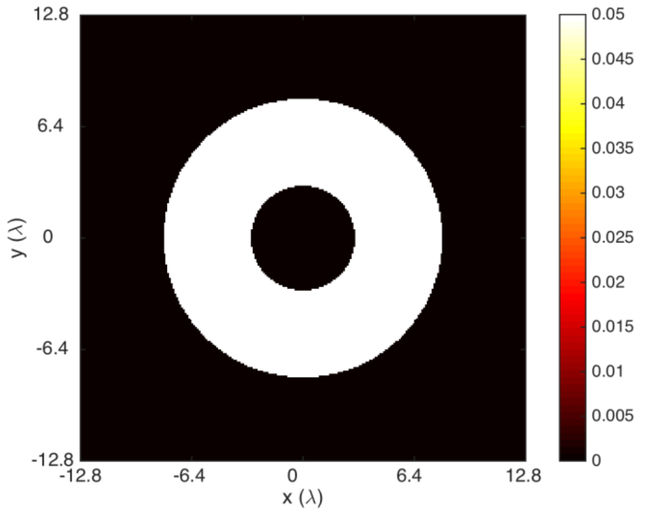
Medium Scatterer



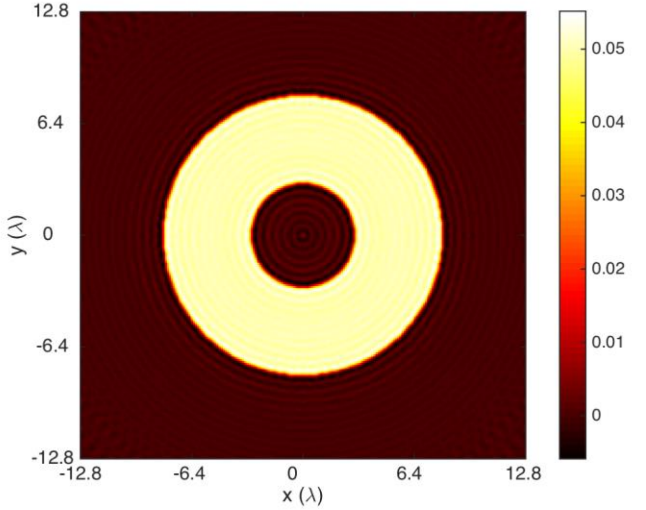
Conjugate-Gradient Convergence



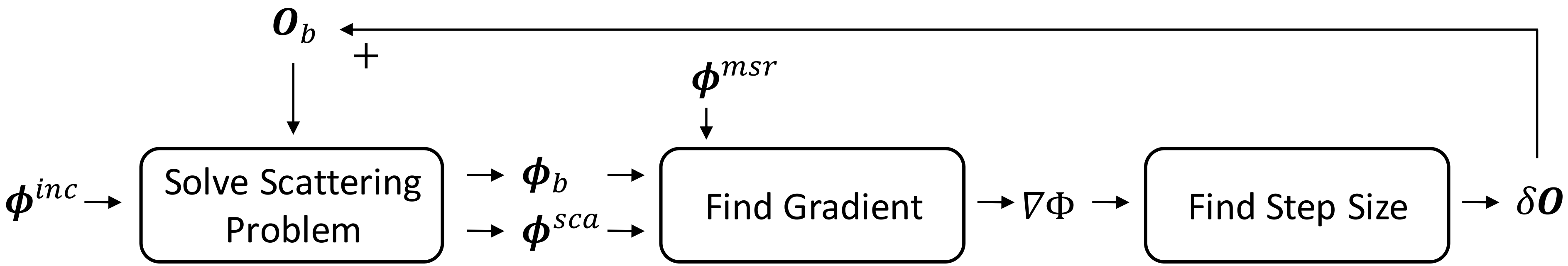
Numerical Phantom

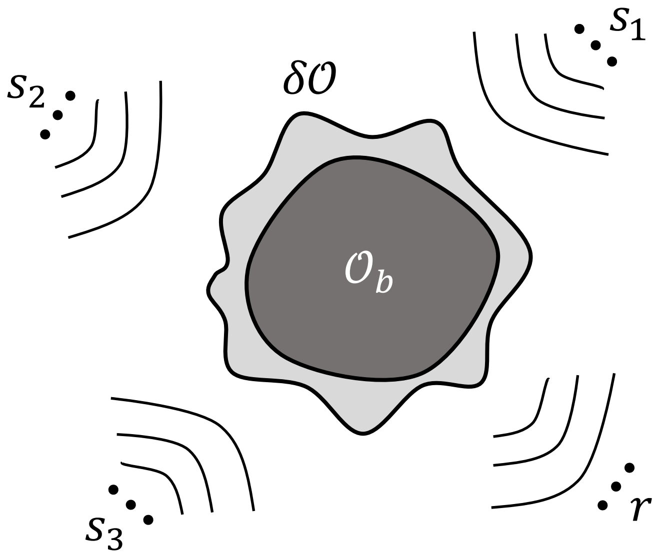


DBIM Reconstruction

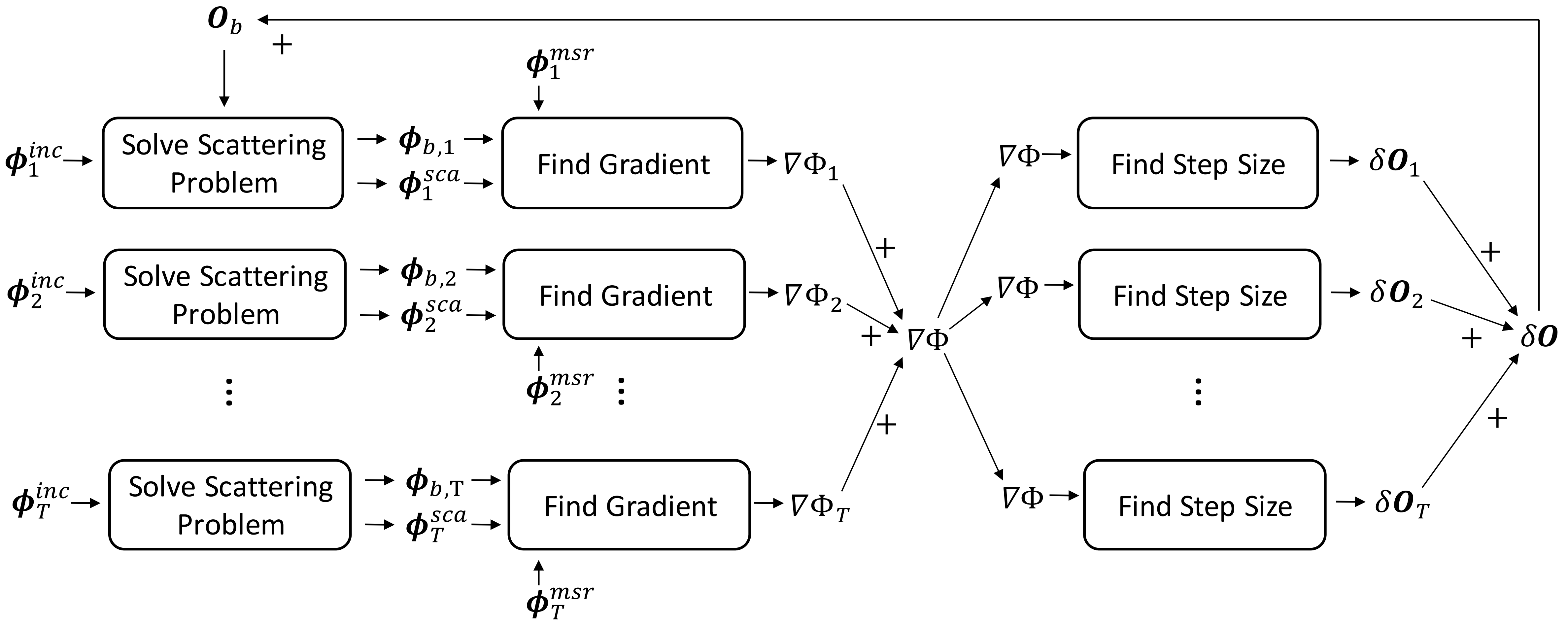


Multiple Illuminations Provide Diversity

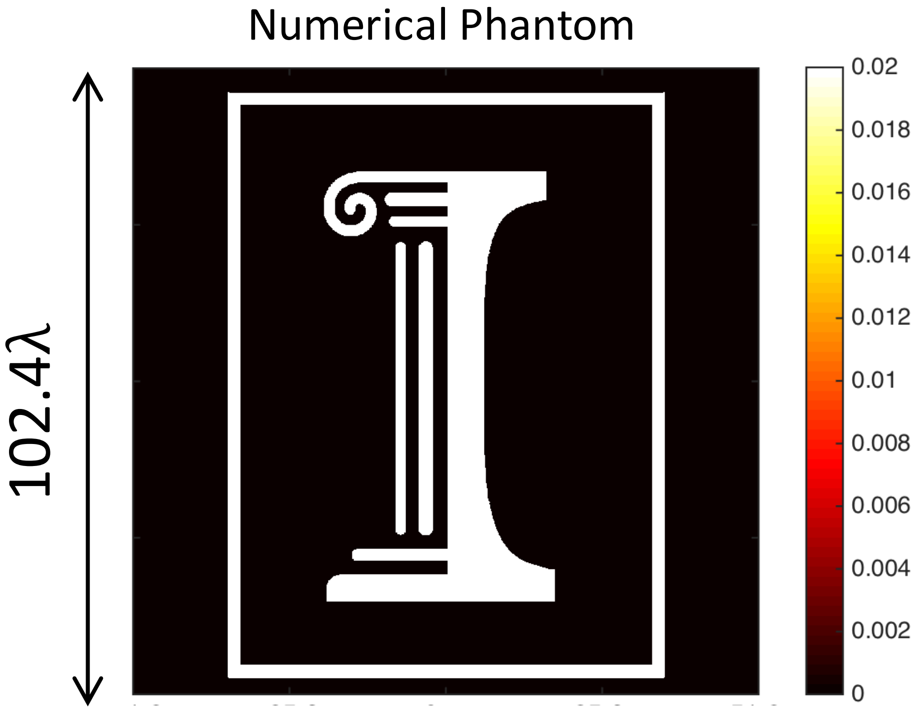


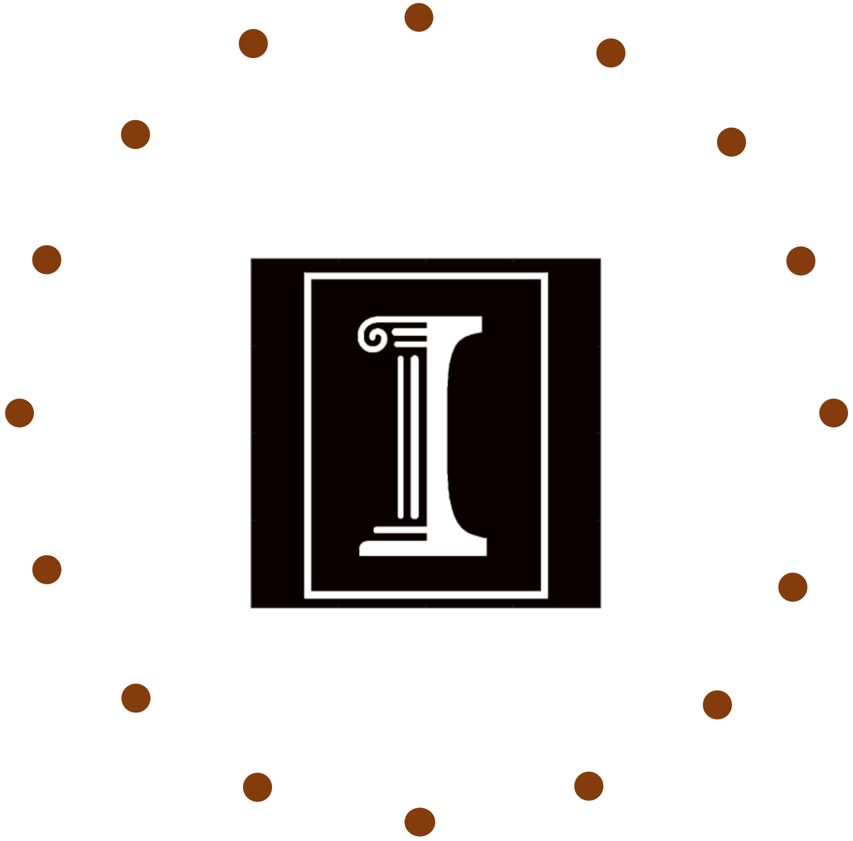


Many MLFMA Solutions per Iteration



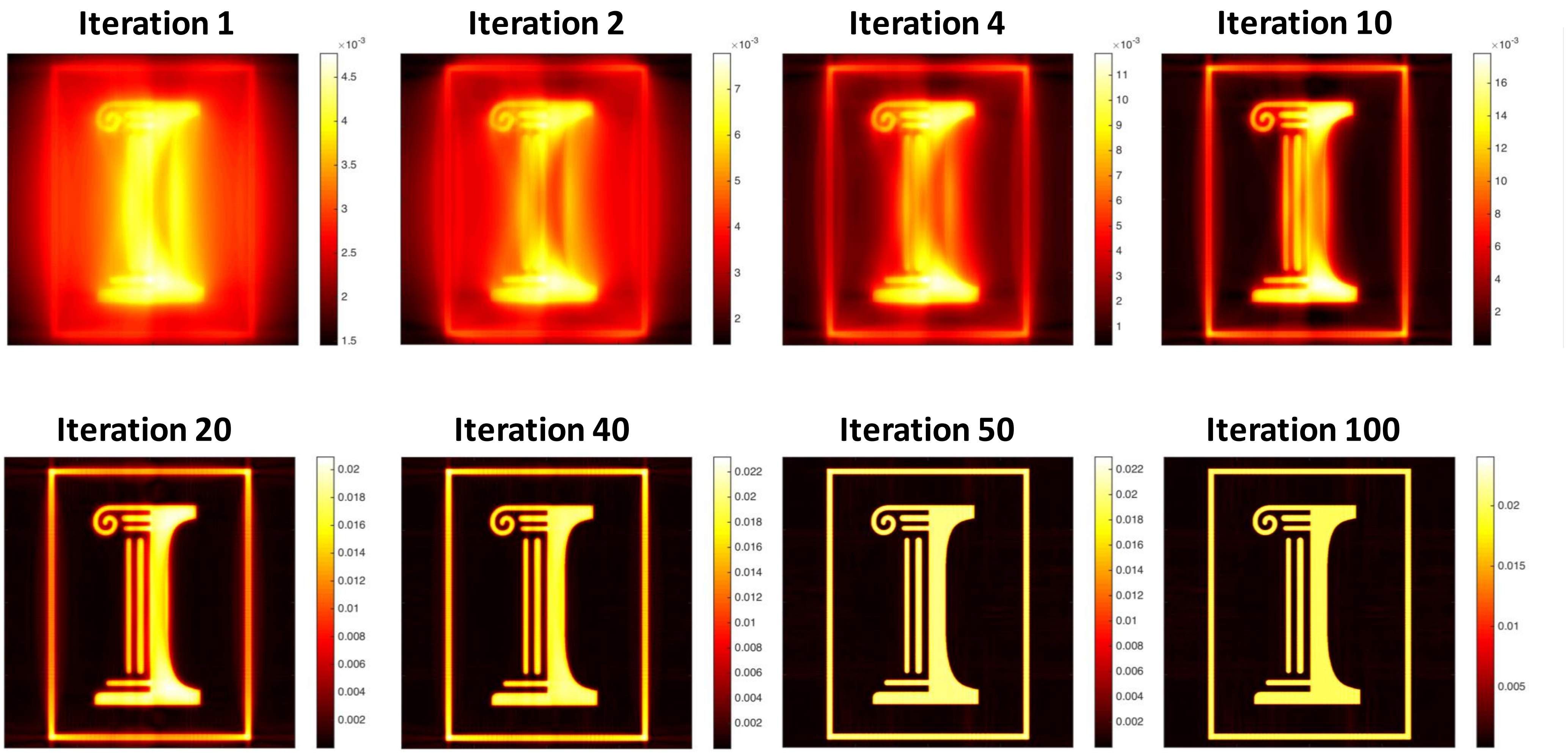
Numerical Setup for Monochromatic Reconstructions



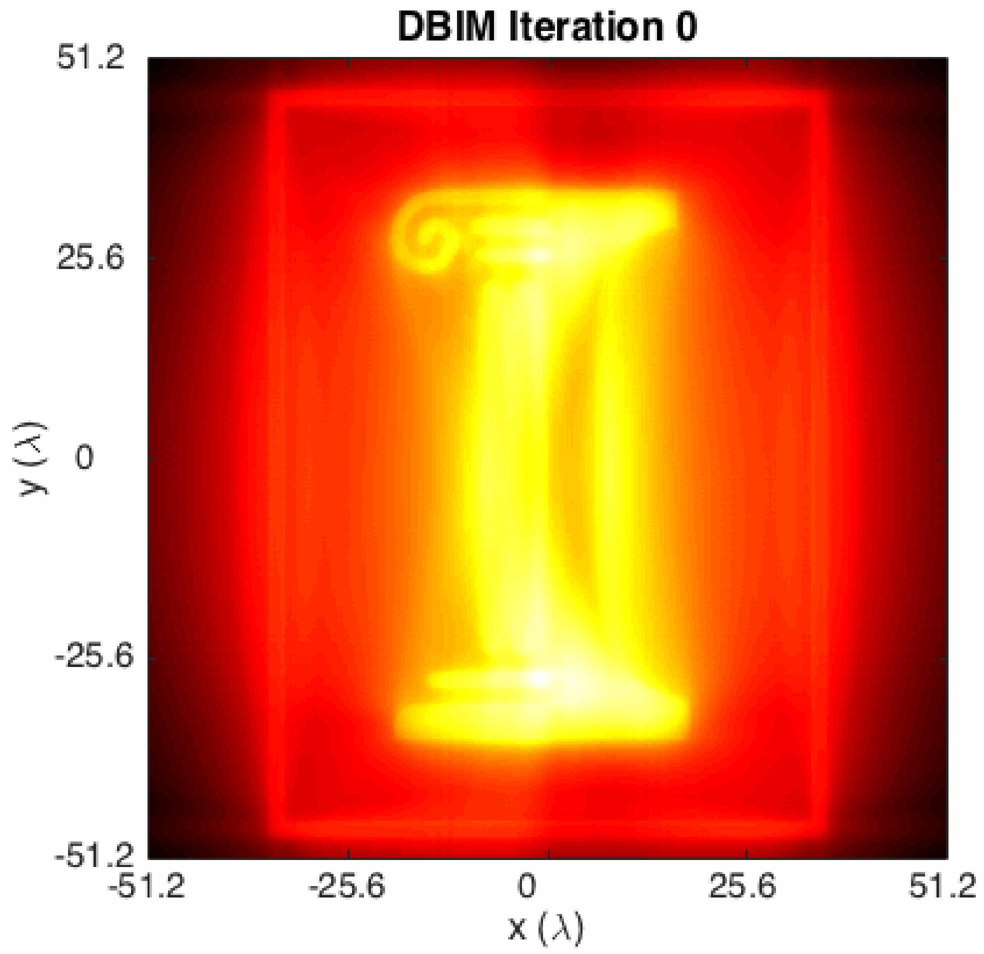


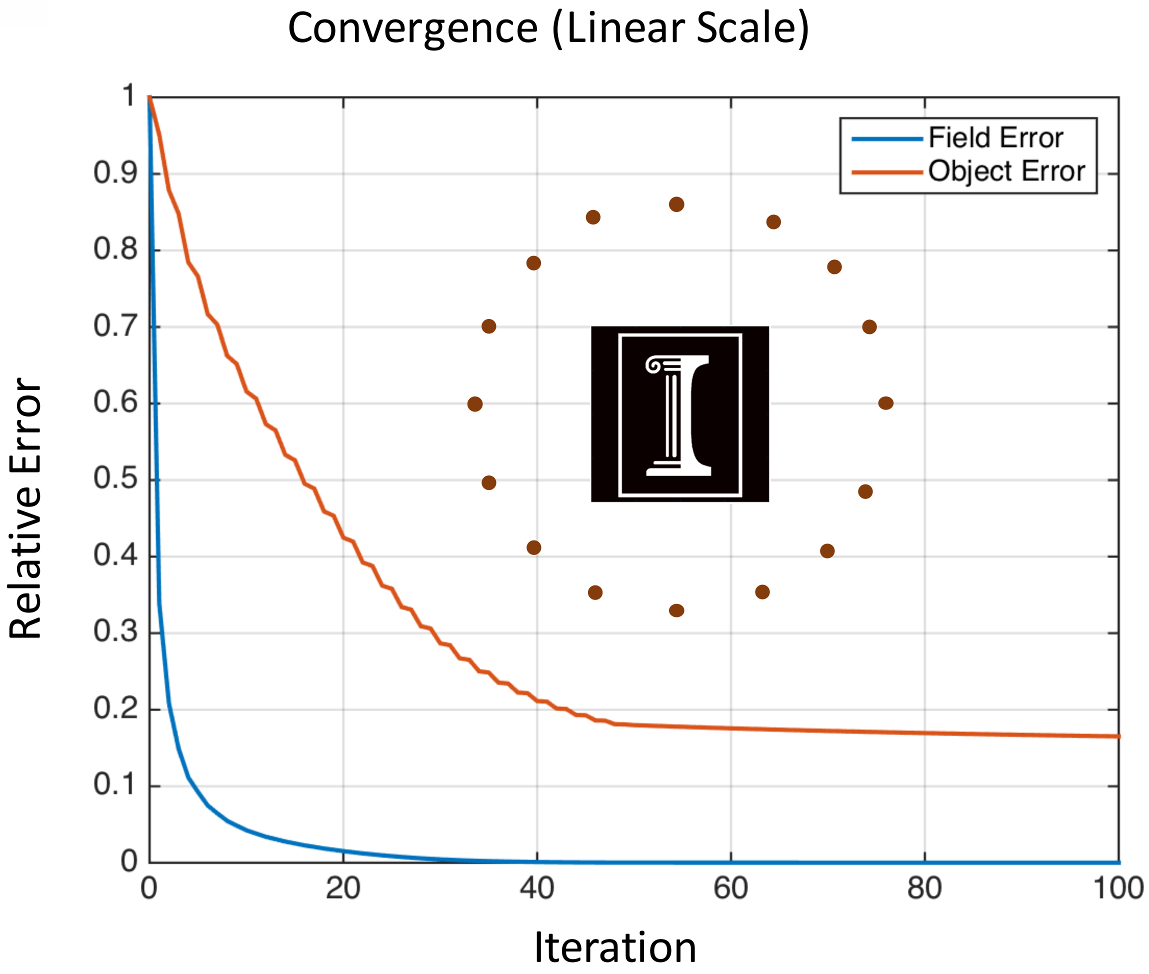
- **256 Transmitters**
- **1,024 Receivers**
- **Monochromatic**

Large-Scale Reconstruction—Almost Perfect!

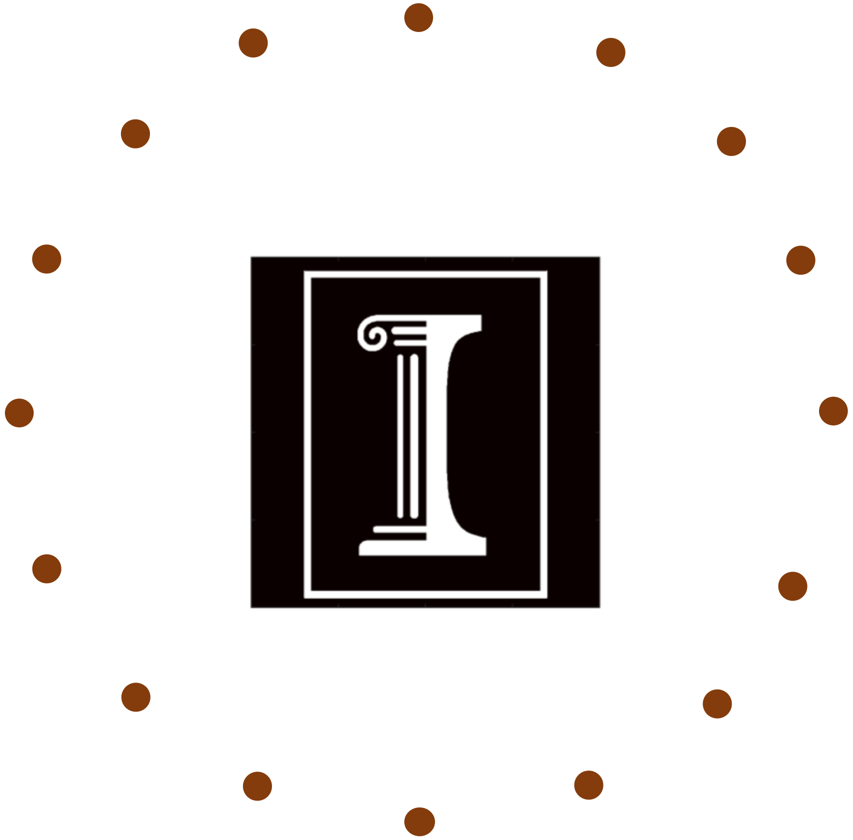


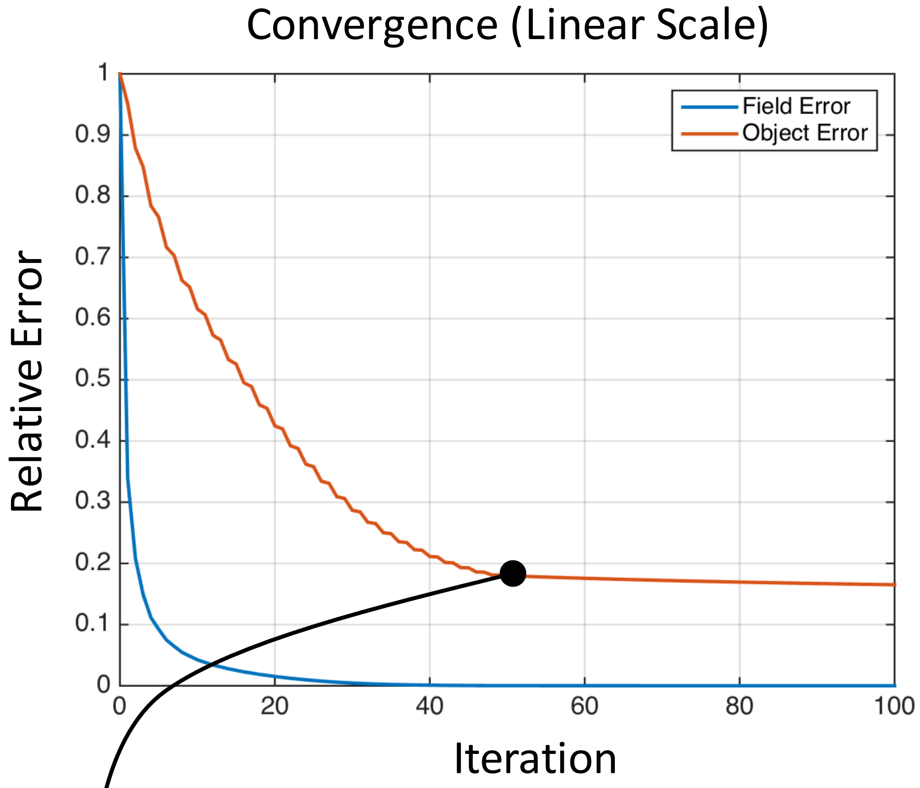
Large-Scale Reconstruction—Almost Perfect!





Large-Scale Reconstruction—Almost Perfect!

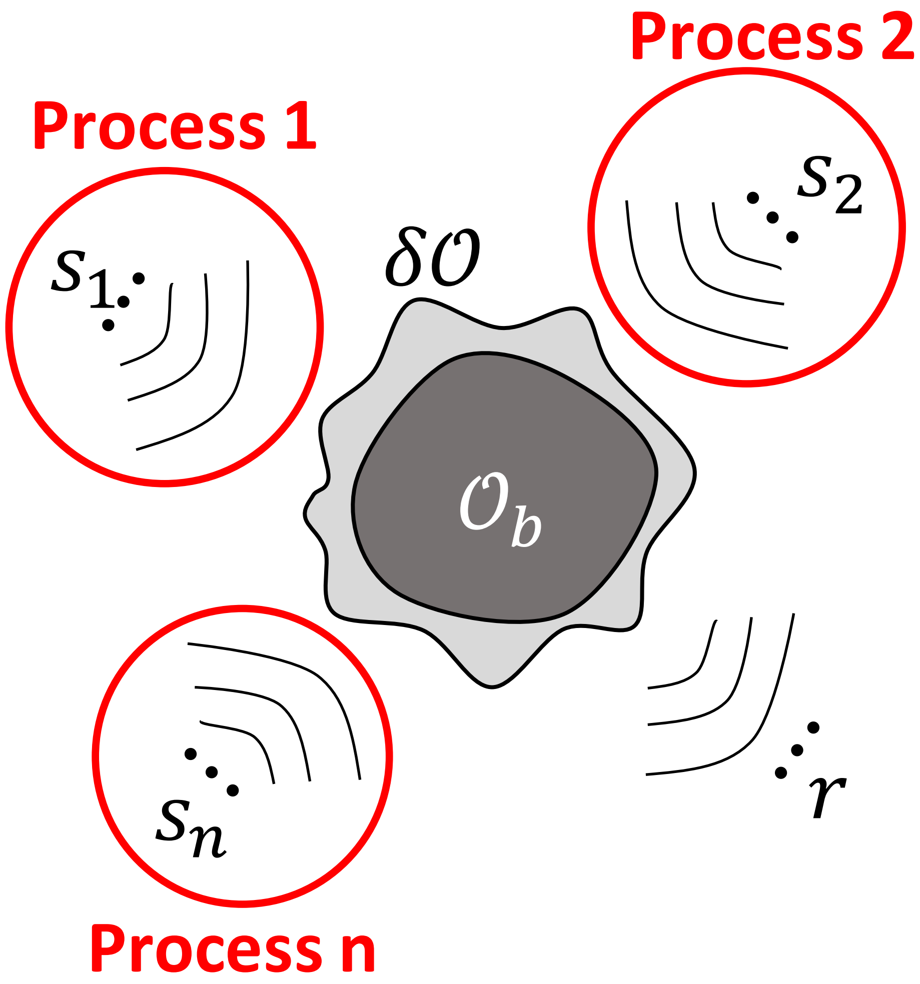


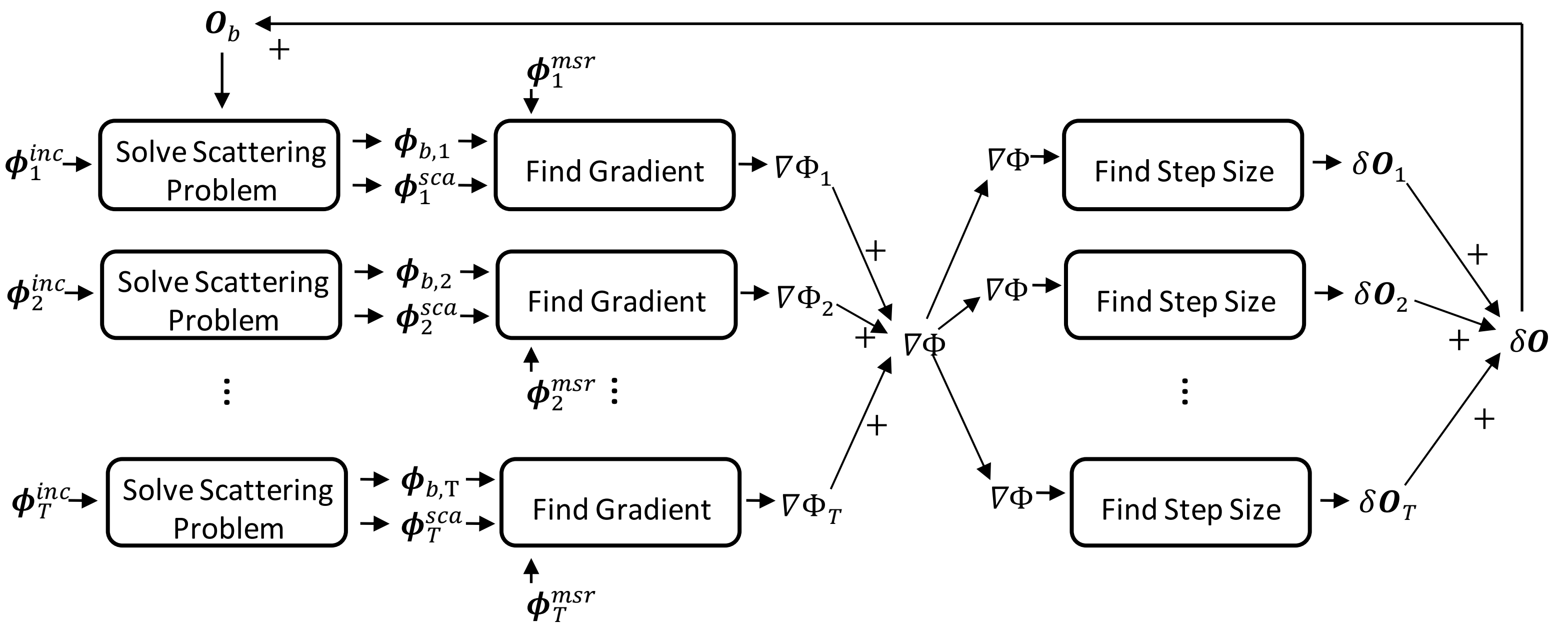


- **256 Transmitters**
- **1,024 Receivers**
- **Monochromatic**

256 Trans. x 50 Iter. x 3 = 38,400 Scattering Solutions

Multiple Illuminations Provide Diversity



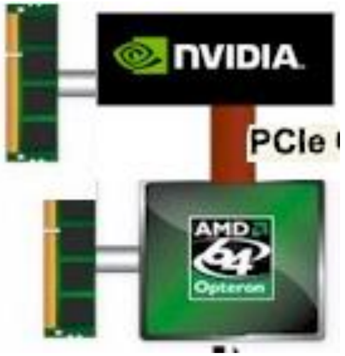


BLUE WATERS
SUSTAINED PETASCALE COMPUTING

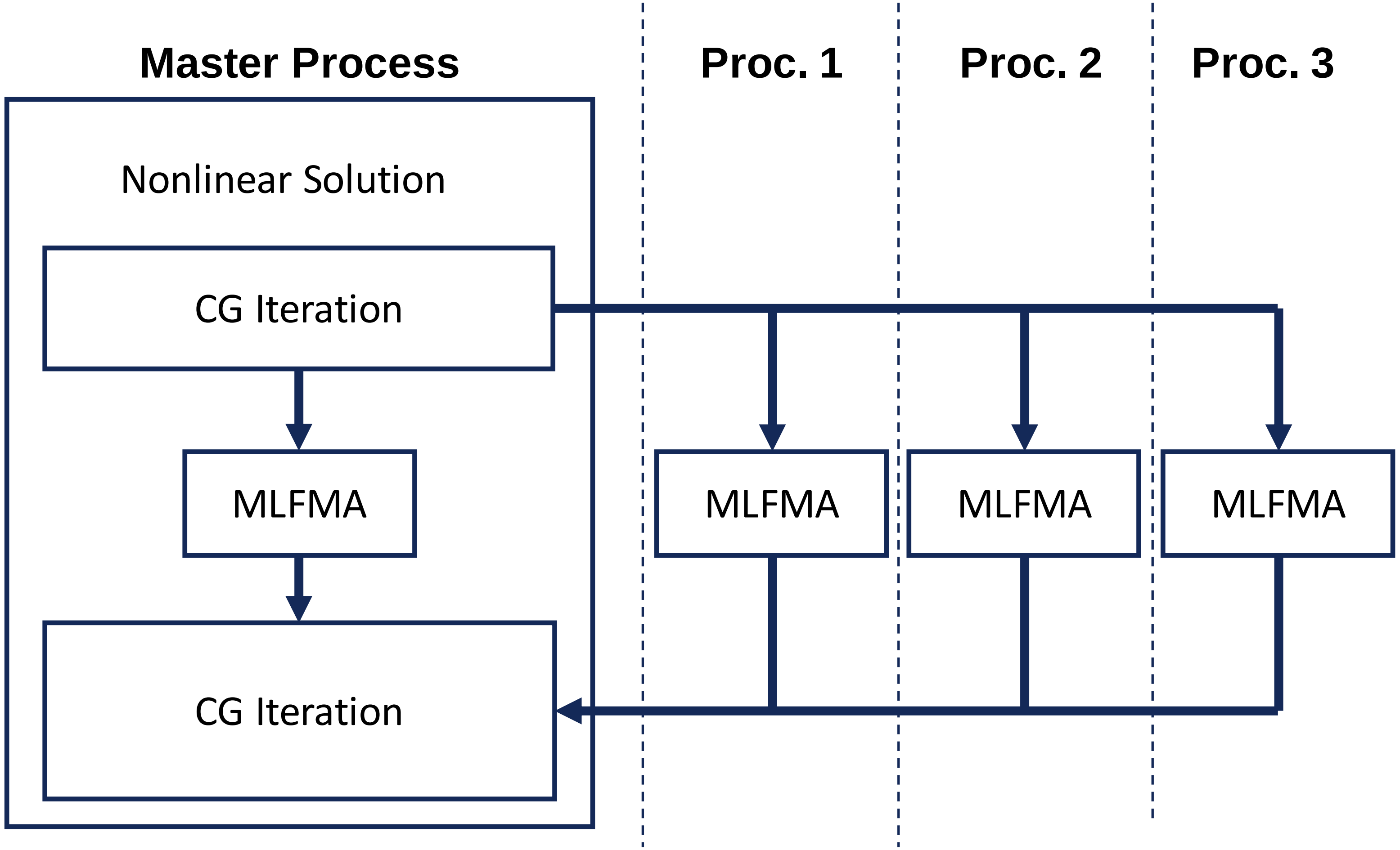
CPU+CPU

22,640 Nodes

CPU+GPU



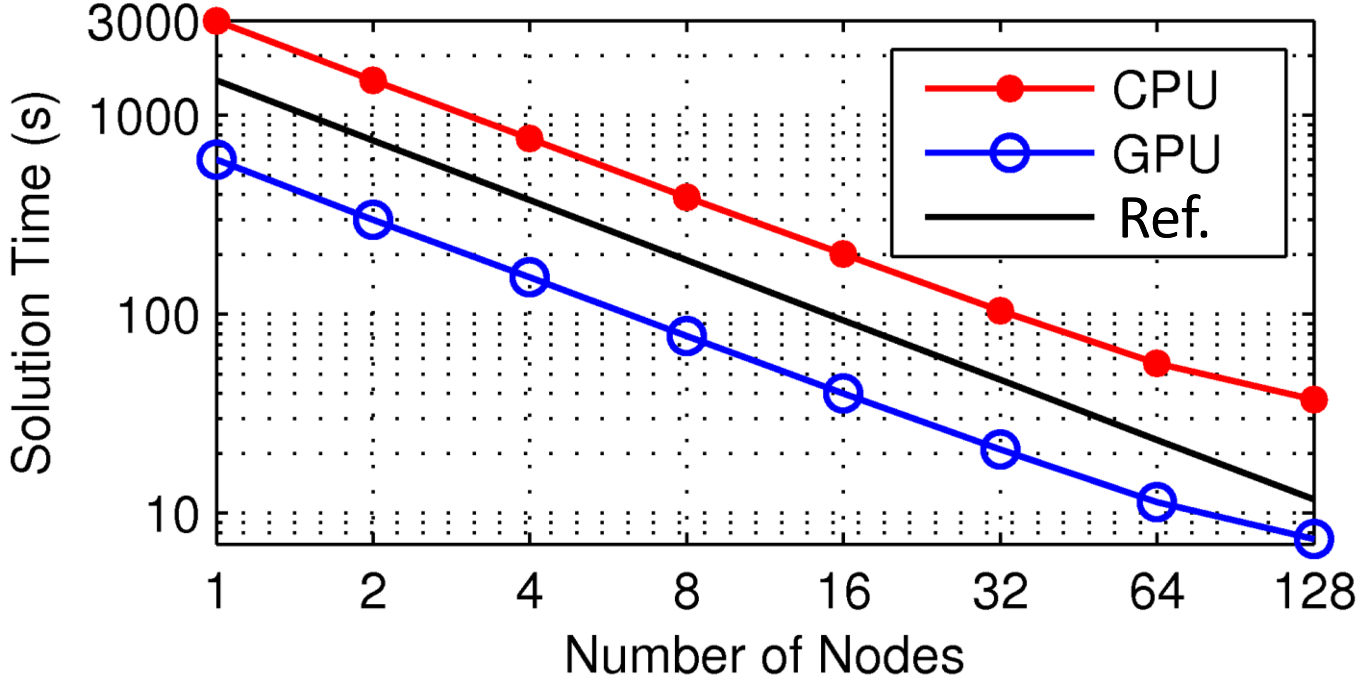
4,228 Nodes



CPU Nodes vs. GPU Nodes

Sequential Execution: 11.5 Hours

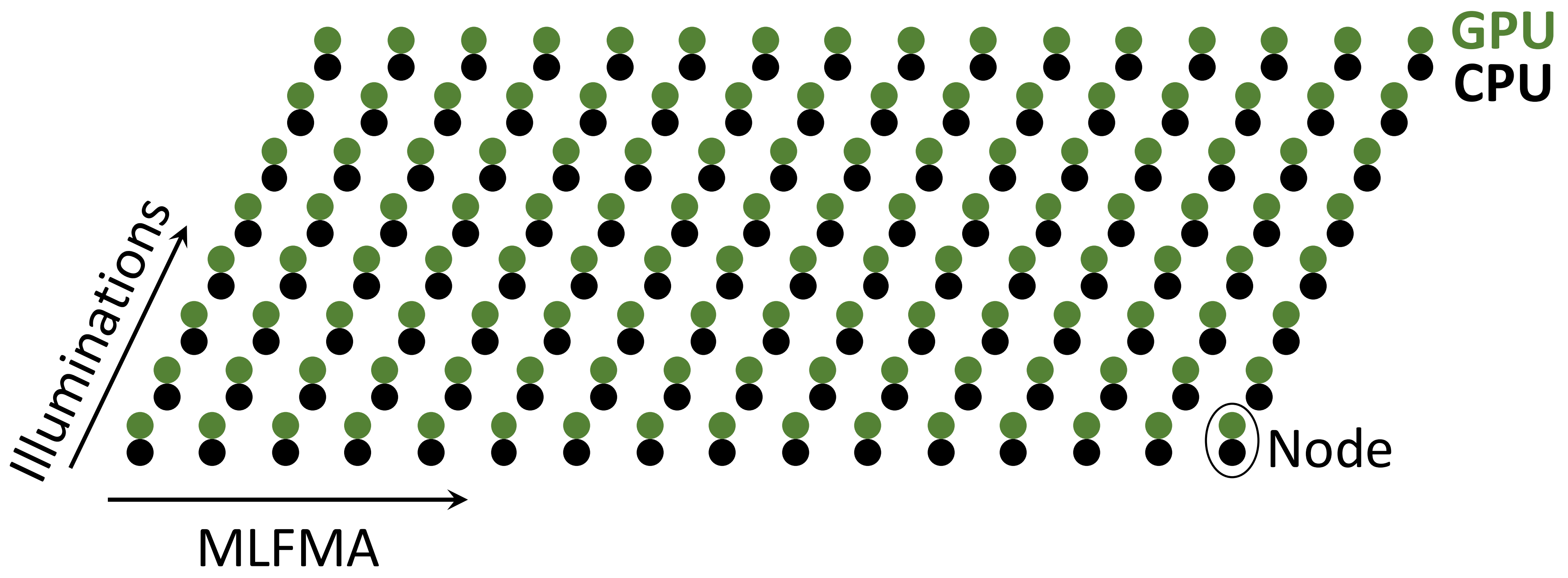
50 min.
(16 CPU cores)



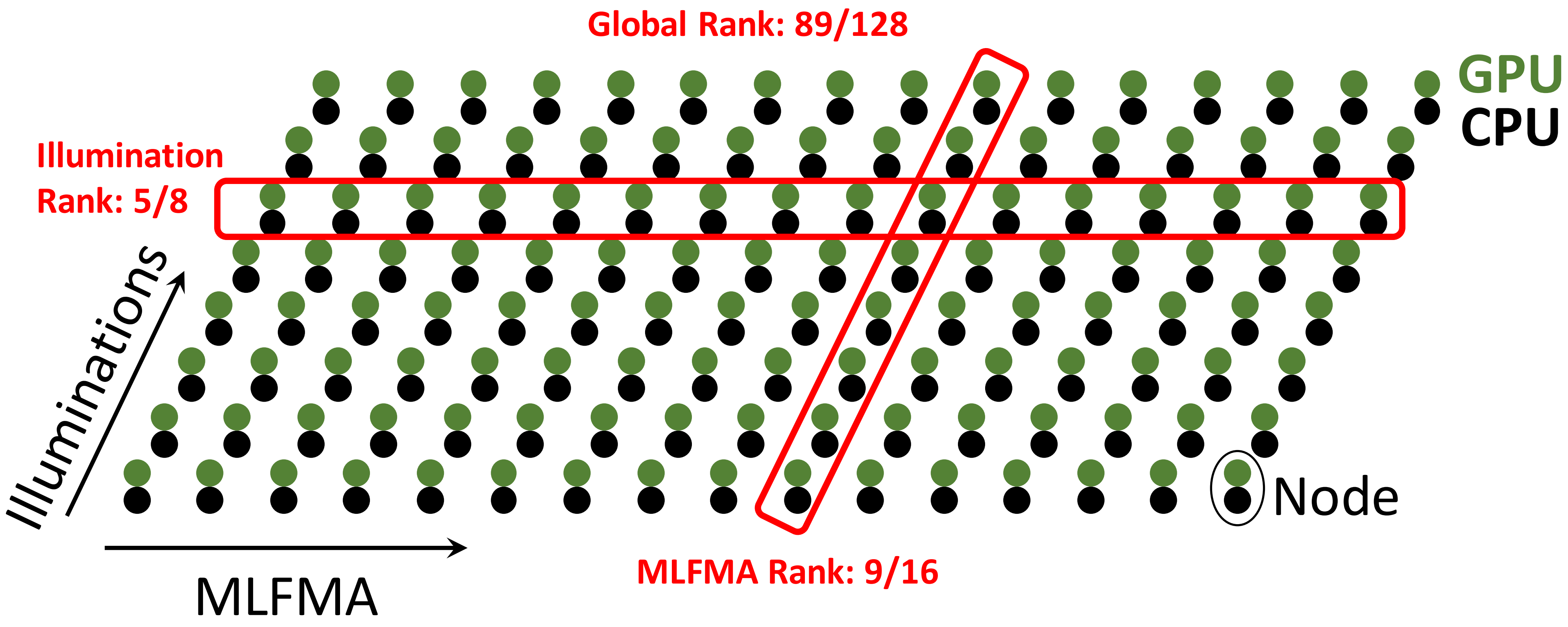
38 sec.
(2,048 CPU cores)

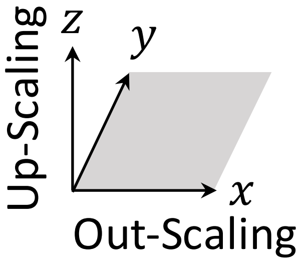
7 sec.
(128 GPUs)

Massively-Parallel Inverse Solution Scheme



Massively-Parallel Inverse Solution Scheme





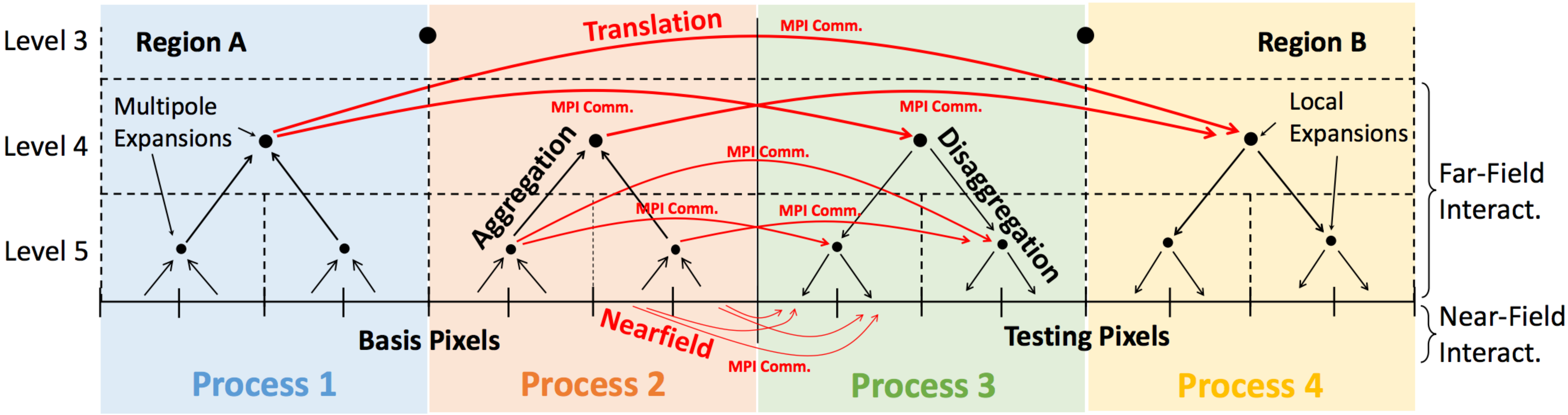

```
MPI_Comm_split( MPI_Comm comm, int color, int key, MPI_Comm* newcomm)
```

Parallelization of MLFMA

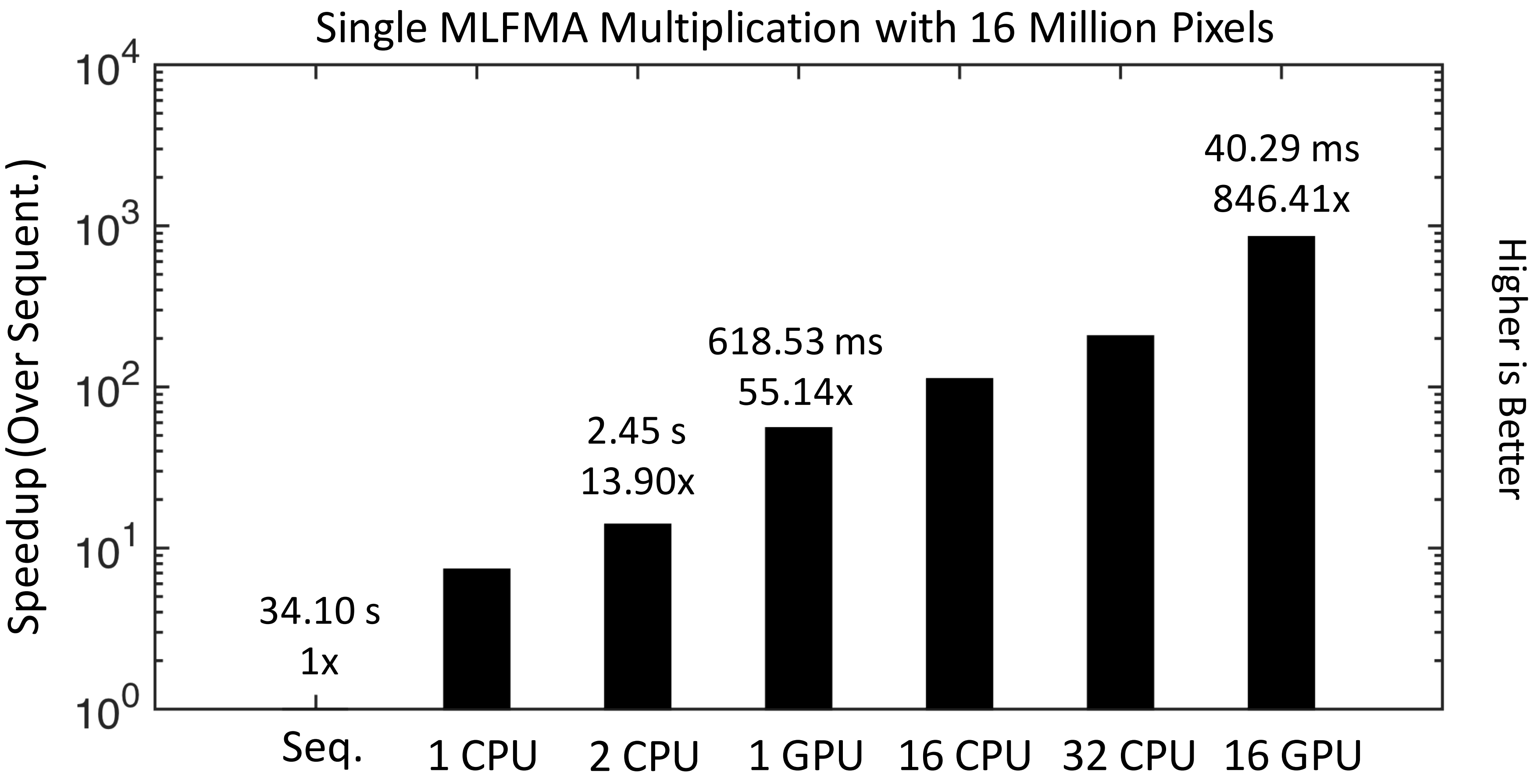
$$\phi = \left[\bar{I} - \bar{G}_0 \bar{O}\right]^{-1} \phi_0$$

4 PB

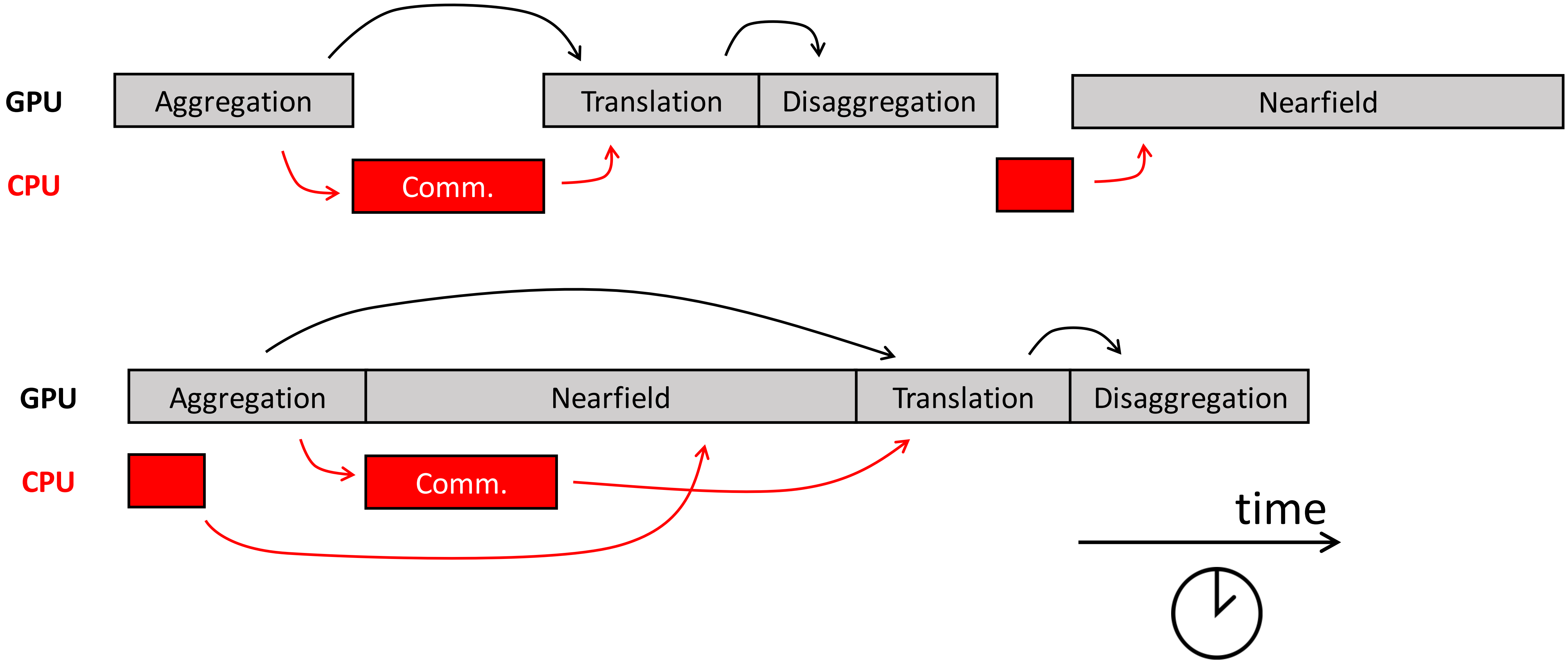
MLFMA Schematic



GPU Provides About 55x Per-Node Speedup

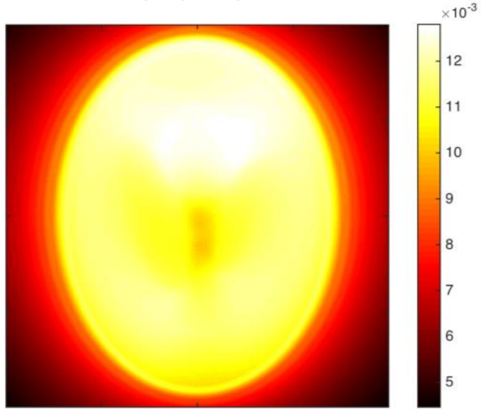


MPI Communications can be Completely Hidden

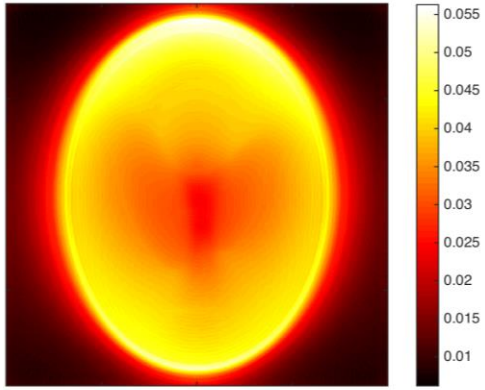


Large-Scale Reconstruction—Almost Perfect!

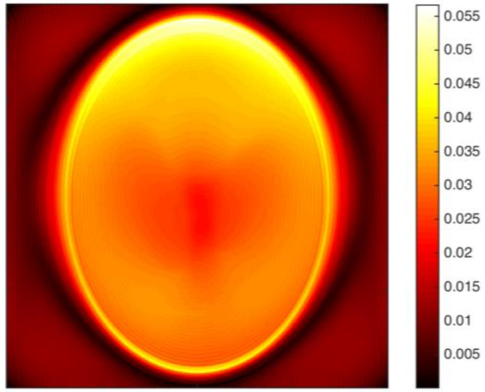
Iteration 1



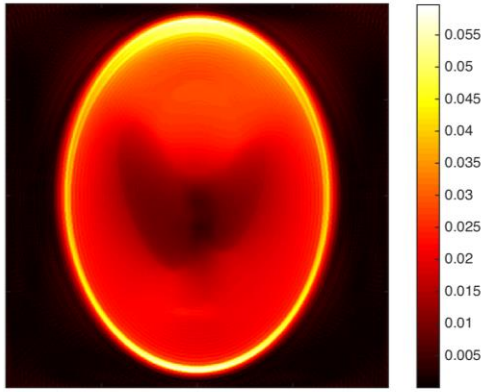
Iteration 2



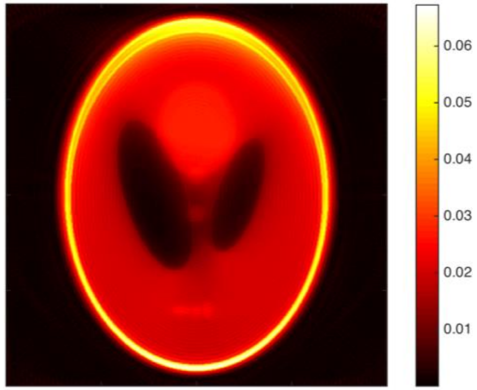
Iteration 4



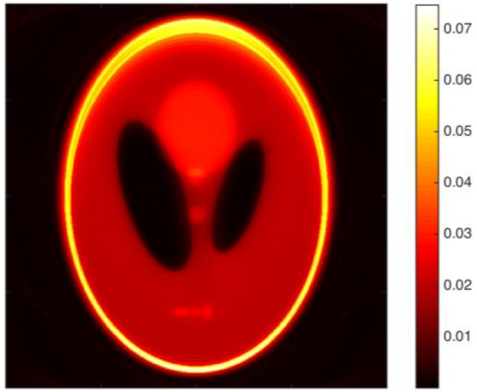
Iteration 10



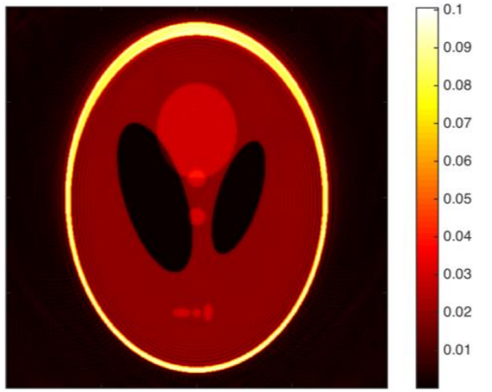
Iteration 15



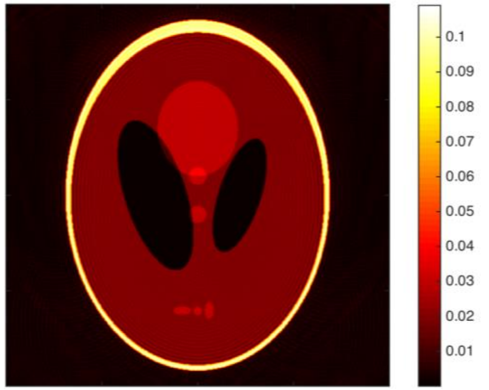
Iteration 20

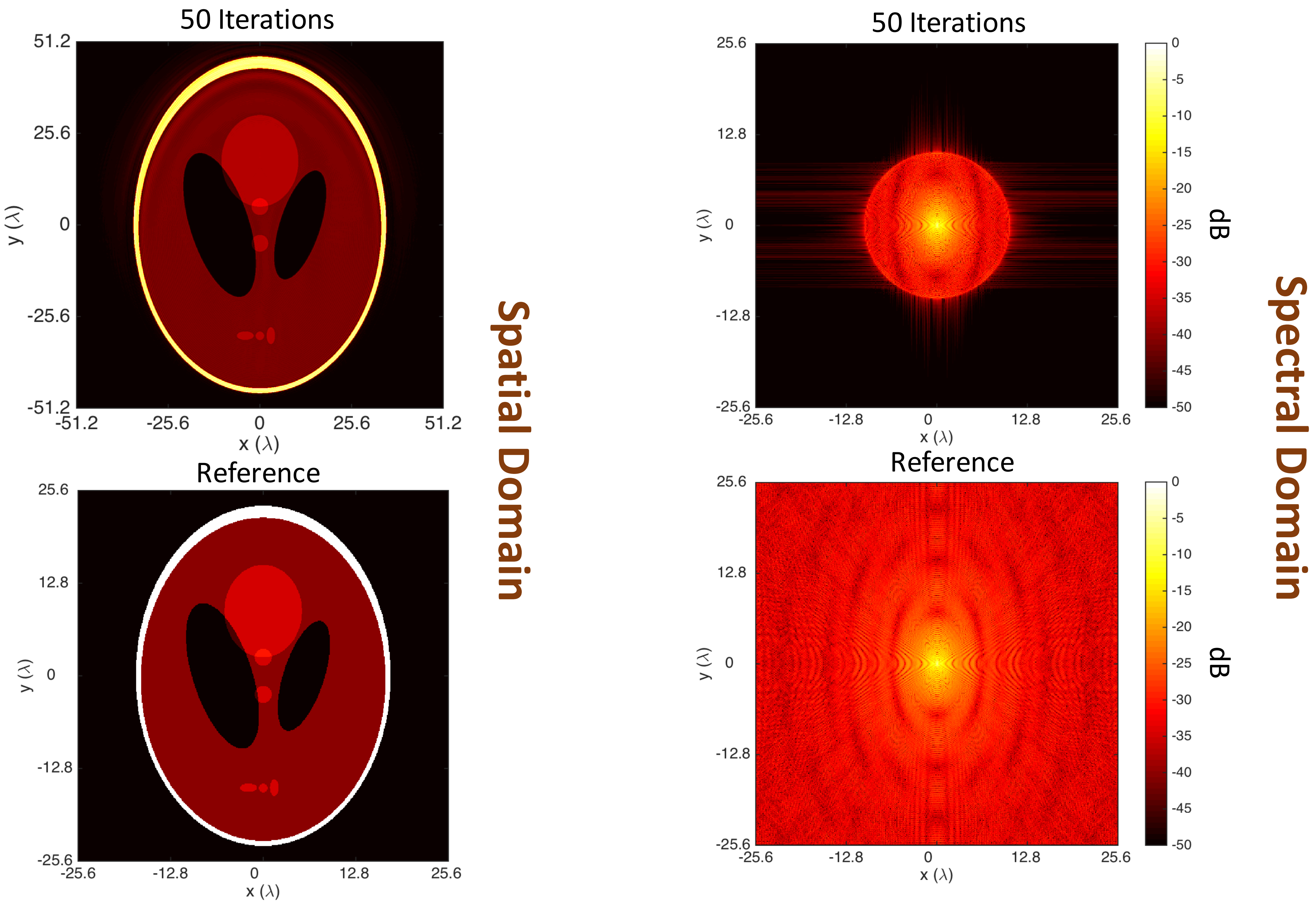


Iteration 60

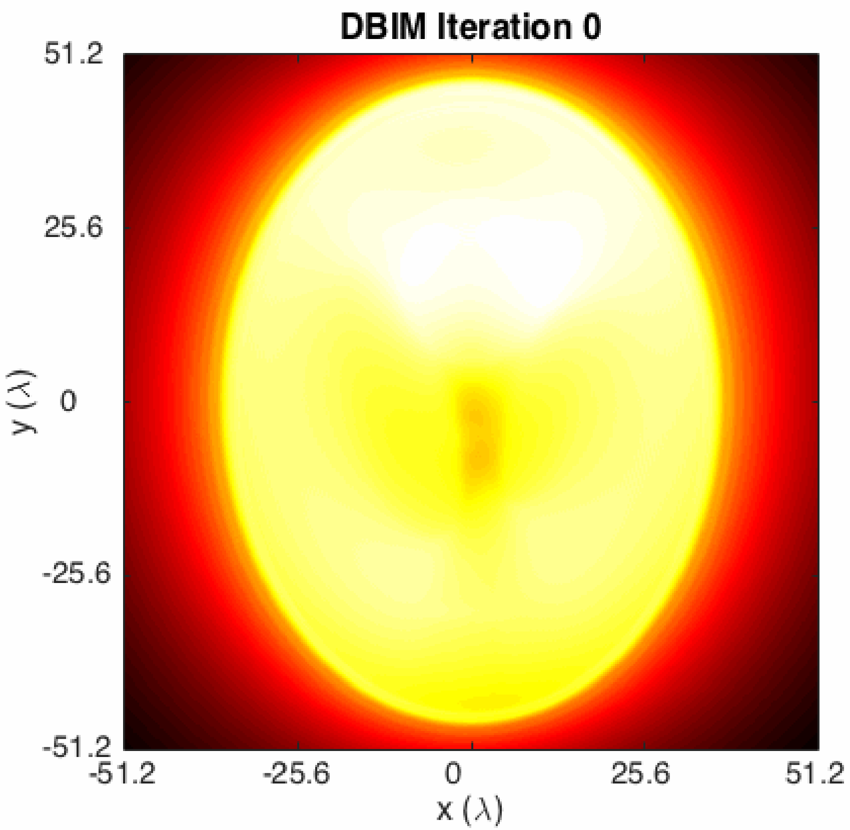


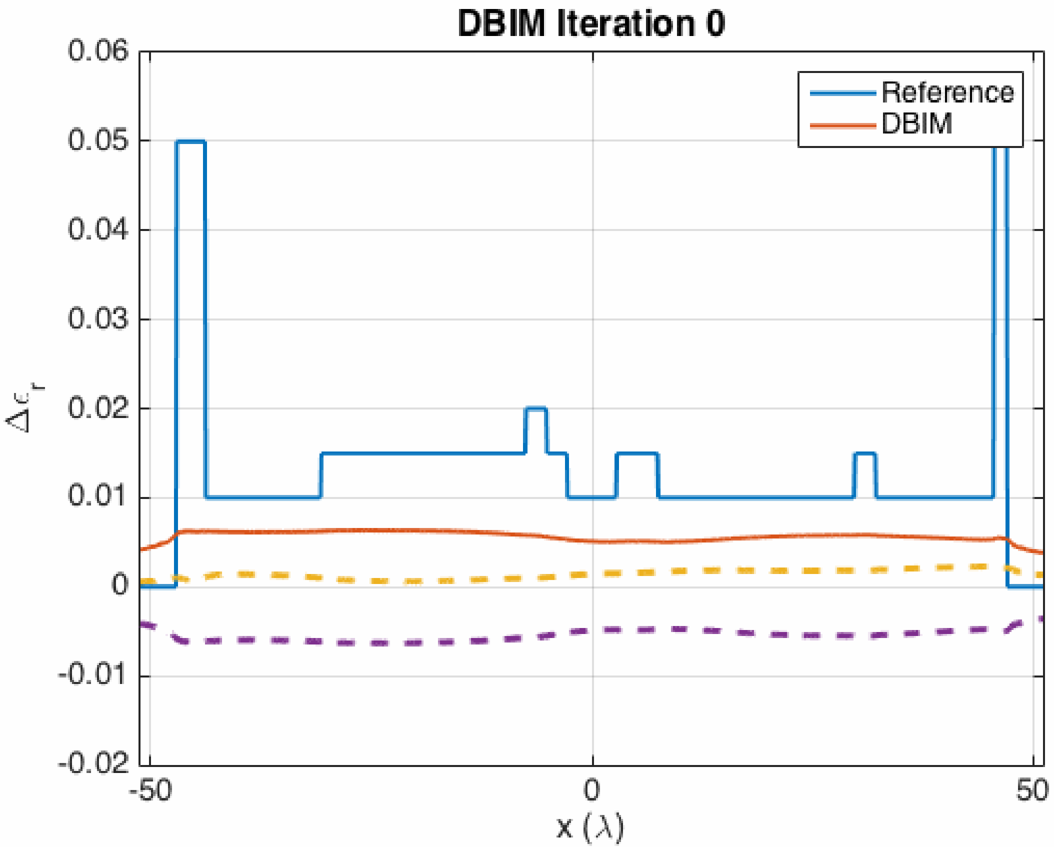
Iteration 100




50 Iterations
51.2
25.6
0
-25.6
-51.2
y (λ)
-51.2
-25.6
0
25.6
51.2
x (λ)
Reference
25.6
12.8
0
-12.8
-25.6
y (λ)
-25.6
-12.8
0
12.8
25.6
x (λ)
Spatial Domain
50 Iterations
25.6
12.8
0
-12.8
-25.6
y (λ)
-25.6
-12.8
0
12.8
25.6
x (λ)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
dB
Reference
25.6
12.8
0
-12.8
-25.6
y (λ)
-25.6
-12.8
0
12.8
25.6
x (λ)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
dB
Spectral Domain

Large-Scale Reconstruction—Almost Perfect!

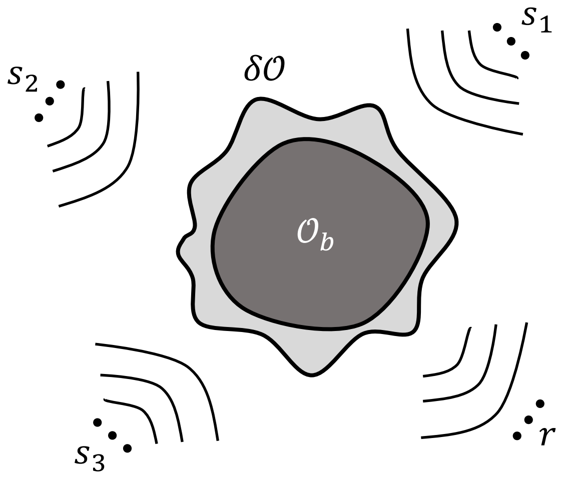




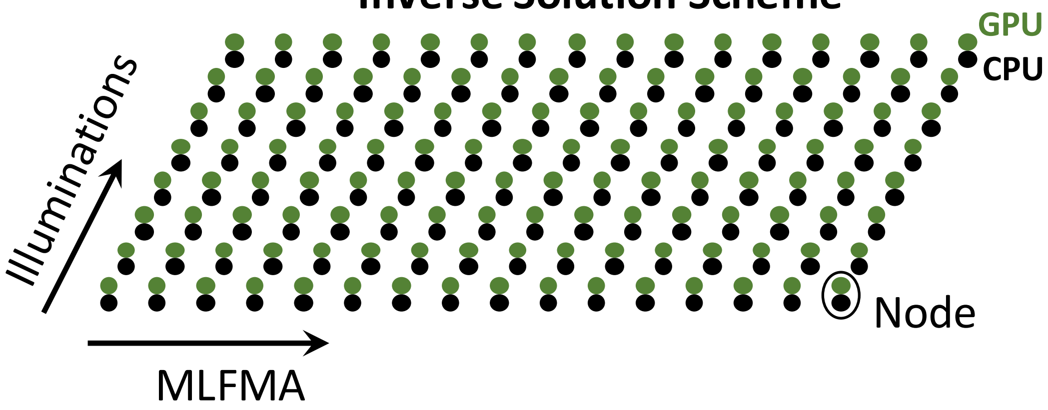
1024 Transmitters
1024 Receivers
Monochromatic

1024 CPU Nodes: 558 sec.
1024 GPU Nodes: 142 sec.

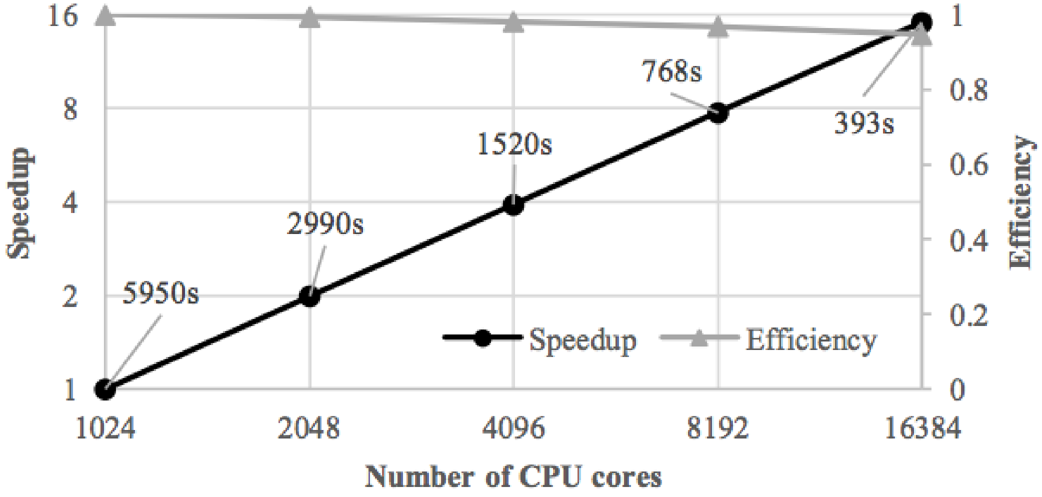
Scalable Parallel Inverse Solutions



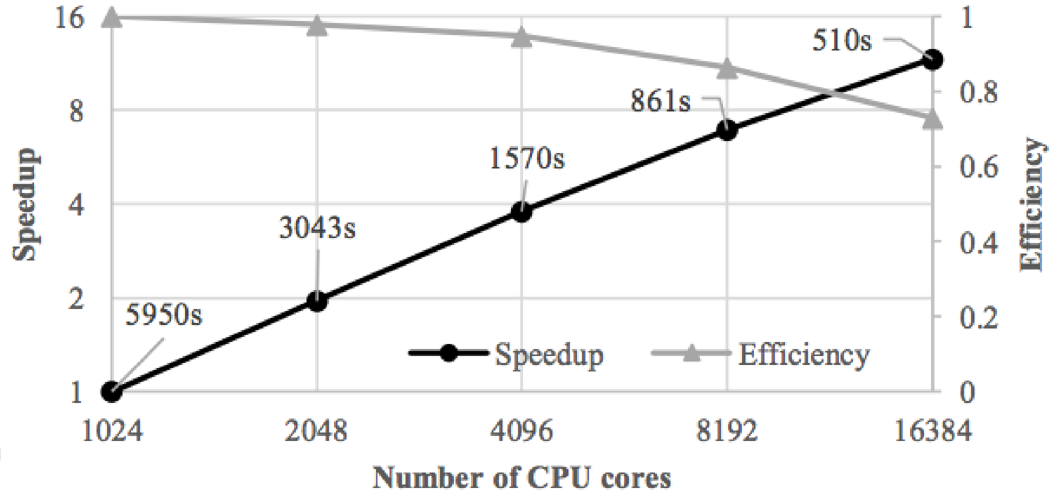
Massively-Parallel Inverse Solution Scheme



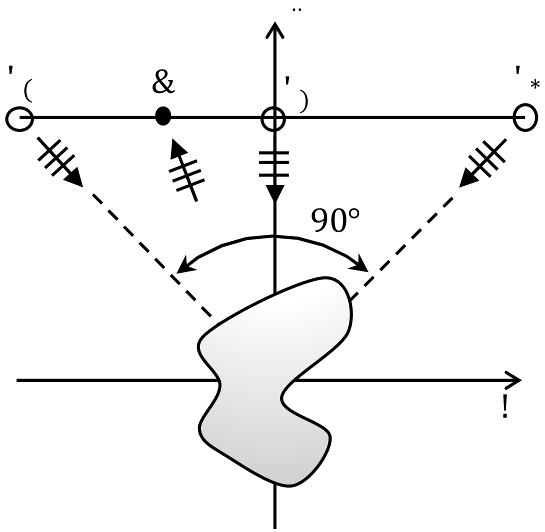
Strong Scaling of Illumination

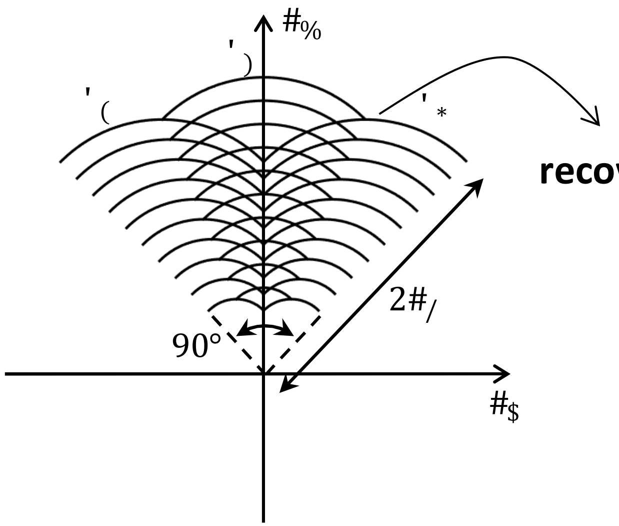


Strong Scaling of MLFMA



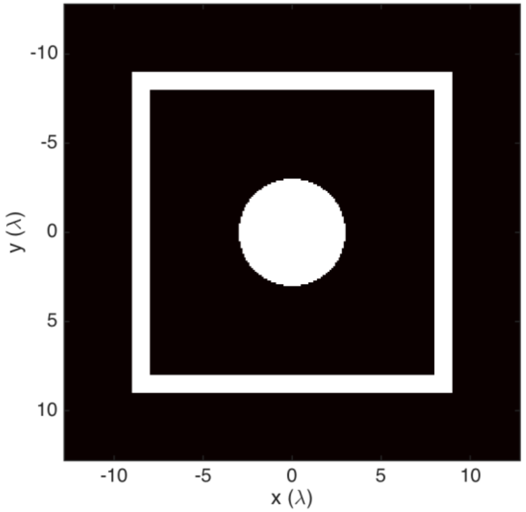
Seeing the "Invisible"



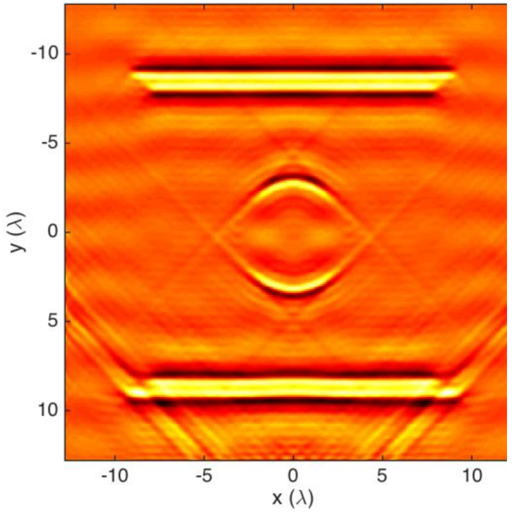


recoverable spectral area with 90° angle sector of illumination/observation

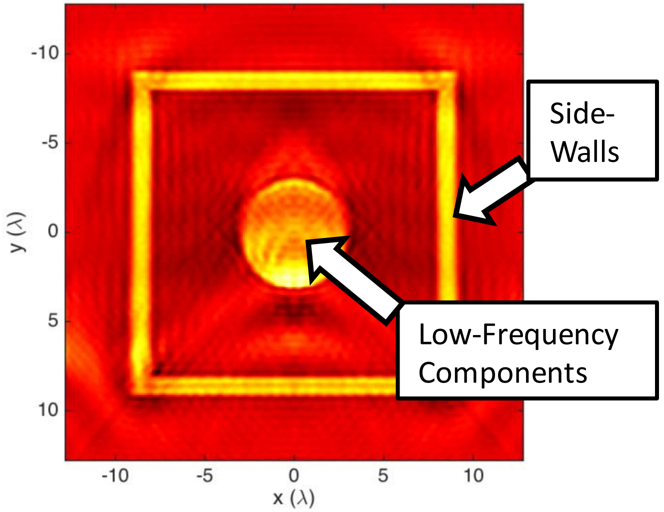
Numerical Phantom



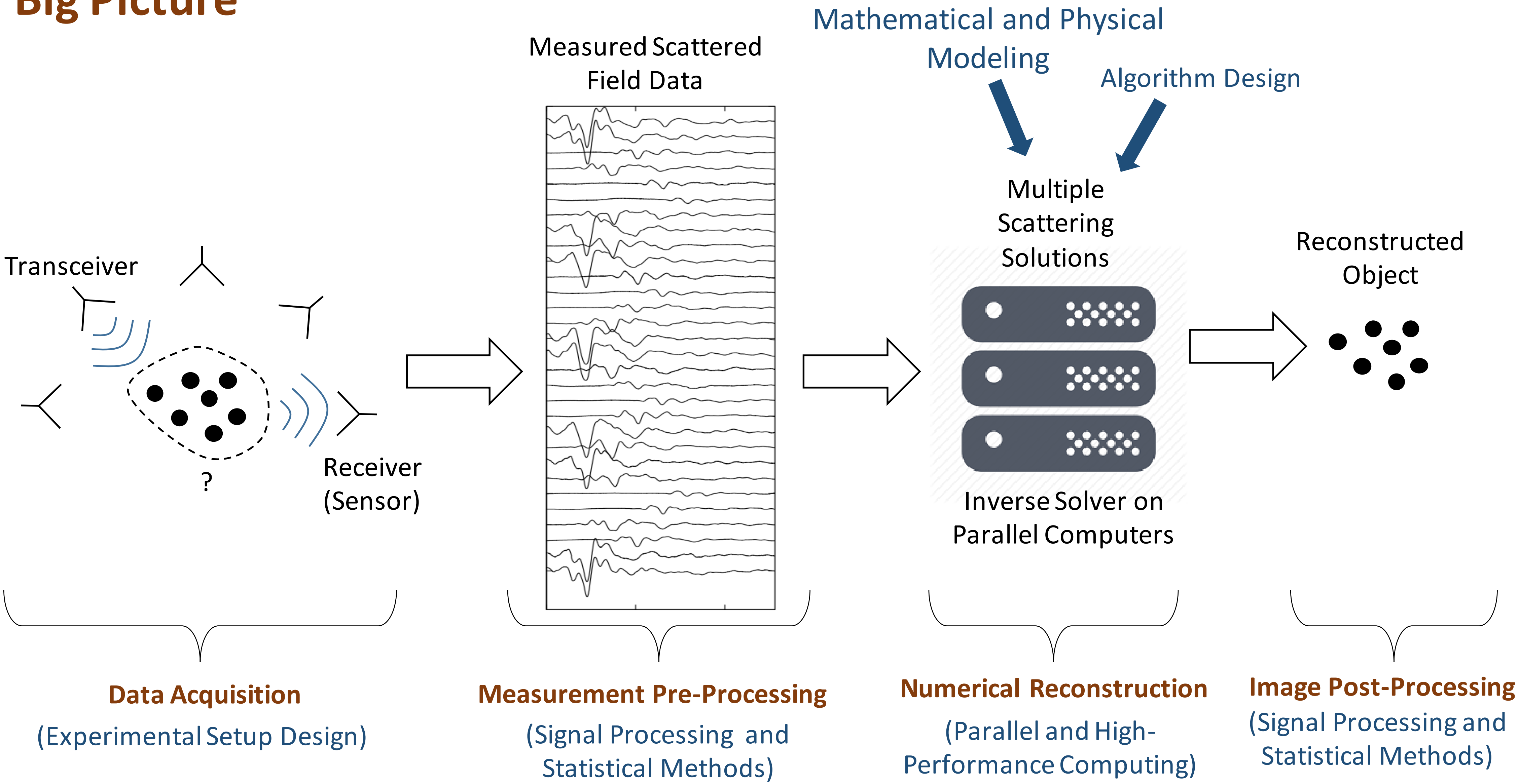
Diffraction-Tomography Imaging



Multiple-Scattering Imaging



The Big Picture



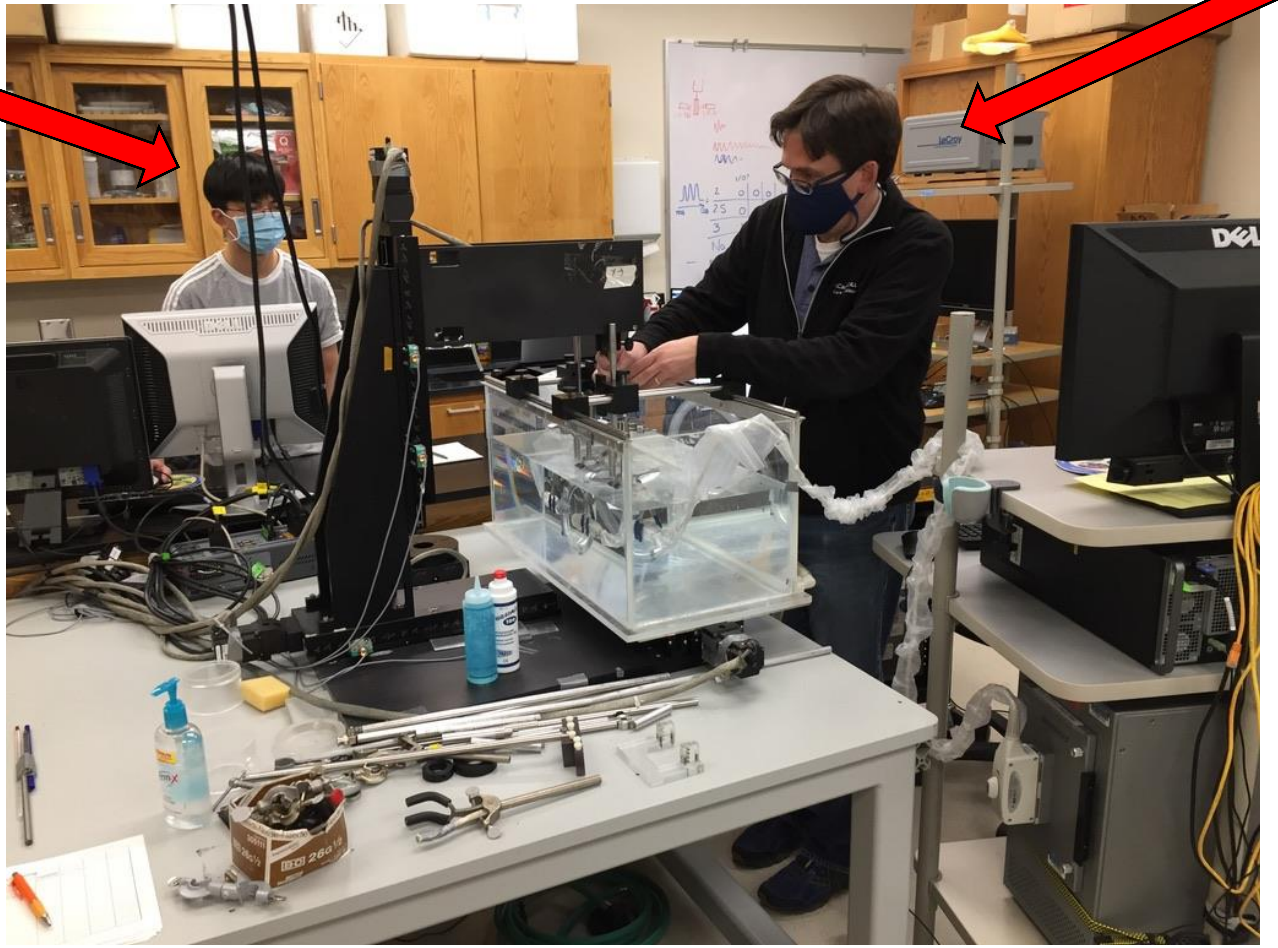
The Dark Side of the Moon:

Calibration

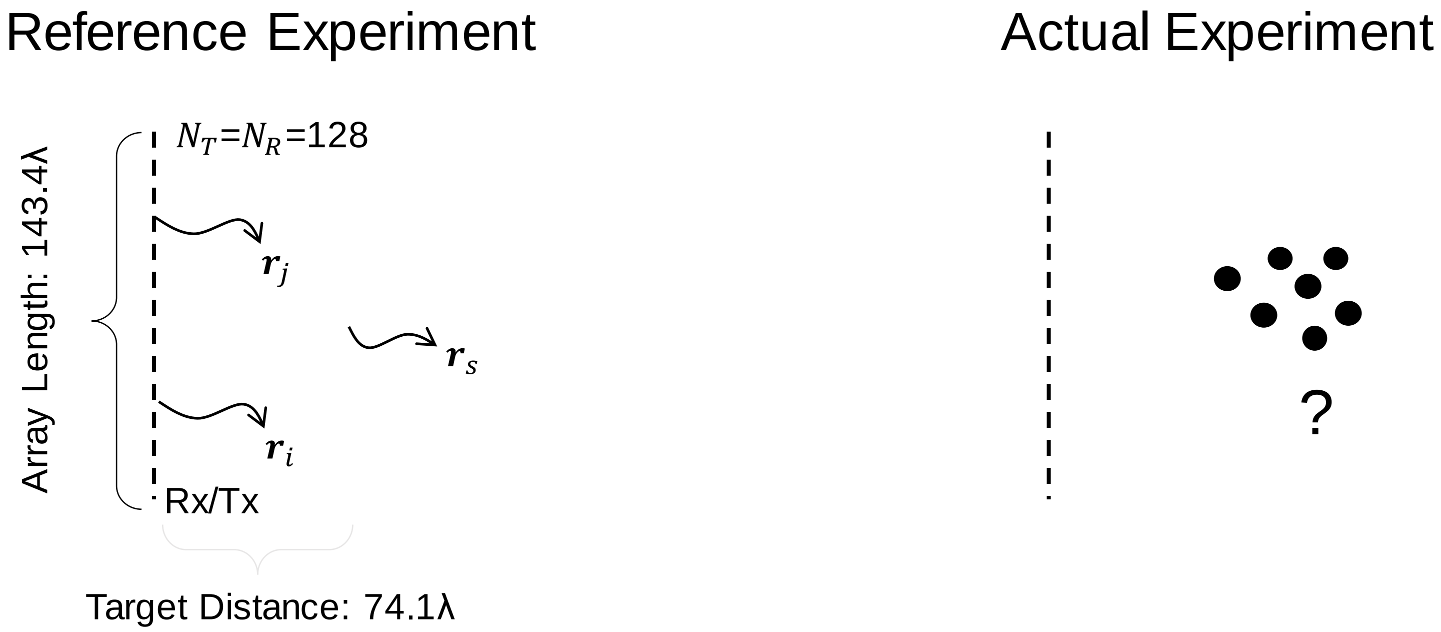
Calibration Step 1: Go down the lab!

Dr. Oelze

PhD Student

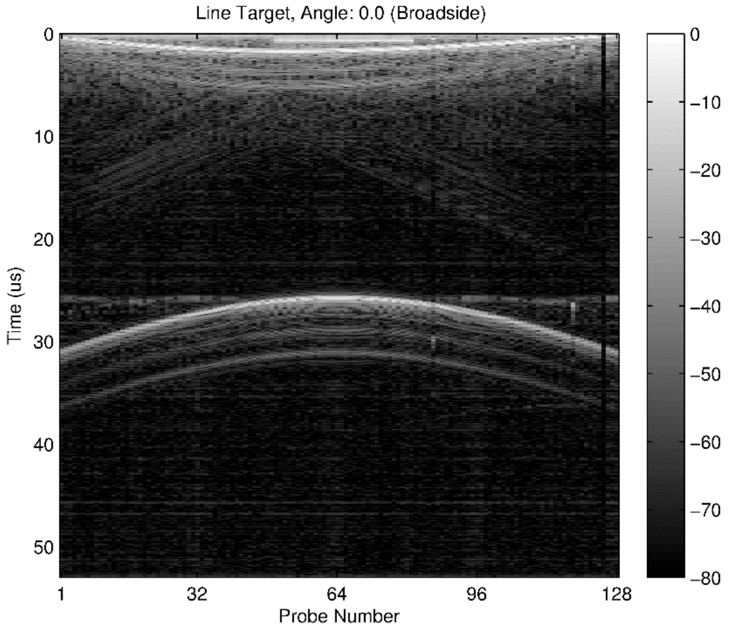


Calibration Step 2: Take Reference Measurements

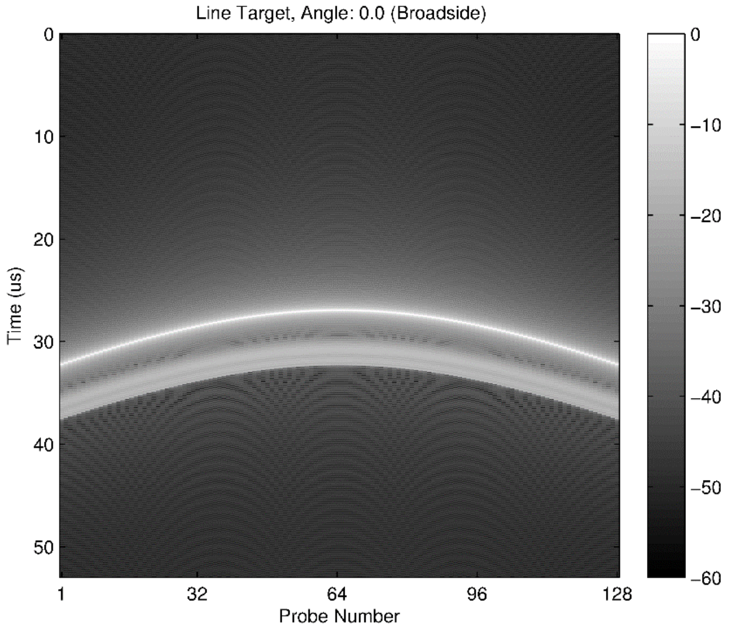


Calibration Step 2: Take Reference Measurements

Measured (For Calibration)

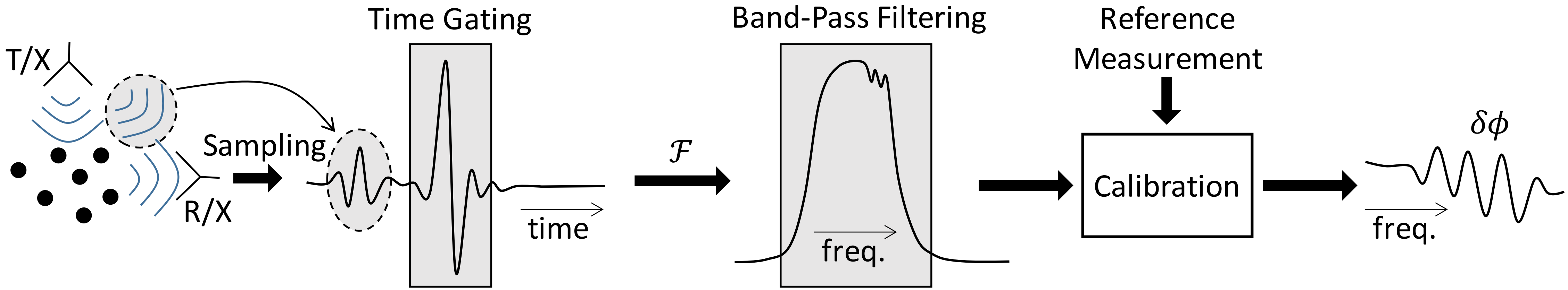


Theoretical (Ideal)



In Time Domain

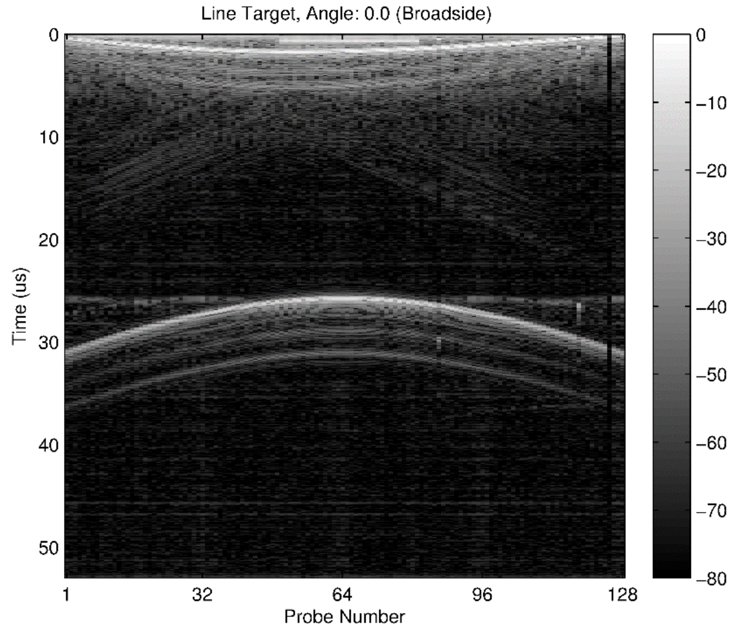
Calibration Step 3: Find Calibration Parameters



Distorted Born Approximation

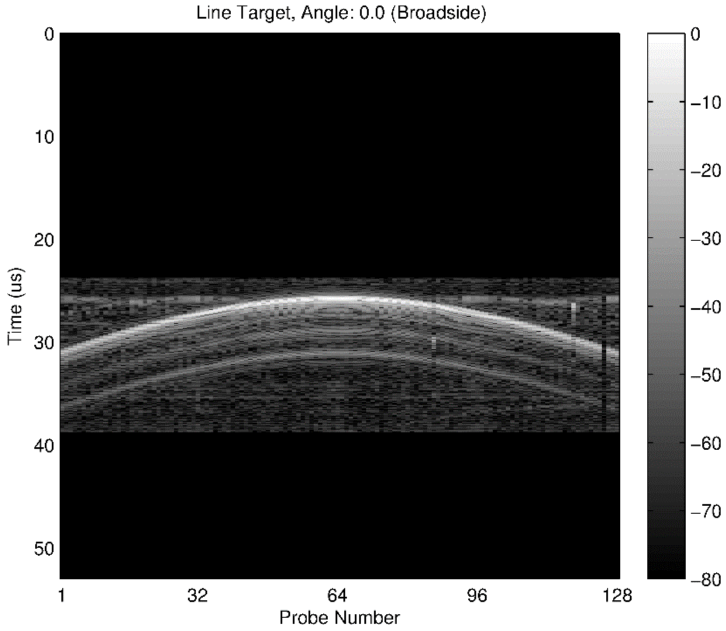
$$\delta\phi \approx \mathcal{G}_b \phi_b \delta\mathcal{O}$$

Measured (For Calibration)

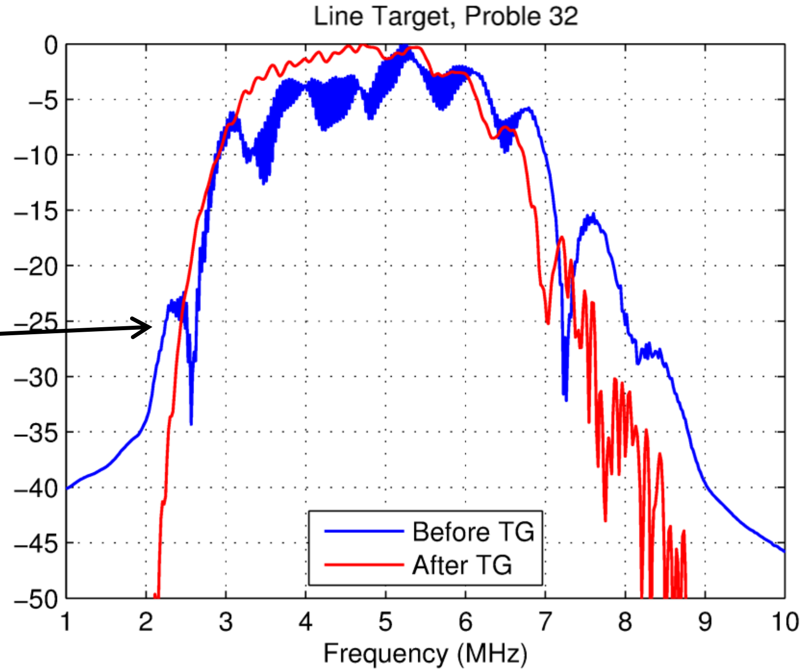


Time
Gating
(Simple)

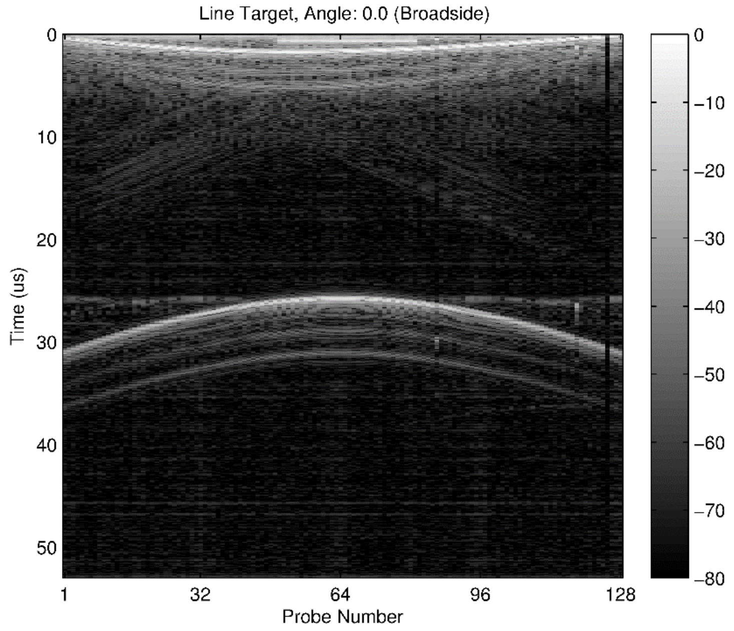
Measured (For Calibration)



Frequency Band:
2.5 – 7.5 MHz



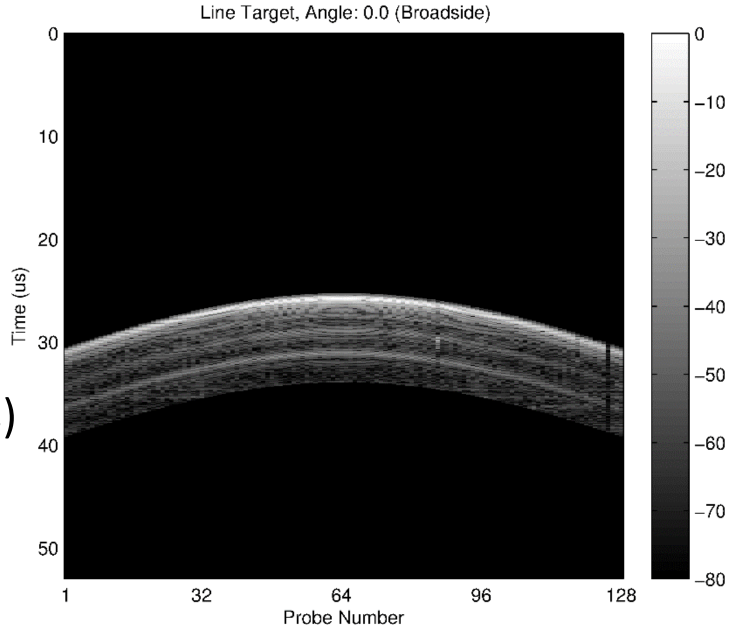
Measured (For Calibration)



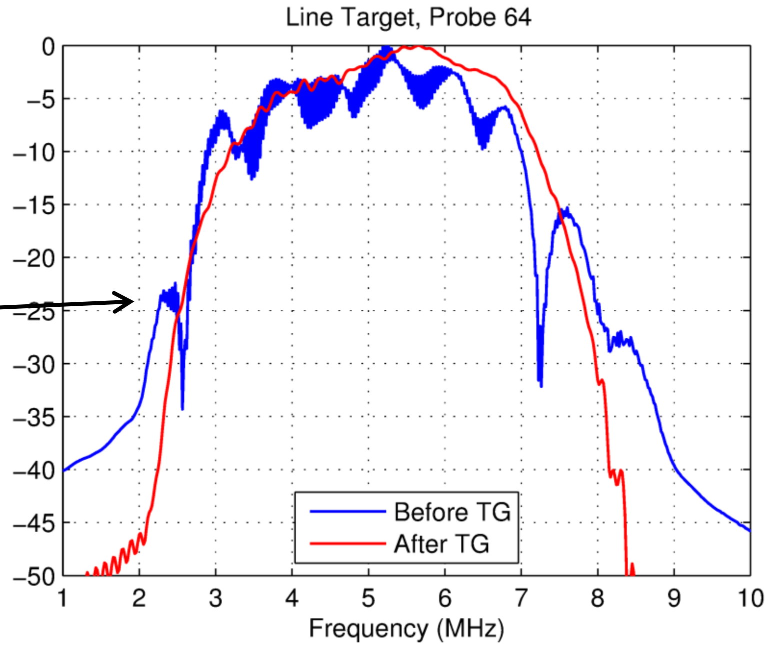
(Clever)
Time
Gating

(By calculating
round-trip times)

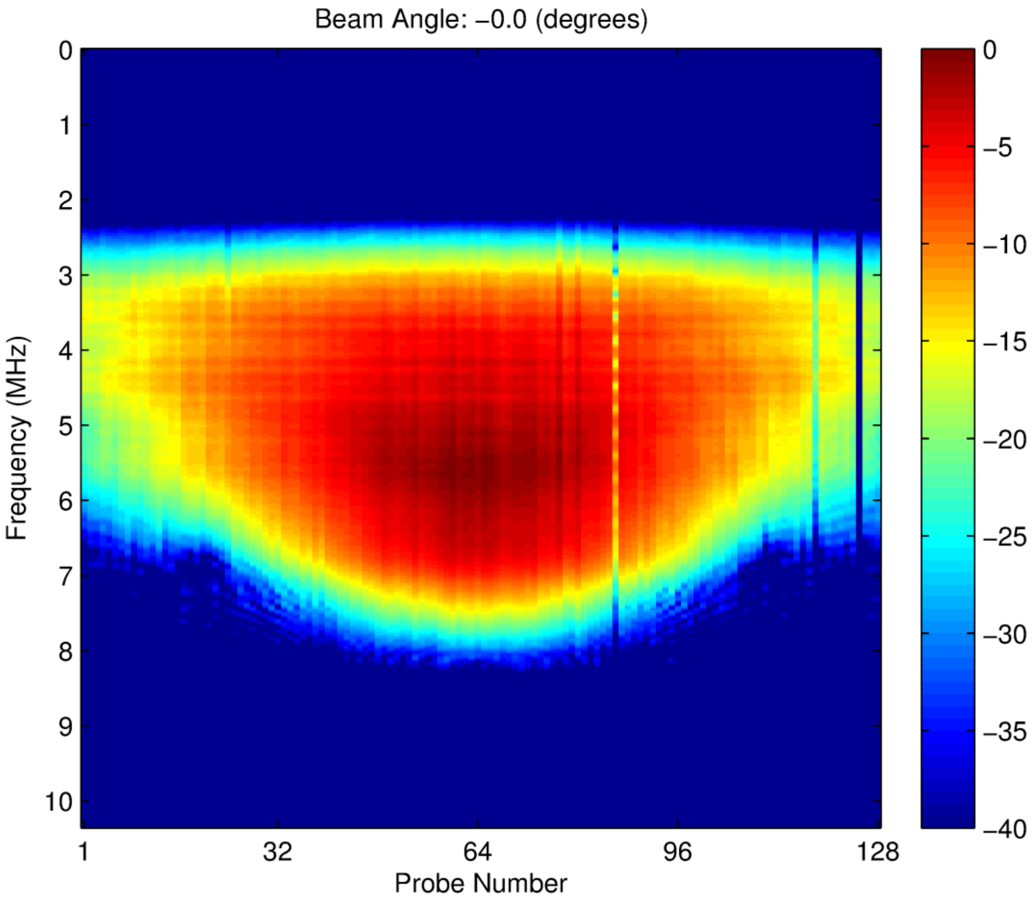
Measured (For Calibration)



Frequency Band:
2.4 – 7.7 MHz



Reference Measurement



Maximum Bandwidth: 2.5 – 8 MHz (in middle probes)
Minimum Bandwidth: 2.5 – 6.5 MHz (in side-probes)

$$M_{R_j,T}(\omega) = r_j(\omega) G_0(\boldsymbol{r}_j, \boldsymbol{r}_s) \overbrace{S(\boldsymbol{r}_s, \boldsymbol{r}_s)}^{1} \sum_{i=1}^{N_T} G_0(\boldsymbol{r}_s, \boldsymbol{r}_i) t_i(\omega)$$

Assumption!

$t_i(\omega) \approx t(\omega)$

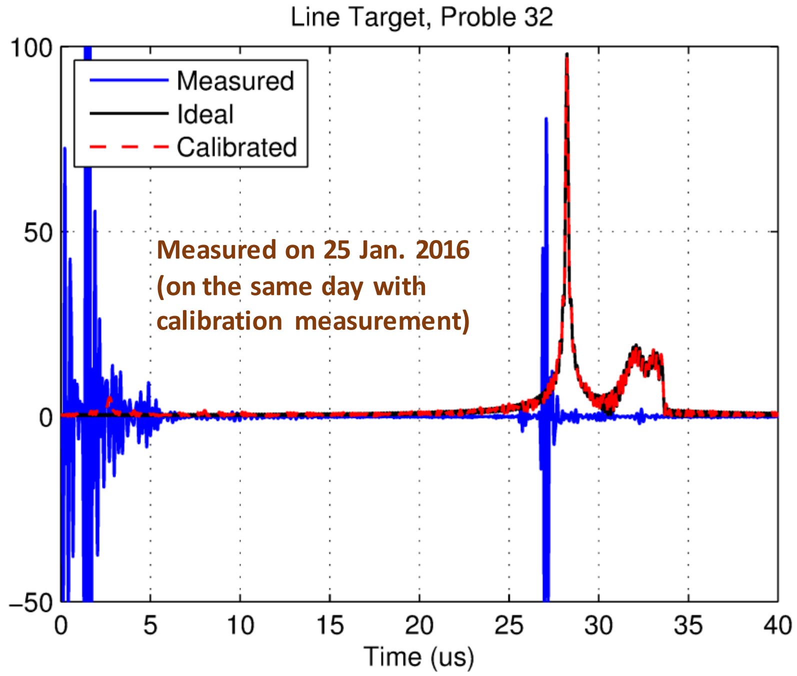
$$M_{R_j,T}(\omega) = r_j(\omega) G_0(\boldsymbol{r}_j, \boldsymbol{r}_s) t(\omega) \sum_{i=1}^{N_T} G_0(\boldsymbol{r}_s, \boldsymbol{r}_i)$$

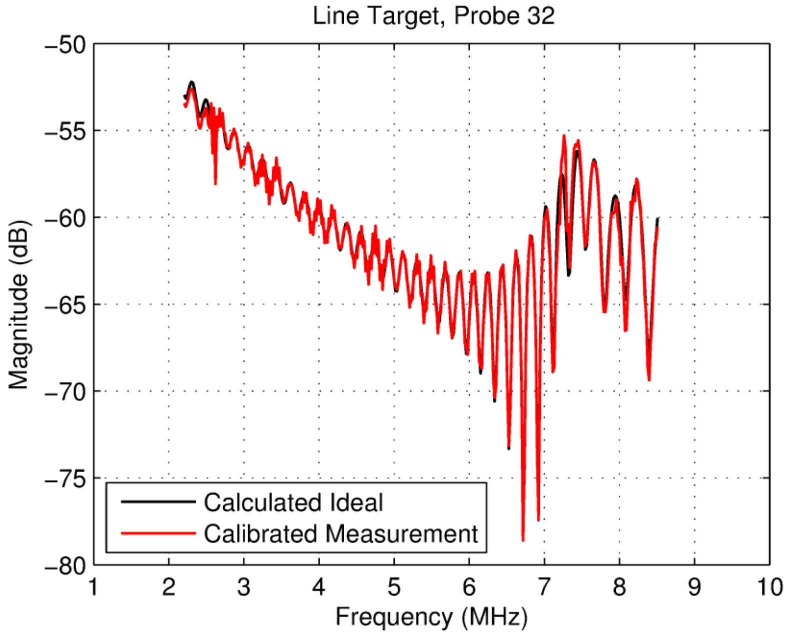
$$M_{R_j,T}(\omega) = r_j(\omega) t(\omega) G_0(\boldsymbol{r}_j, \boldsymbol{r}_s) \sum_{i=1}^{N_T} G_0(\boldsymbol{r}_s, \boldsymbol{r}_i)$$

$$\underbrace{r_j(\omega) t(\omega)}_{\text{Weights}} = \frac{M_{R_j,T}(\omega)}{G_0(\boldsymbol{r}_j, \boldsymbol{r}_s) \sum_{i=1}^{N_T} G_0(\boldsymbol{r}_s, \boldsymbol{r}_i)}$$

Measured

Calculated (Ideal)

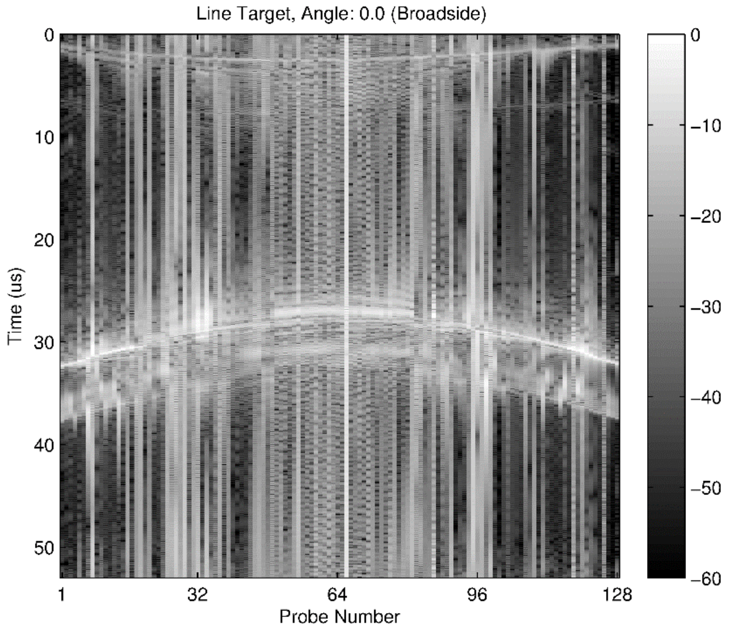


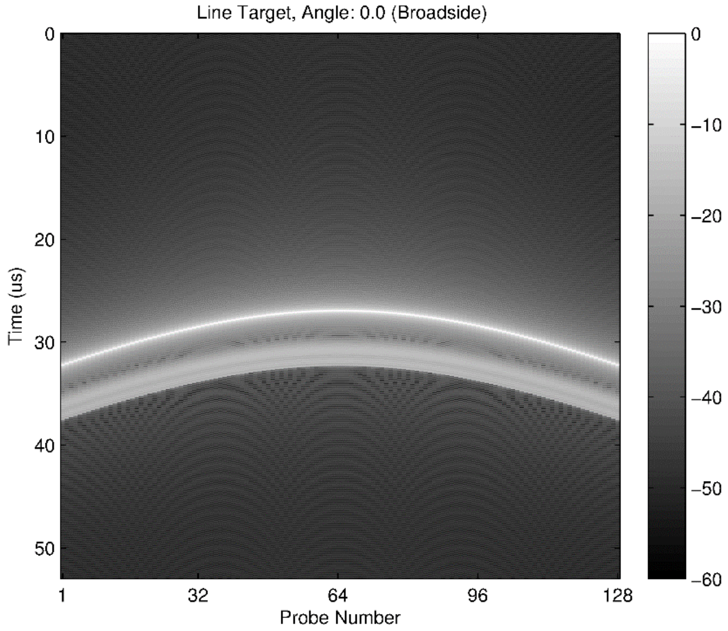


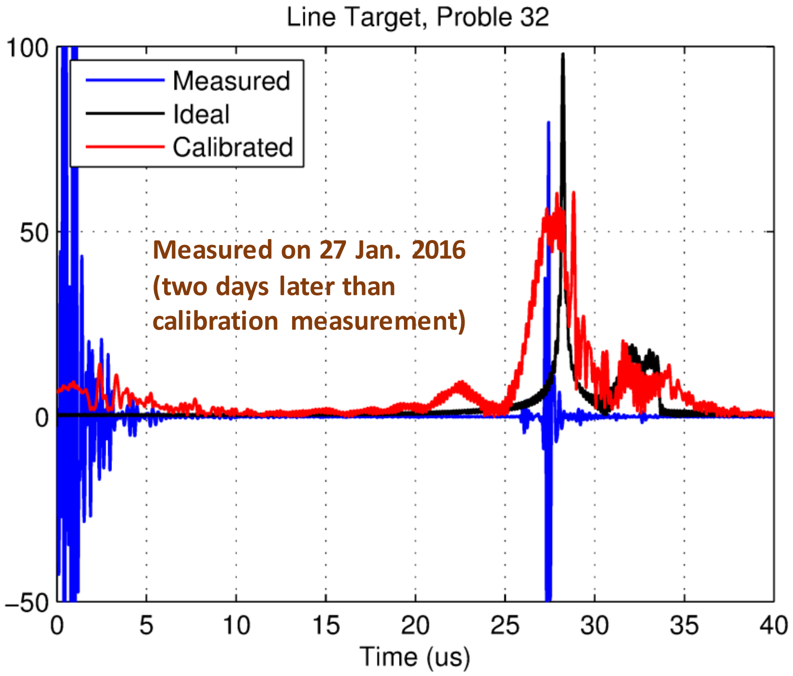
Measured (Calibrated)

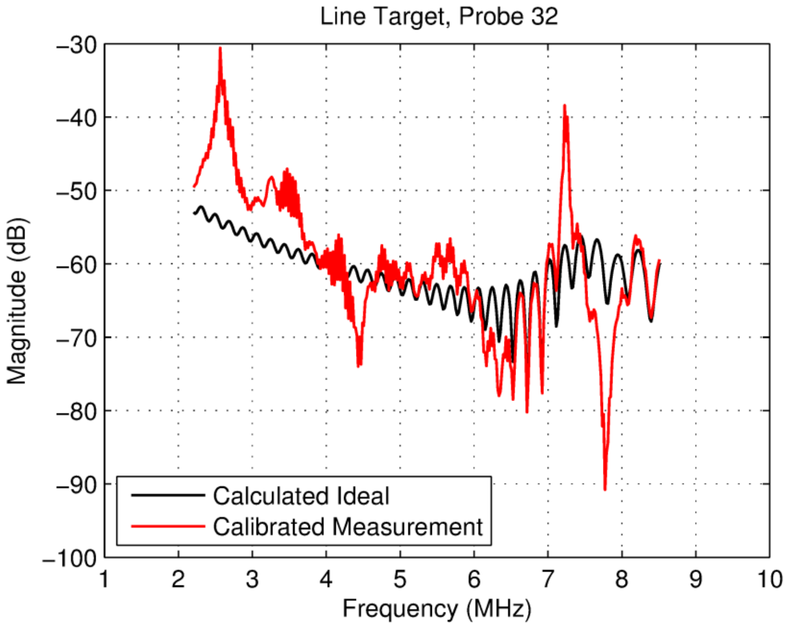
Another meas. than what we used for calib.

Theoretical



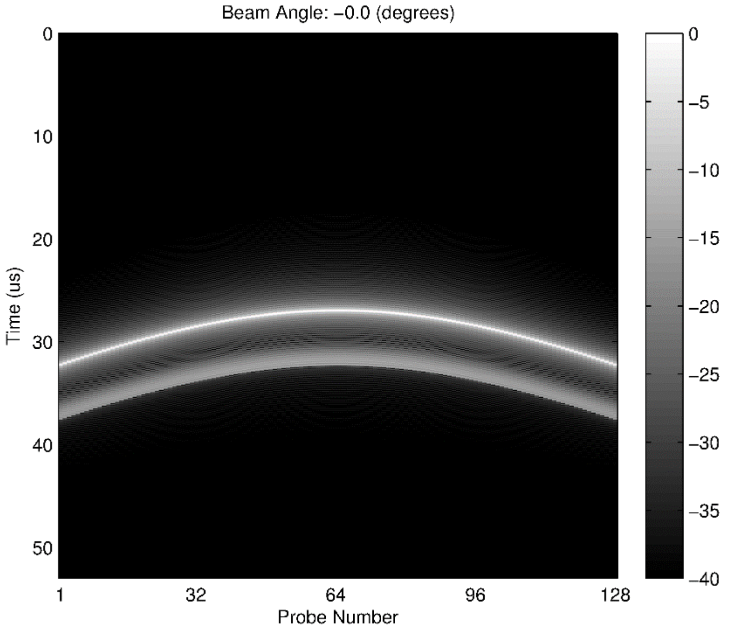






Bandwidth 2.5 – 6.5 MHz

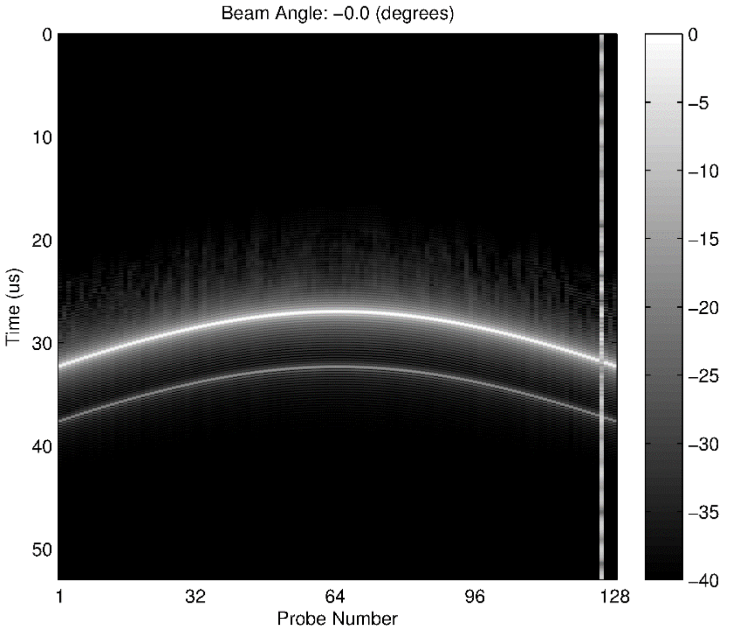
Theoretical



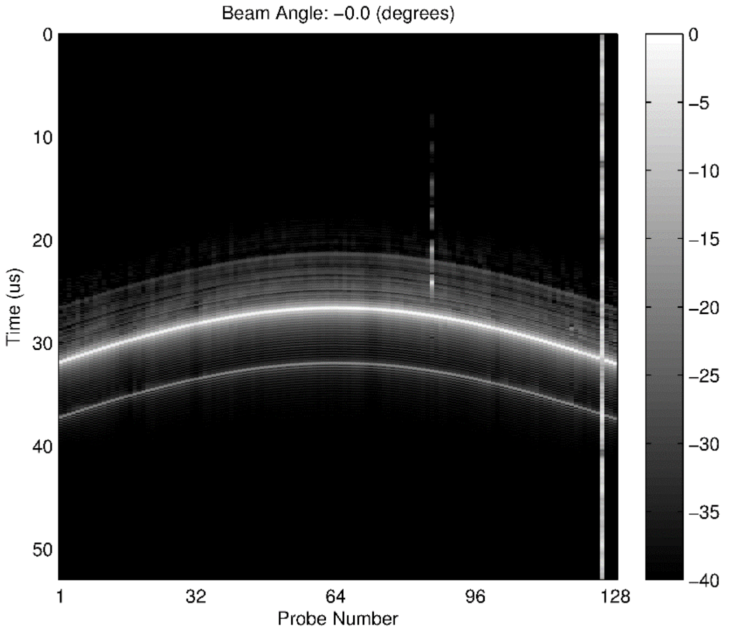
Measured on the same day with the ref. measurement

Measured two days after the ref. measurement

Measured (Calibrated)



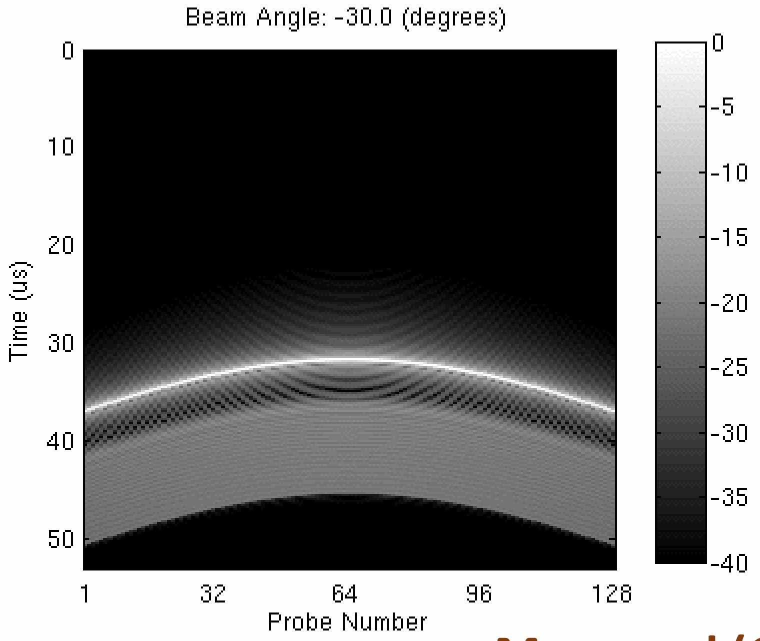
Measured (Calibrated)



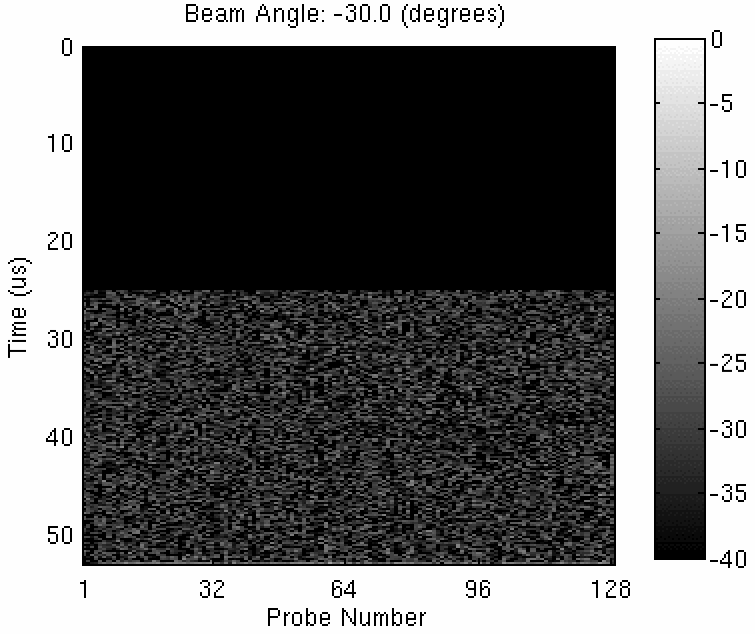
Bandwidth 2.5 – 6.5 MHz

Complex Mag.

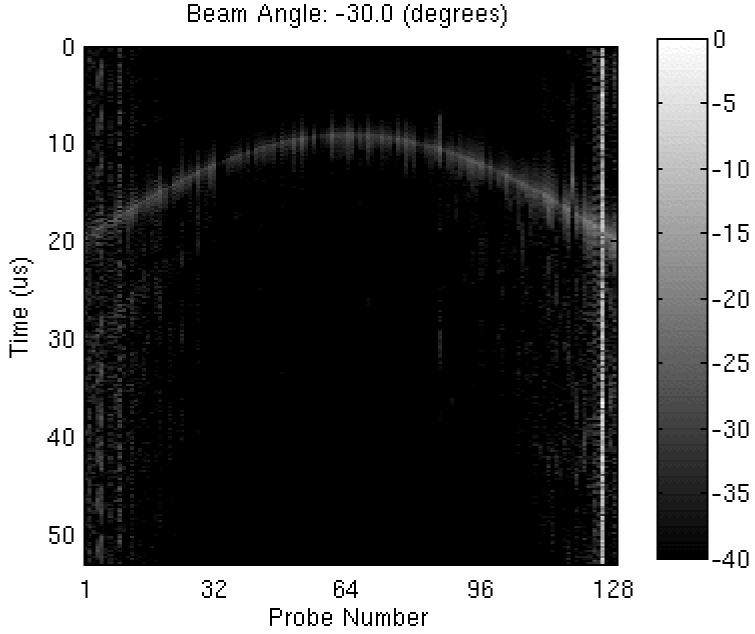
Theoretical



Measured

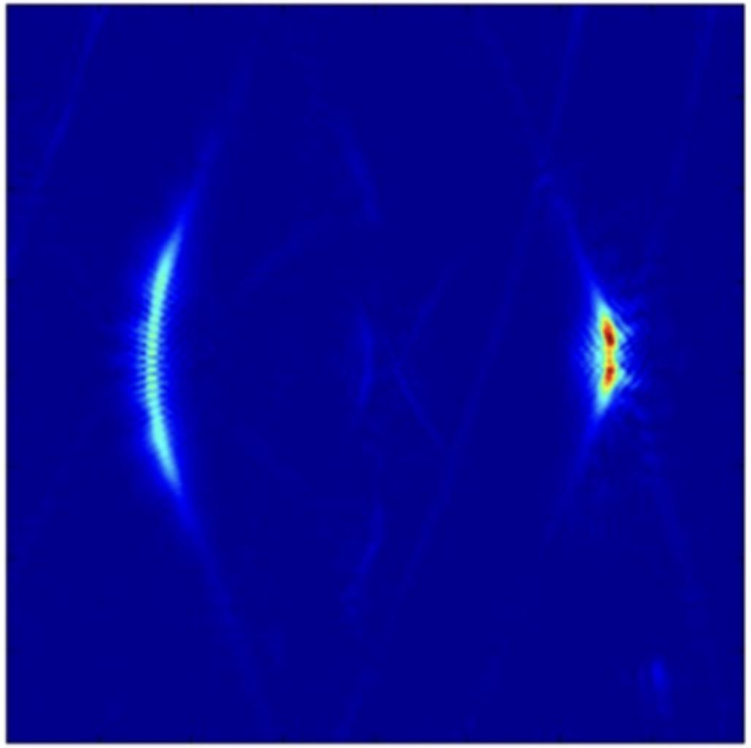


Measured (Calibrated)

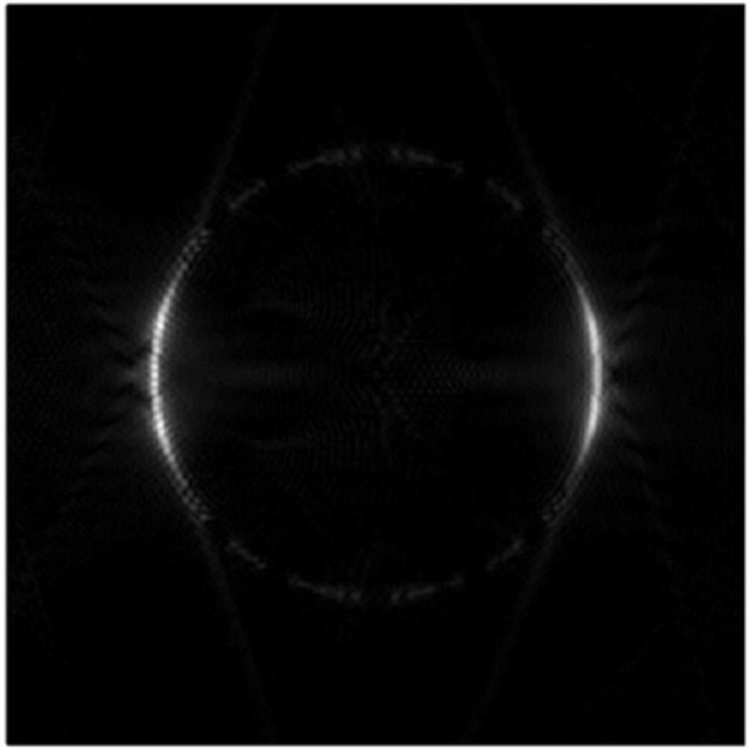


Calibration Step 4: Run the Numerical Solver!

Real Scatterer



Numerical Scatterer

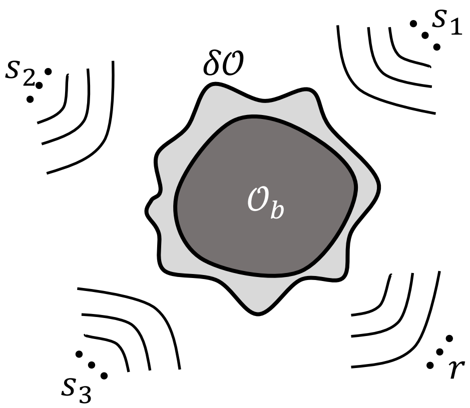


Large-Scale Inverse Multiple-Scattering Imaging on GPU Supercomputers with Real Data

Mert Hidayetoğlu
Stanford University

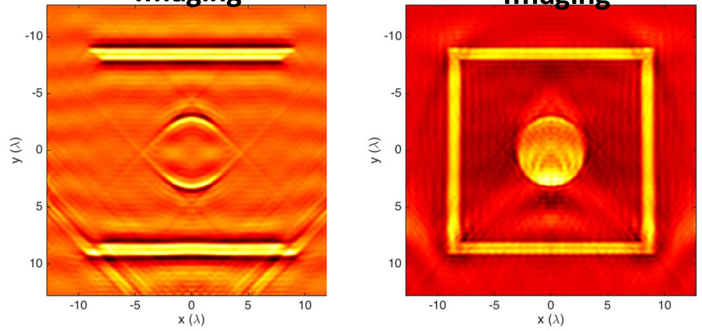
In courtesy of Weng Cho Chew, Michael Oelze, and Wen-mei Hwu

merth@stanford.edu

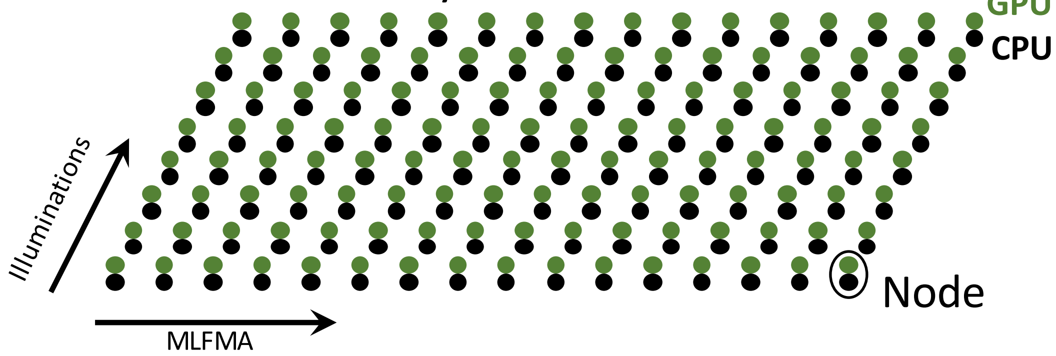


Diffraction-Tomography Imaging

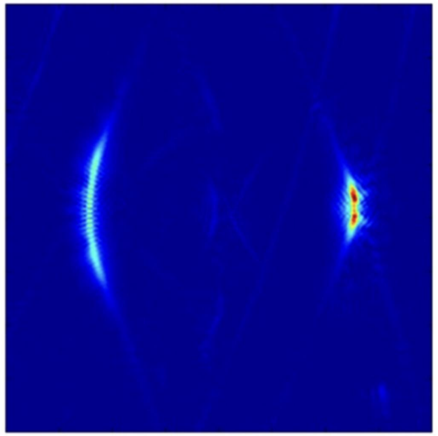
Multiple-Scattering Imaging



Massively-Parallel Inverse Solution Scheme



Real Scatterer



Numerical Scatterer