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Provable and Robust Wavefront Sensing via Self-Reference Interferometry

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TL;DR Self-interference of wavefront with spatially shifted copies (with co-prime shift) and the pairwise phase differences integrated along a connected graph enable phase retrieval in a single, non-iterative pass, with provable robustness guarantees.

Background

Phase matters

- Light is a wave – with intensity and phase
- Phase carries wavefront information – can enable adaptive optics, aberration correction, and imaging through scattering media.

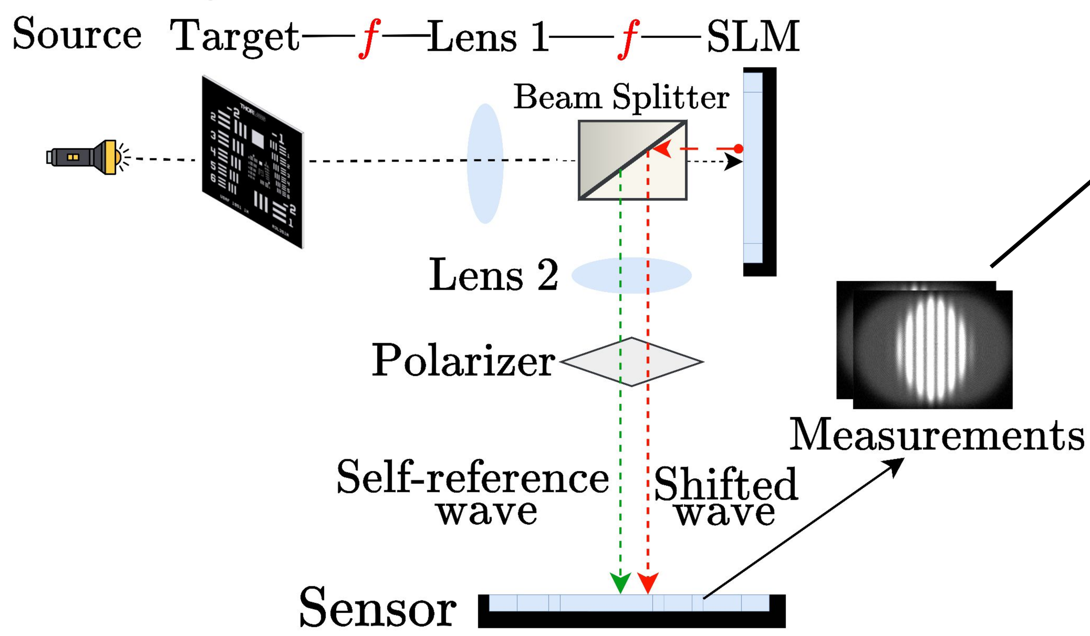
Phase is missing

- Image sensors record only intensity
- Phase retrieval from intensity is a highly non-convex and (slow) iterative process

Our goal – provide an analytical, non-iterative, provably robust solution for phase retrieval.

Approach

1. Self-reference interferometry. Interfere incoming wave with a spatially shifted copy



2. Forward Model. Spatial and phase shifts

$$\mathbf{y}_{k,q} = \left|\mathbf{x} + \underbrace{e^{j\varphi_q}}_{\text{Phase shifts}}\underbrace{\mathcal{S}_{\Delta_k}(\mathbf{x})}_{\text{Spatial shifts}}\right|^2 + \eta_{k,q}$$

$\varphi_q \in \{0, \pi/2, \pi, 3\pi/2\}$

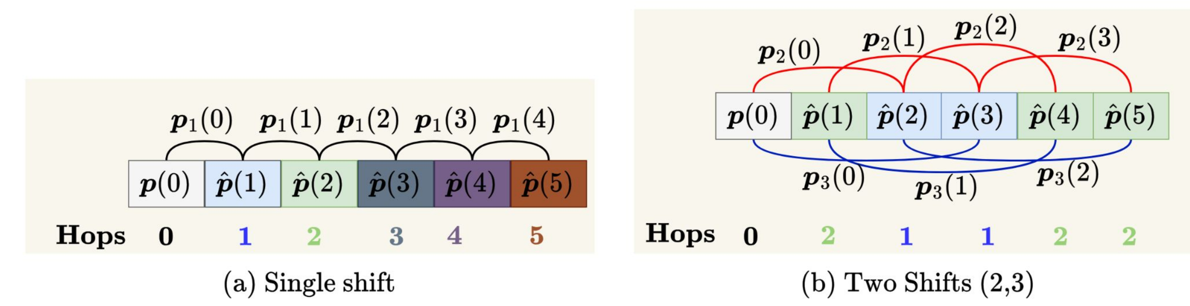
- Phasor differences can be obtained as

$$\mathbf{p}_k = \frac{\sum_q \mathbf{y}_{k,q} e^{-j\varphi_q}}{\left|\sum_q \mathbf{y}_{k,q} e^{-j\varphi_q}\right|} \approx e^{j(\mathcal{S}_{\Delta_k}(\phi)-\phi)}$$

- $\mathbf{p}_k(i)$ encodes phase difference between pixel i and $i+\Delta_k$

3. Recovery on a Graph.

- Pixels ⇒ nodes; Phasor differences ⇒ edges.
- Fix a reference $\mathbf{p}(0) = 1$ and estimate $\widehat{\mathbf{p}}(i+\Delta_k) = \widehat{\mathbf{p}}(i)\,\mathbf{p}_k(i)$



- Error **grows** with **propagation distance** from the reference.
  - **Single shift**: long propagation paths
  - **Two shifts:** fewer hops and less noise accumulation.

Challenges

Common approaches have the following limitations

- Phase-shifting interferometry (PSI): needs a stable external reference beam, which can be bulky and vibration-sensitive
- Self-reference / Point-diffraction: The self-reference is very dim ⇒ low SNR
- Slope-based sensors (Shack–Hartmann, pyramid): limited resolution, noise-sensitive
- Iterative phase retrieval (Gerchberg-Saxton, deep priors): non-convex, slow, limited guarantees on convergence and accuracy

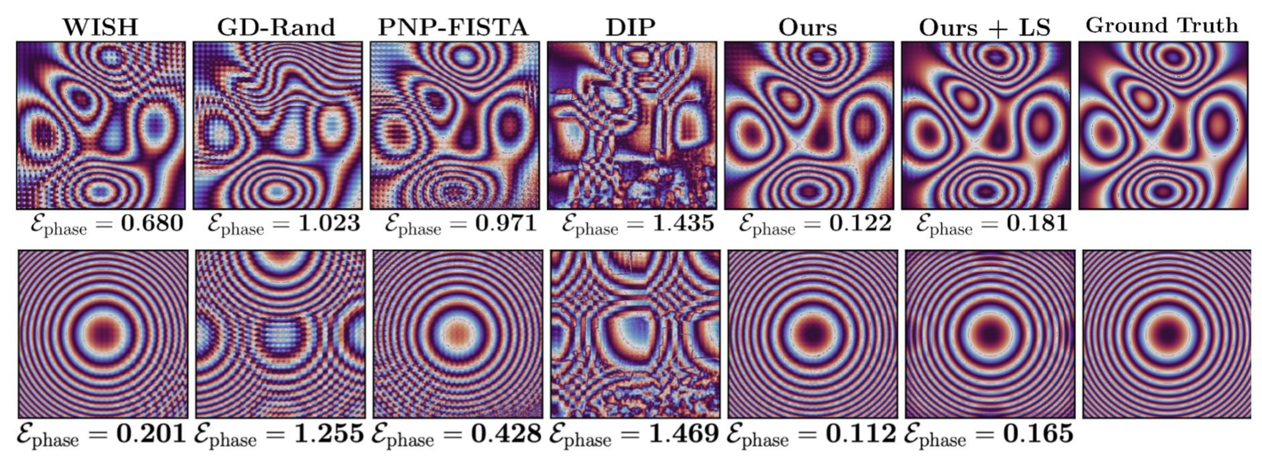
Simulated Experiments: Phase Recovery

Simulated scenes, quadratic and smooth phase, realistic sensor noise, compared against multiple baselines

(e.g., 16 or 32 measurements with 2 or 4 spatial shifts in horizontal/vertical directions and 4 phase shifts).

Our method

- achieves best or second-best accuracy across phase type and measurement count.
- recovers phase from as few as 8 measurements and runs 8× faster.

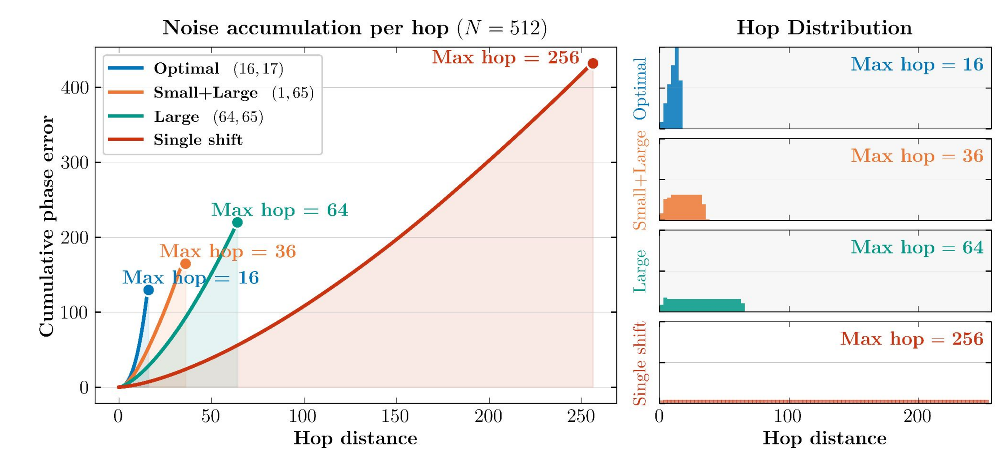


Method \ #Meas.	Quadratic phase		Random phase		Smooth phase (peaks)	
	16	32	16	32	16	32
GD-Rand	0.695 ± 0.365	0.470 ± 0.434	**0.138 ± 0.148**	**0.079 ± 0.152**	0.791 ± 0.361	0.570 ± 0.404
GD-Spec	0.737 ± 0.400	0.400 ± 0.432	0.691 ± 0.367	0.449 ± 0.440	0.686 ± 0.397	0.371 ± 0.374
WISH	0.852 ± 0.299	0.423 ± 0.366	0.854 ± 0.320	0.453 ± 0.377	0.898 ± 0.330	0.425 ± 0.367
PnP-FISTA	0.669 ± 0.341	0.456 ± 0.304	0.735 ± 0.329	0.425 ± 0.264	0.663 ± 0.341	0.479 ± 0.338
DIP	1.486 ± 0.031	1.491 ± 0.051	1.495 ± 0.037	1.447 ± 0.065	1.442 ± 0.063	1.423 ± 0.081
Ours	**0.158 ± 0.104**	**0.099 ± 0.083**	0.156 ± 0.099	0.094 ± 0.075	**0.155 ± 0.096**	**0.097 ± 0.071**
Ours with LS	0.183 ± 0.082	0.126 ± 0.065	0.158 ± 0.075	0.121 ± 0.055	0.205 ± 0.063	0.159 ± 0.050

Optimal Shifts and Robustness

Question. Which shift pair (s, t) should we pick?

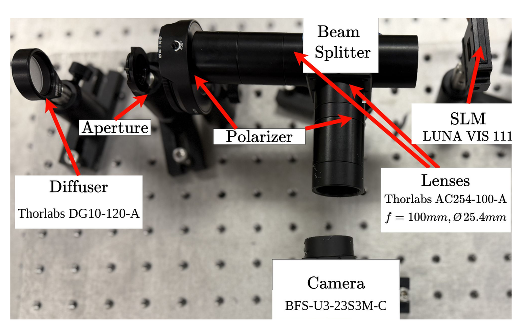
- **Connectivity** is guaranteed with co-prime shifts
- **Optimal pair** $s = \left\lceil\sqrt{\frac{N}{2}}\right\rceil, t = s+1$ minimizes the maximum hop and bounds worst-case error.



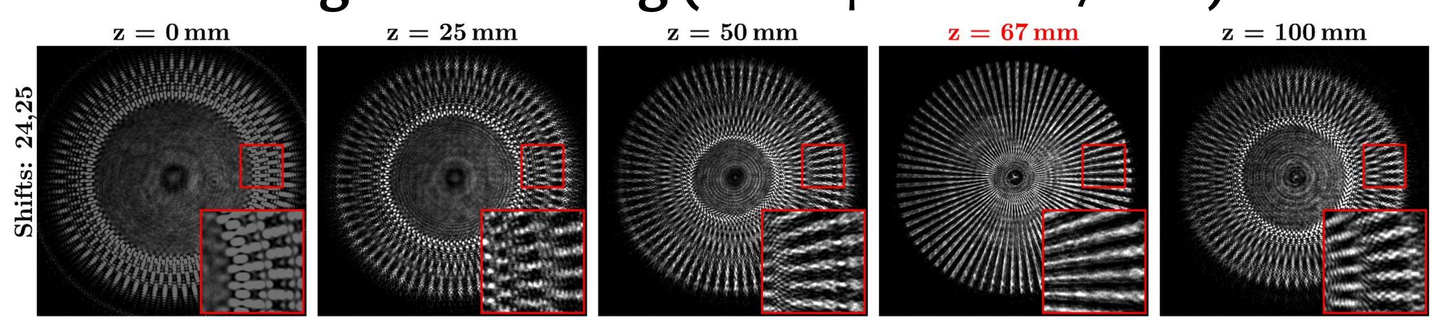
Verification of worst-case error accumulation (1D signal)

Real Hardware Experiments

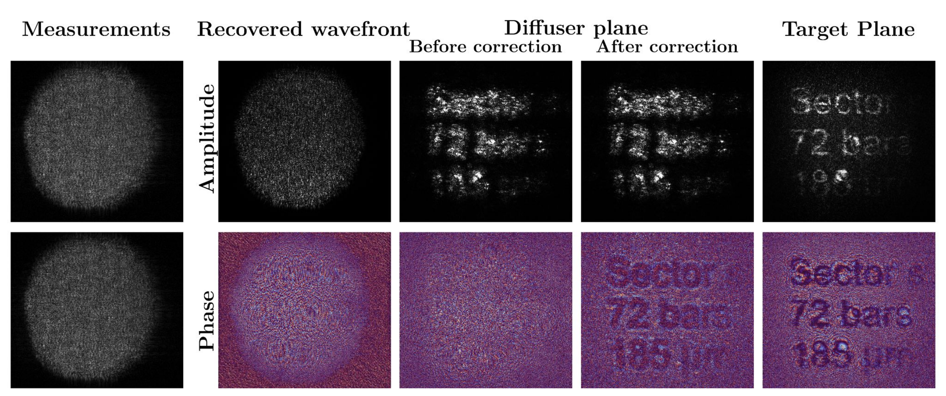
Hardware prototype



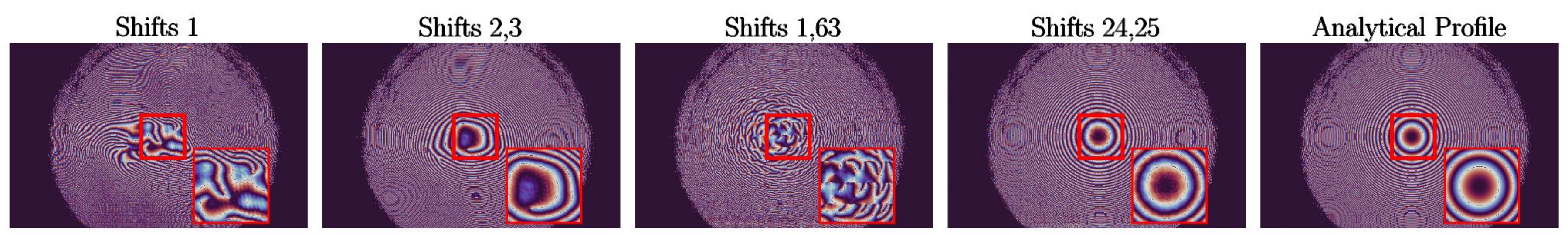
Target refocusing (focus point at 67 mm)



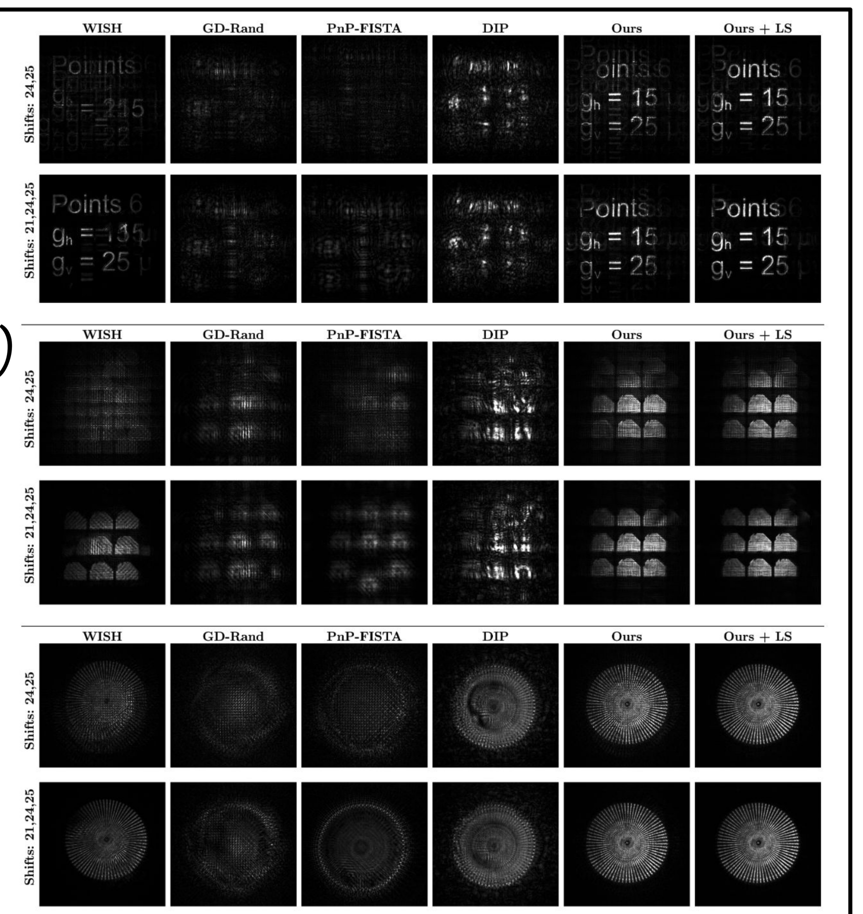
Seeing through a diffuser



Optical profile recovery (biconvex lens f=75 mm)



Qualitative comparison with existing methods *(our method is faster and accurate)*



Conclusion

- A simple, robust method for wavefront sensing without an external reference beam.
- Analytical, non-iterative phase recovery via graph propagation with provable guarantees.
- Further improvements possible by averaging multiple paths and least-squares refinement.
- Validated through simulations and real hardware experiments.

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More info: https://csiplab.github.io/coprime-psi/