Advanced Imaging Methods Using Coded Aperture Digital Holography

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Holography meets Advanced Manufacturing

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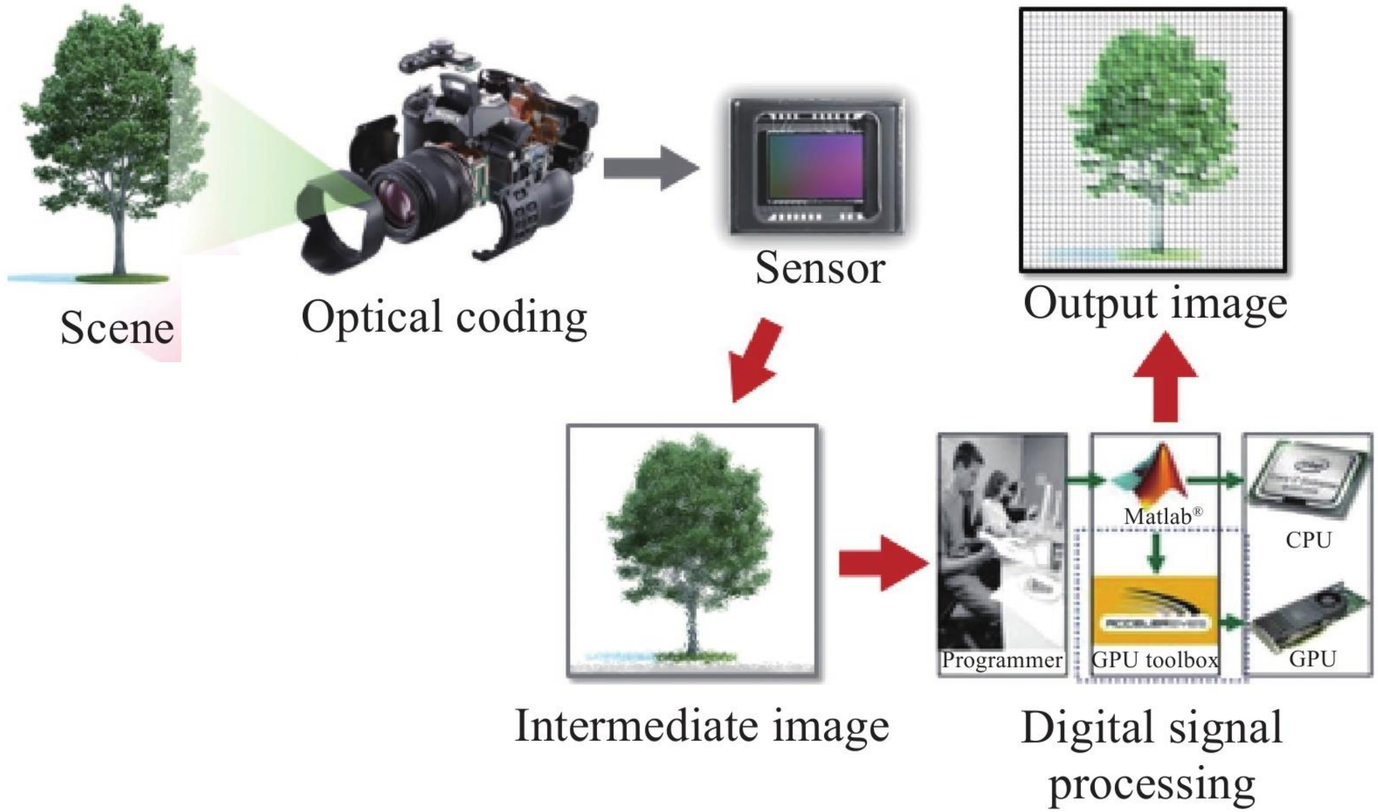
Introduction

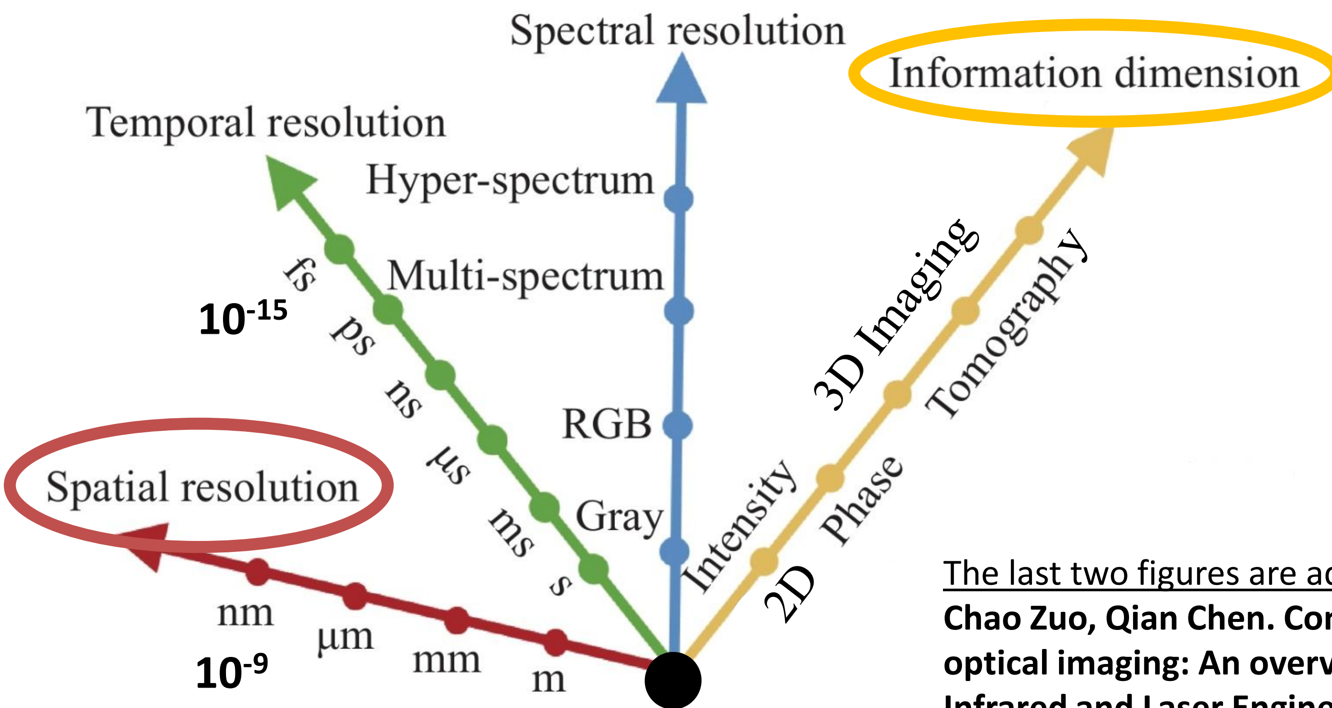
Coded Aperture Digital Holography is part of Computational Imaging



The advanced model of computational imaging

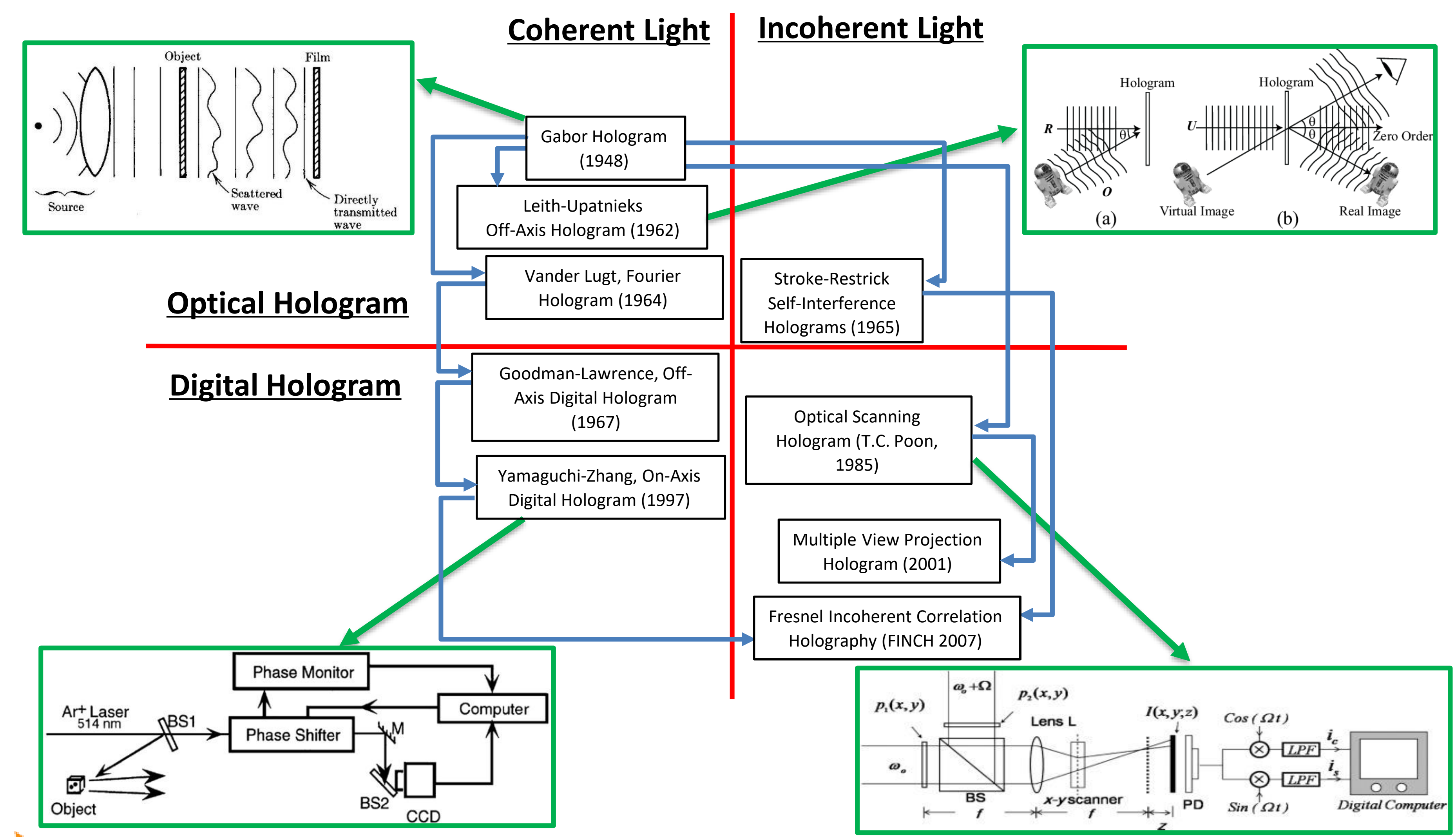
Computational Imaging

Goals for the development of optical imaging technology



The last two figures are adapted from:
Chao Zuo, Qian Chen. Computational optical imaging: An overview[J]. Infrared and Laser Engineering, 2022, 51(2): 20220110 (in Chinese)

Historical Introduction of Holography for Imaging



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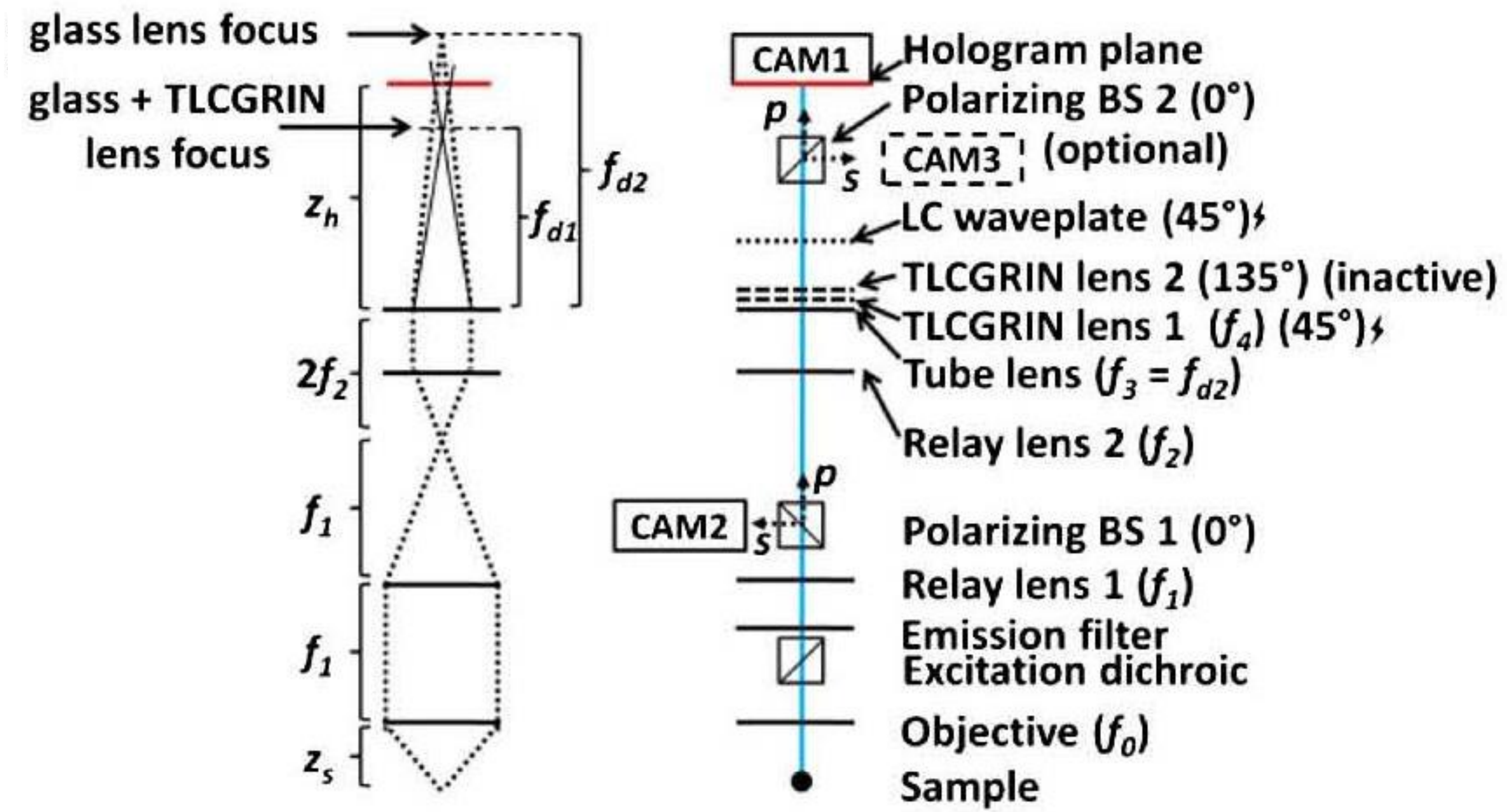
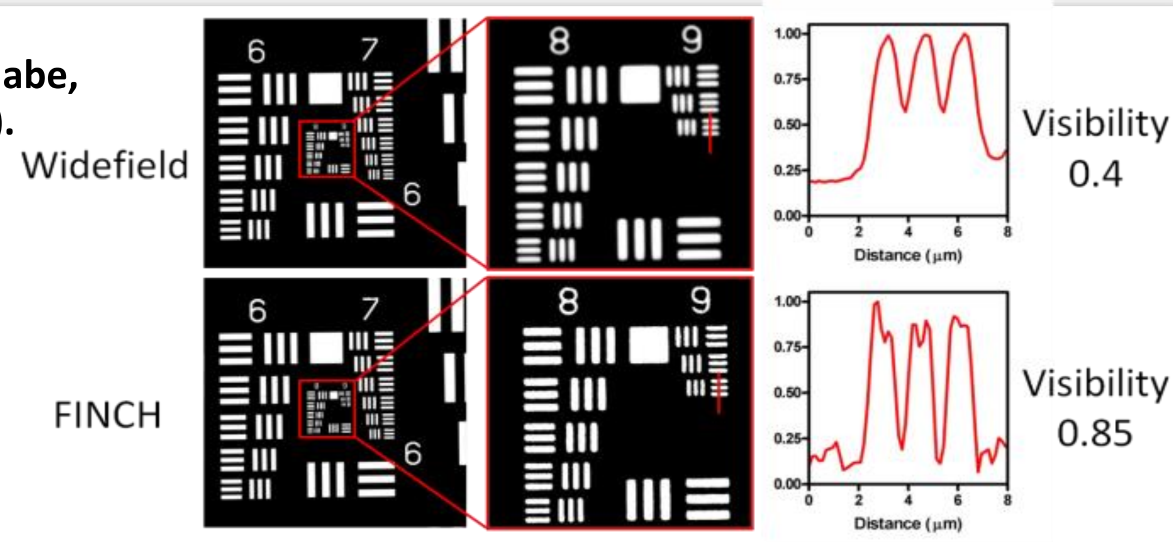
FINCH Fluorescence Microscope (2013)

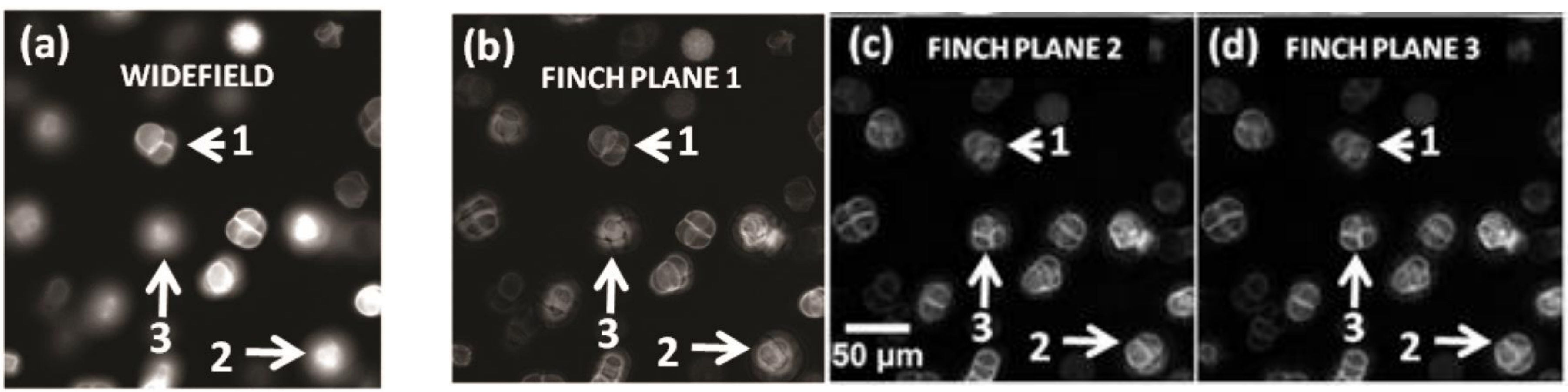


FINCH fluorescence microscope

G. Brooker, N. Siegel, J. Rosen, N. Hashimoto, M. Kurihara, and A. Tanabe, *Optics Letters* 38, 5264–5267 (2013).

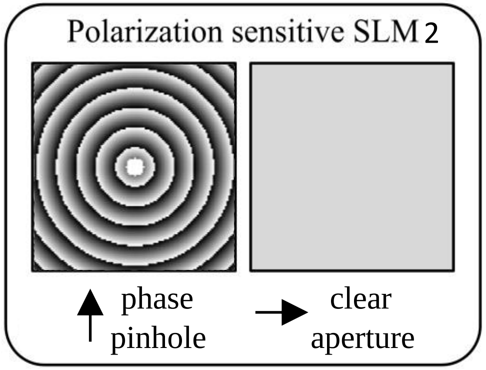


(a) Widefield and (b)–(d) reconstructed FINCH images of pollen grains captured using a 20× (0.75 NA) objective, showing the ability of FINCH to refocus at depths that were out of focus under widefield conditions.

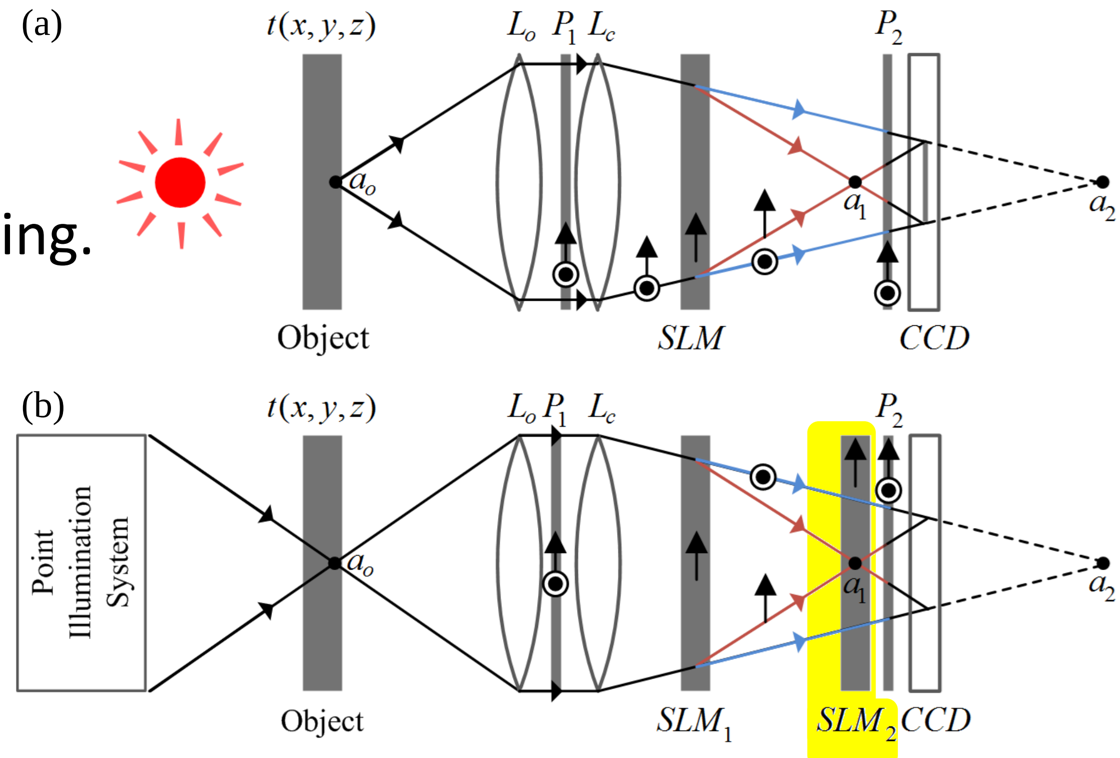


FINCH fluorescence microscope

- Goal: Achieve optical sectioning in FINCH.
  - 'Phase pinhole':
- Added cost: target scanning.



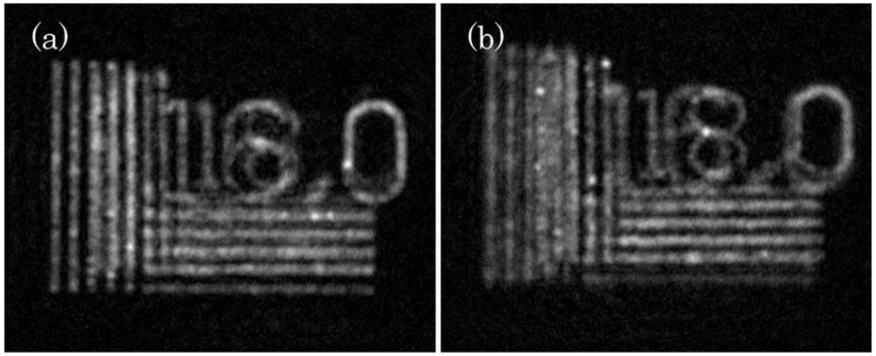
R. Kelner, B. Katz, and J. Rosen, "Optical sectioning using a digital Fresnel incoherent-holography-based confocal imaging system," Optica 1, 70-74 (2014).



Schematics of FINCH recorders: (a) a dual lens FINCH system; (b) a confocal FINCH system. L_o, objective lens; L_c, converging lens; SLM_1 and SLM_2, spatial light modulators; P_1 and P_2, polarizers; *CCD*, charge-coupled device.

Confocal Fresnel Incoherent Correlation Holography
Results (wide-field illumination)

FINCH



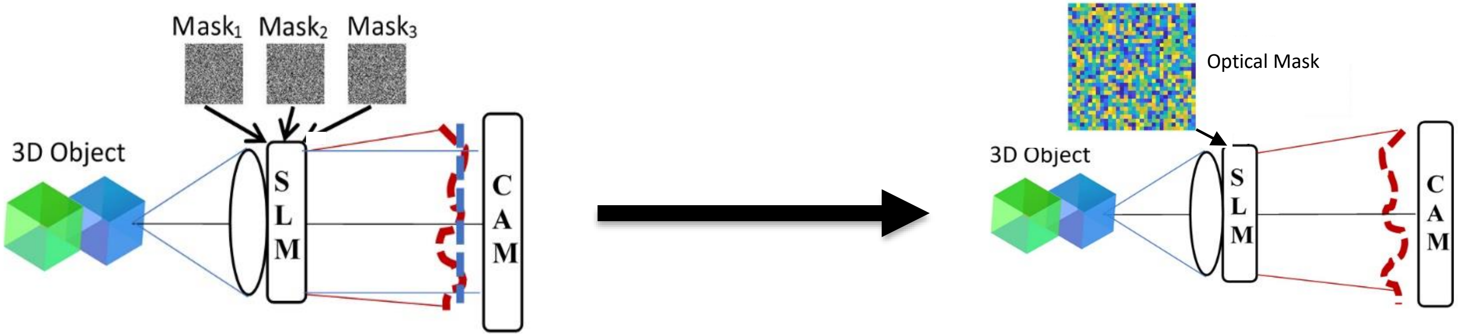
FINCH

R. Kelner, B. Katz, and J. Rosen, "Optical sectioning using a digital Fresnel incoherent-holography-based confocal imaging system," Optica 1, 70-74 (2014).

I-COACH (2017)

A. Vijayakumar, Y. Kashter, R. Kelner, and J. Rosen, "Coded aperture correlation holography–a new type of incoherent digital holograms," Opt. Express 24, 12430-12441 (2016).

A. Vijayakumar and J. Rosen, “Interferenceless coded aperture correlation holography–a new technique for recording incoherent digital holograms without two-wave interference,” Opt. Express 25(12) 13883-13896 (2017).

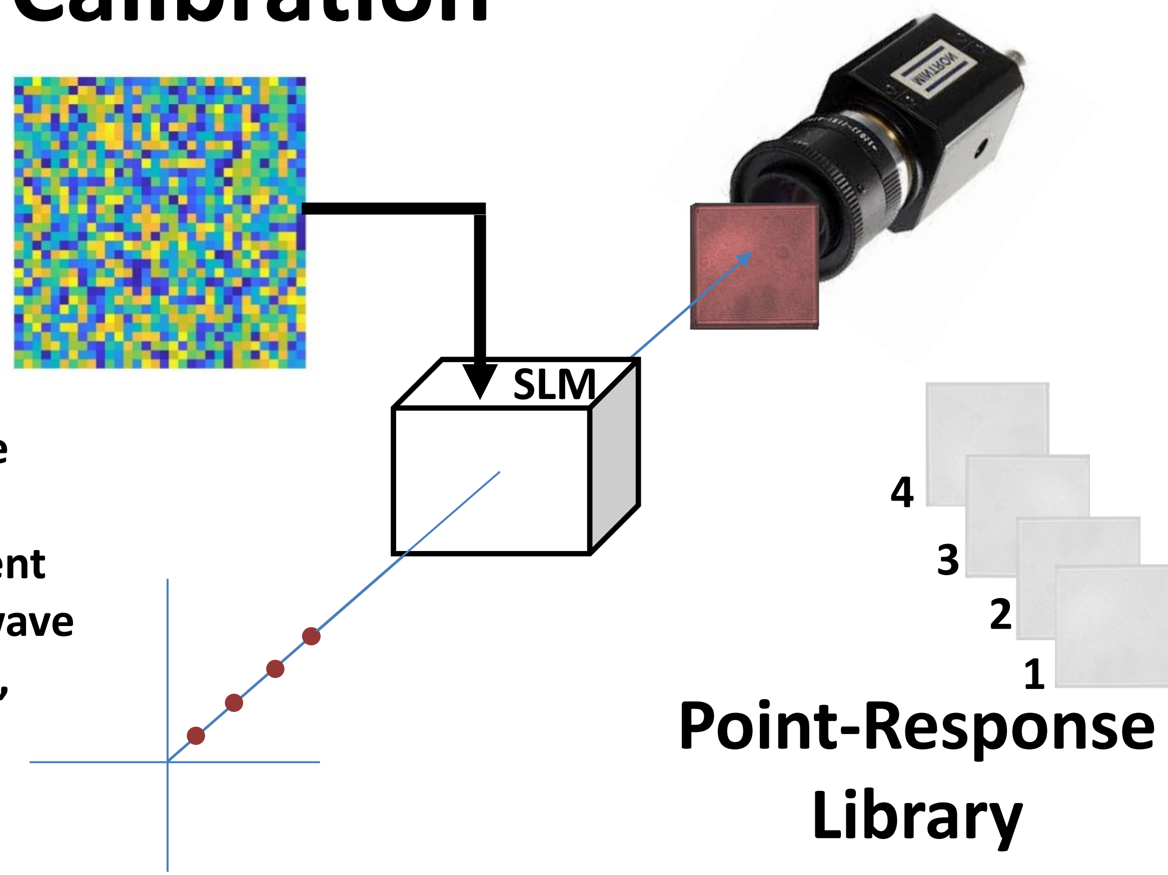


The hologram is recorded without two beam interference

Interferenceless Coded Aperture Correlation Holography I-COACH

3D-I-COACH

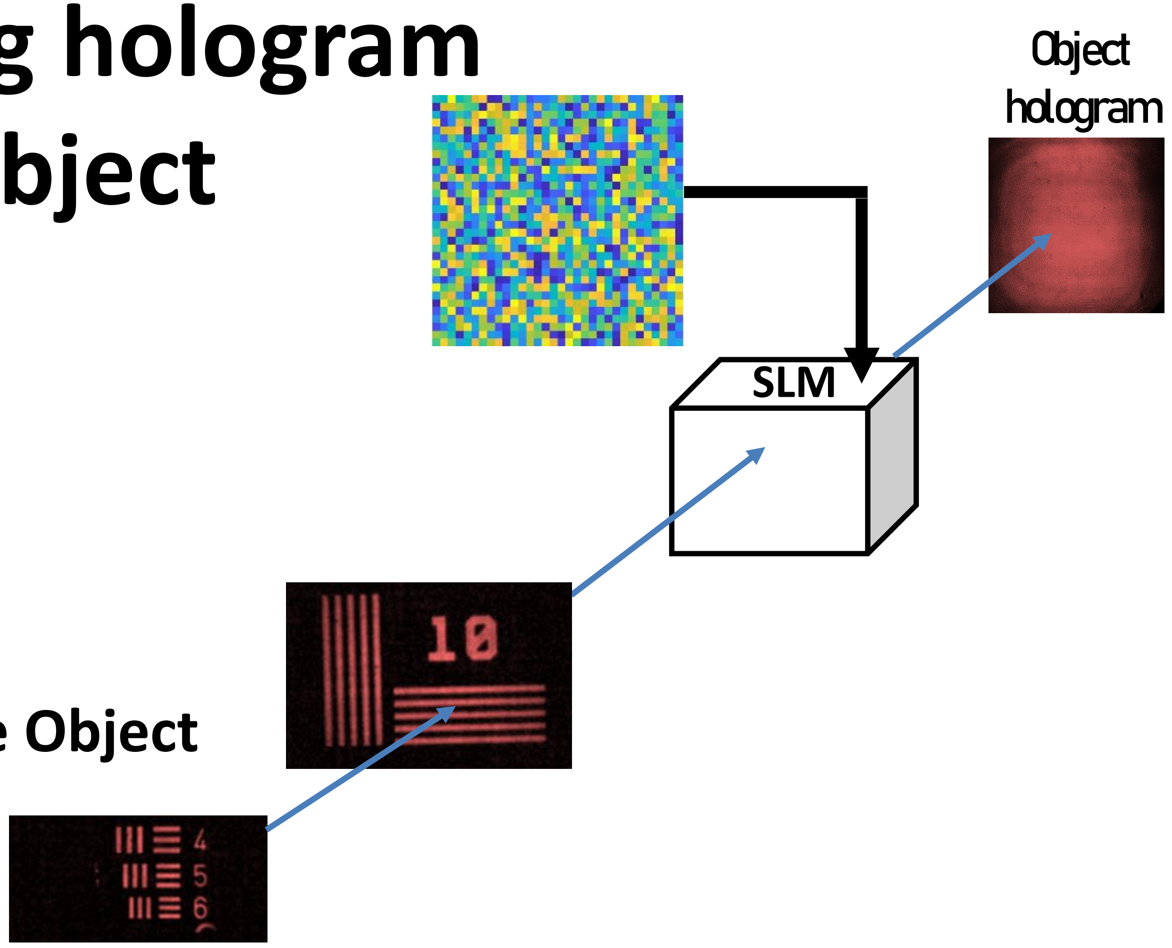
1. System Calibration



A. Vijayakumar and J. Rosen, "Interferenceless coded aperture correlation holography- a new technique for recording incoherent digital holograms without two-wave interference," Optics Express 25, 13883-13896 (2017).

3D-I-COACH

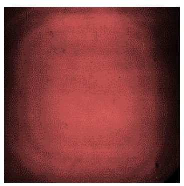
2. Recording hologram of 3D object



Multi-Plane Object

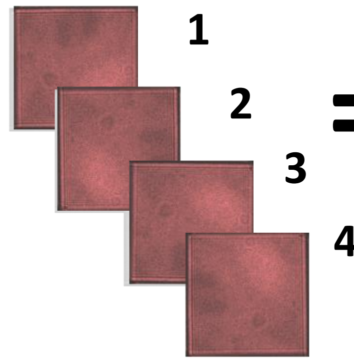
3. Image Reconstruction

Object hologram



CORRELATION

Point-Response Library



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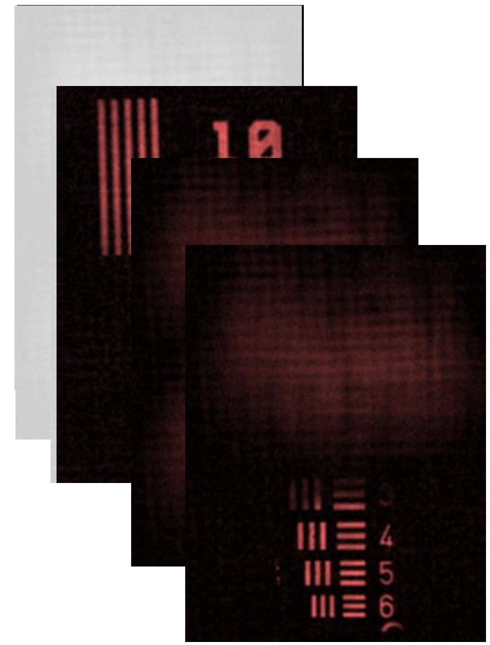


Nonlinear image Reconstruction

Linear Reconstruction: $I=O\circledast h'$
Optimal Reconstruction: $h\circledast h'=\delta$

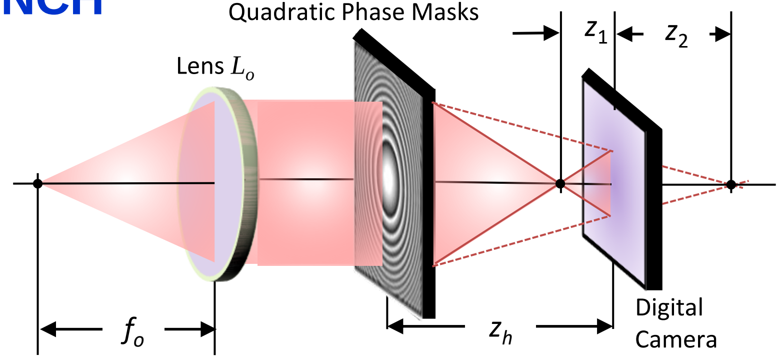
O=**Object** h=**Impulse Response**
I=**Image** $\circledast$=**Correlation**
h'=**Reconstructing Function**

In Fourier Plane: $H\cdot H'^{*}=|H|\exp(i\Phi_H)\cdot|H|^{r}\exp(-i\Phi_H)=|H|^{r+1}$
Optimal Reconstruction: $|H|^{r+1}=\text{Constant}$
$r=-1\rightarrow$ **Inverse Filter**
Instead, Nonlinear Reconstruction:
$|H|^{o}\exp(i\Phi_H)\cdot|H|^{r}\exp(-i\Phi_H)=|H|^{o+r}$
Where o **and** r **are chosen as the parameters that minimize some cost function**
Nonlinear Reconstruction of the Object:
$I=FT^{-1}\{|O|^{o}\exp(i\Phi_O)\cdot|H|^{r}\exp(-i\Phi_H)\}$

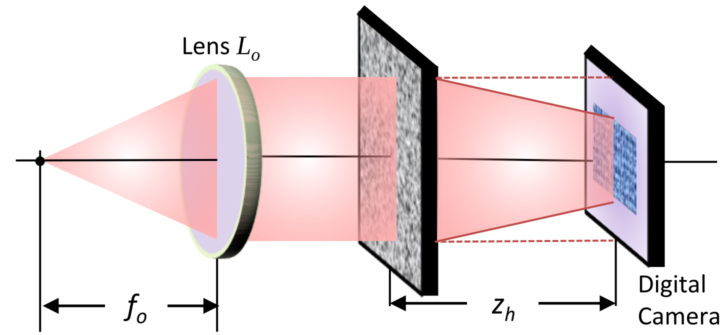
M.R. Rai, A. Vijayakumar, and J. Rosen, "Non-linear adaptive three-dimensional imaging with interferenceless coded aperture correlation holography (I-COACH)," Opt. Express 26, 18143-18154 (2018).

CAFIR - Coded Aperture with FINCH Intensity Responses

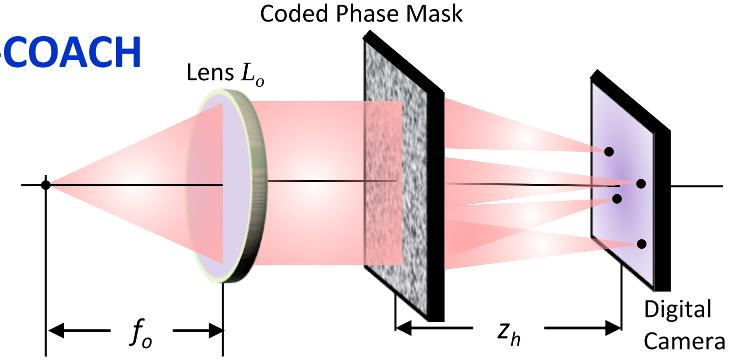
FINCH



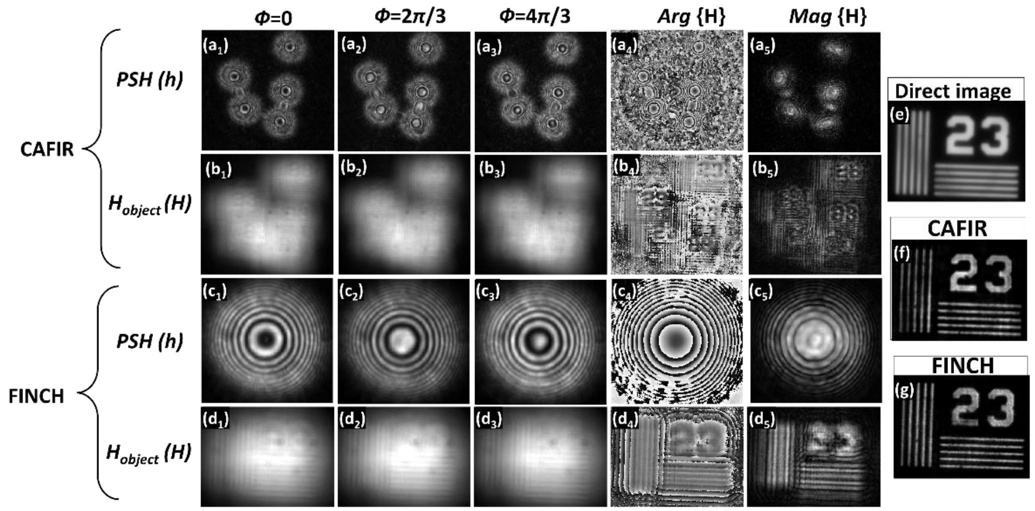
COACH



I-COACH

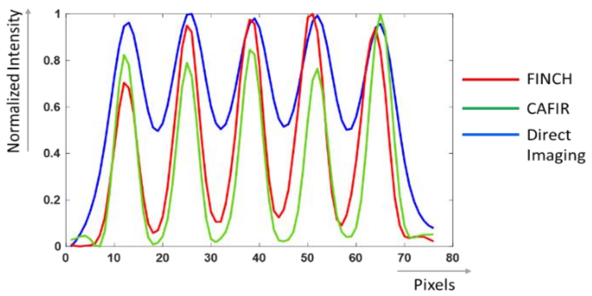


Coded Aperture with FINCH Intensity Responses (CAFIR)

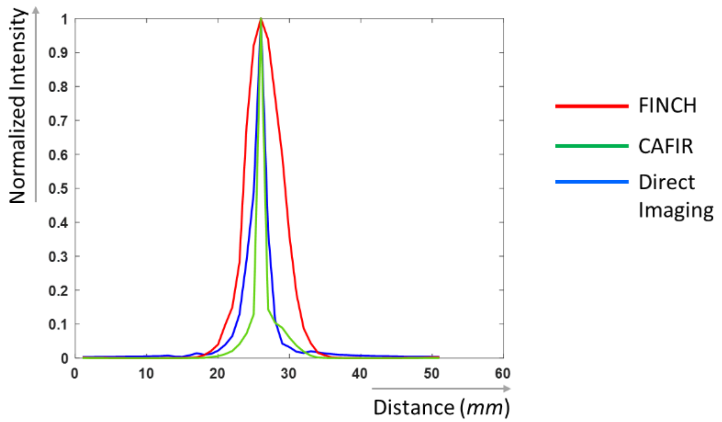


(a_1-a_3), (b_1-b_3) and (c_1-c_3), (d_1-d_3) recorded intensity for point-object (*h*) and object (*H*) respectively with Φ= 0, 2π/3 and 4π/3 (a_4, a_5); (b_4, b_5) and (c_4, c_5), (d_4, d_5) phase and magnitude of superimposed PSH and object holograms for CAFIR and FINCH, respectively. (e) Direct imaging, (f) POF reconstructed image for CAFIR (g) FINCH reconstructed image.

Coded Aperture with FINCH Intensity Responses (CAFIR)

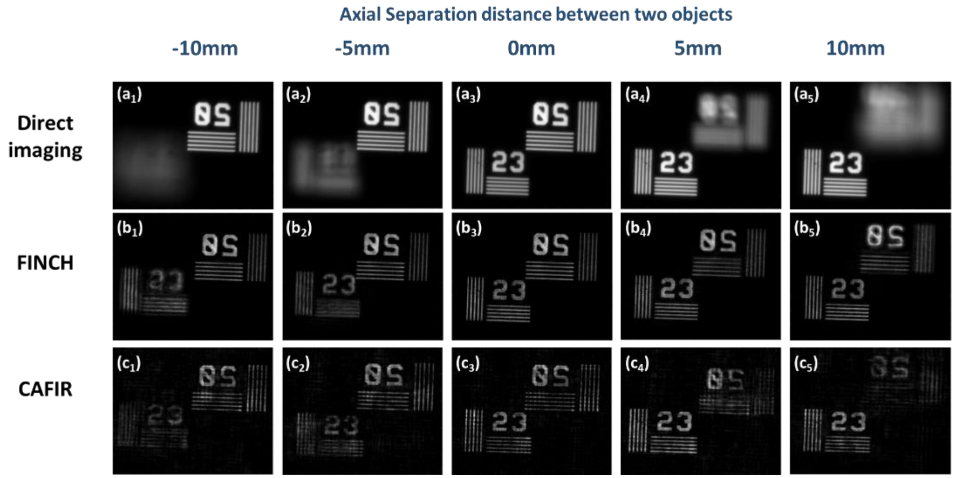


Average cross-sections of gratings of direct image and reconstructed images with FINCH and CAFIR with f_1=32 *cm*



Axial distance of pinhole from f_0 in *mm*.

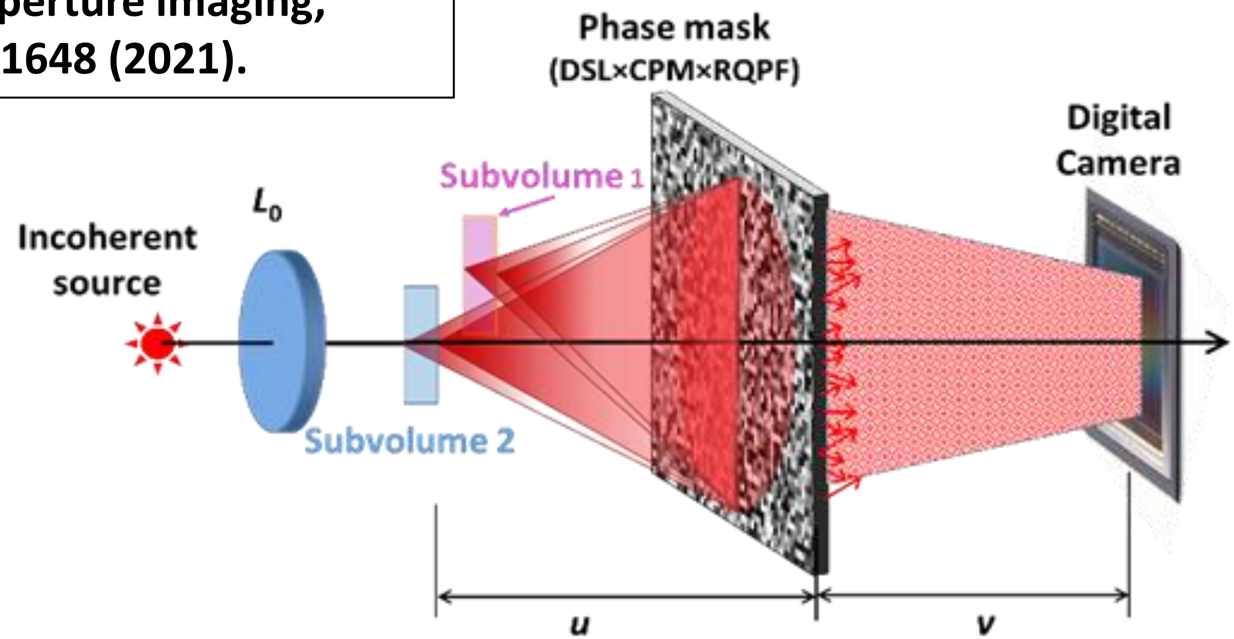
Direct image and reconstructed images with FINCH and CAFIR with f_1=32 *cm* at different axial distances from f_0 varying between 10 to -10 *mm* with 5 *mm* intervals.



Depth of Field Engineering-incoherent imaging

<u>Goal:</u> imaging objects positioned at different sub-volumes of the object space, and only in these sub-volumes.

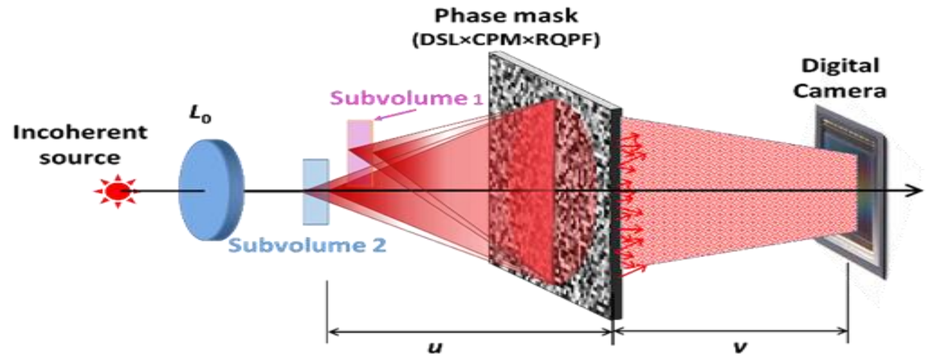
M. Rai and J. Rosen, "Depth-of-field engineering in coded aperture imaging," Opt. Express 29, 1634-1648 (2021).

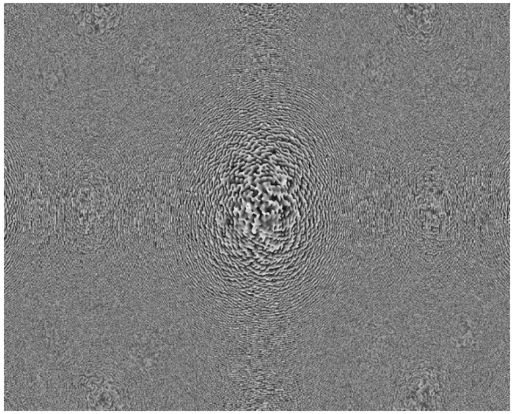


Depth of Field Engineering

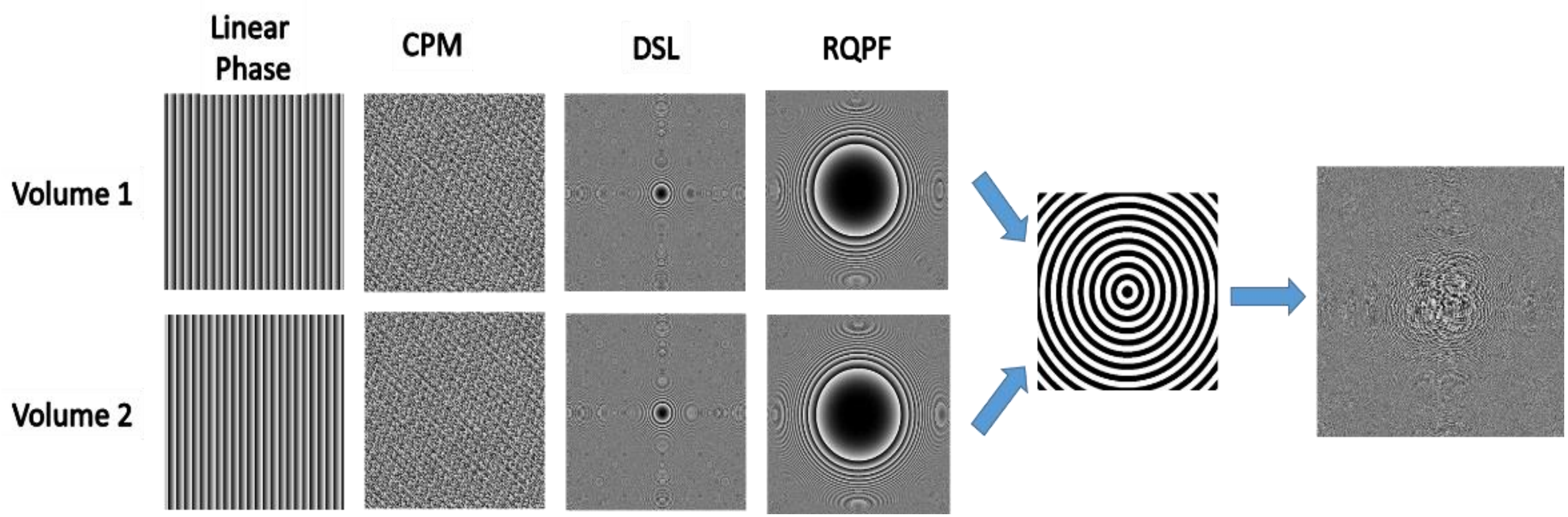
Phase mask displayed on the SLM for each sub-volume is the product of 3 phase masks:

1. **Diffractive Spherical Lens (DSL) – defines the axial location of the sub-volume.** $\exp\left(i\pi r^2/\lambda f\right)$
2. **Radial Quartic Phase Function (RQPF) – defines the axial length of the sub-volume or the DOF.** $\exp\left(i2\pi\left(r/p\right)^4\right)$
3. **Coded Phase Mask (CPM)– Responsible to the point response on the camera plane in the form of sparse, randomly distributed, dots.**





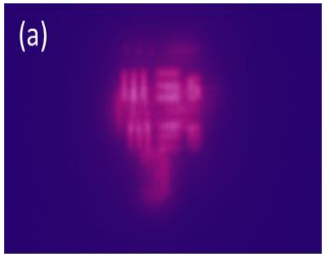
Depth of Field Engineering



Multiplexing process of two sets of phase masks for multi-volume imaging.

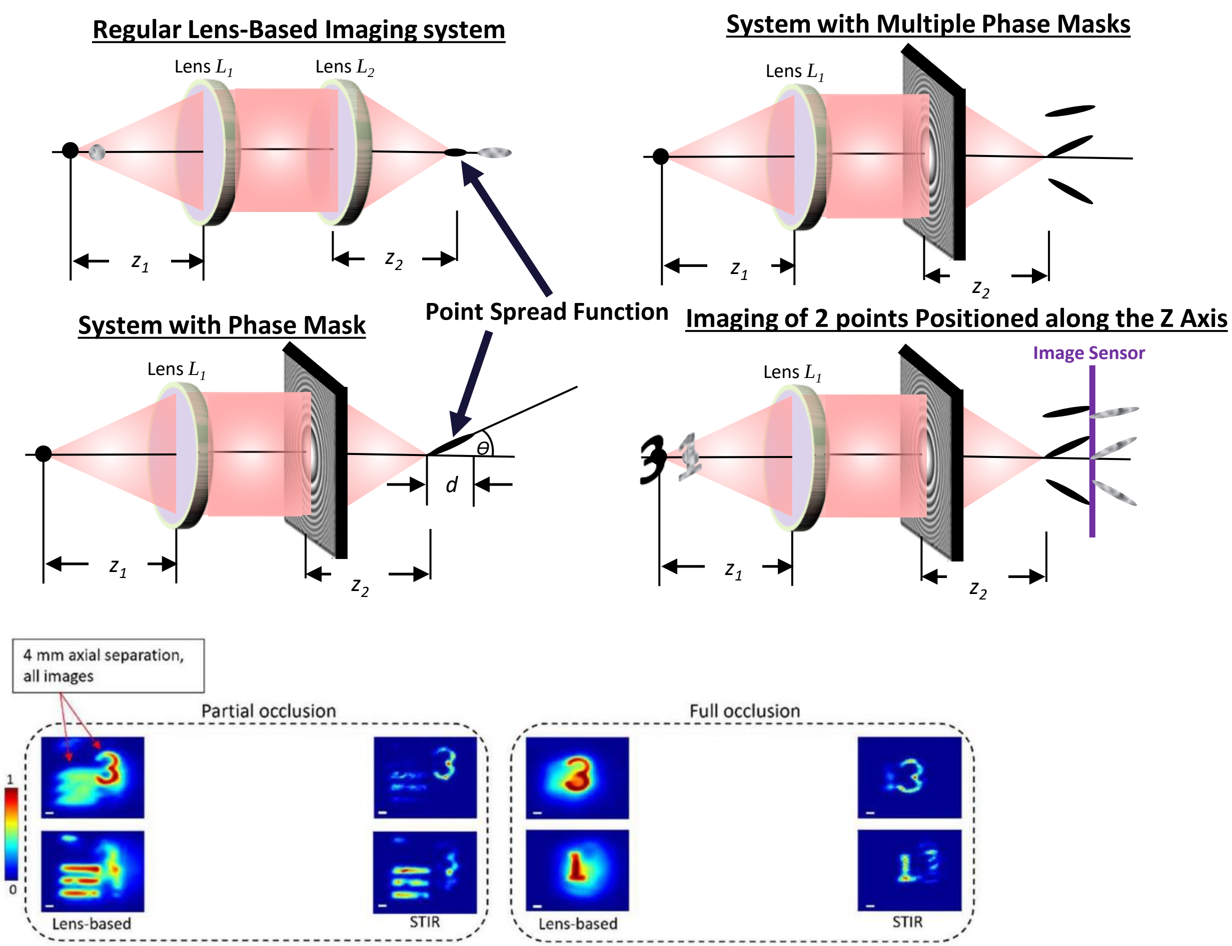
Depth of Field Engineering

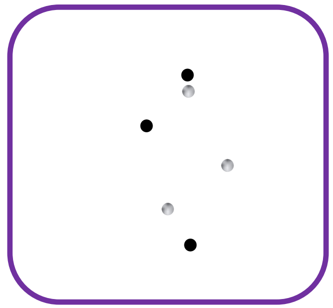
Direct images with an overlap between the objects because they are placed on the same sightline.



STIR - Sectioning by Tilted Intensity Rods

N. Hai, and J. Rosen, "Single Viewpoint Tomography Using Point Spread Functions of Tilted Pseudo-Nondiffracting Beams in Interferenceless Coded Aperture Correlation Holography with Nonlinear Reconstruction," SSRN 4216569





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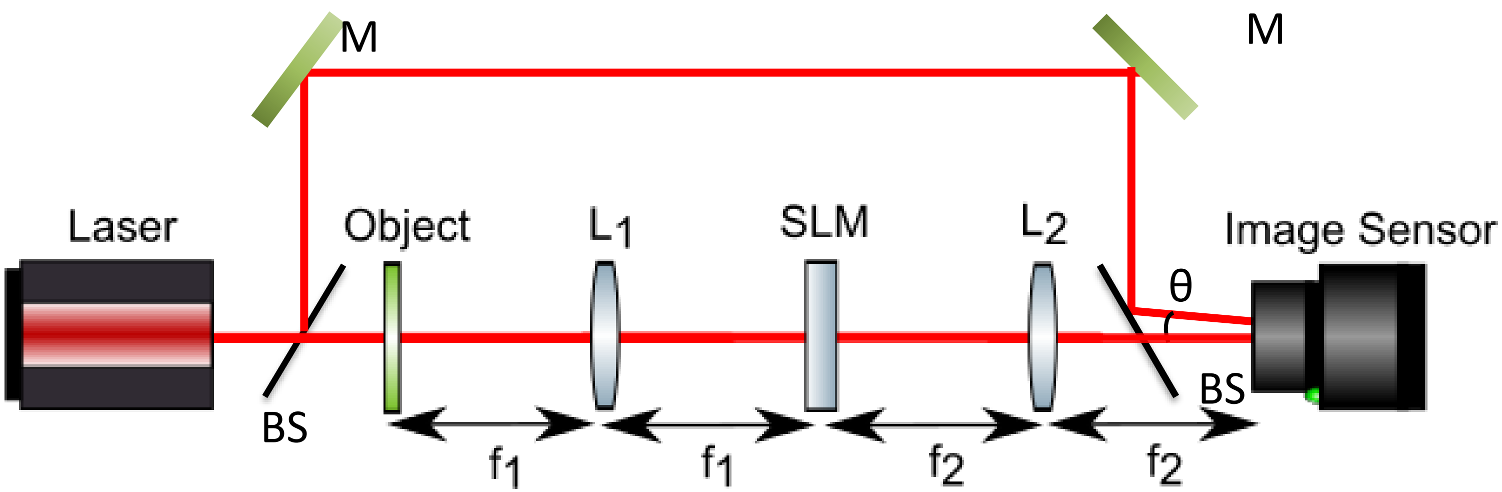
Quantitative Phase Imaging

<u>Goal:</u> Quantitative Phase imaging of coherently illuminated objects

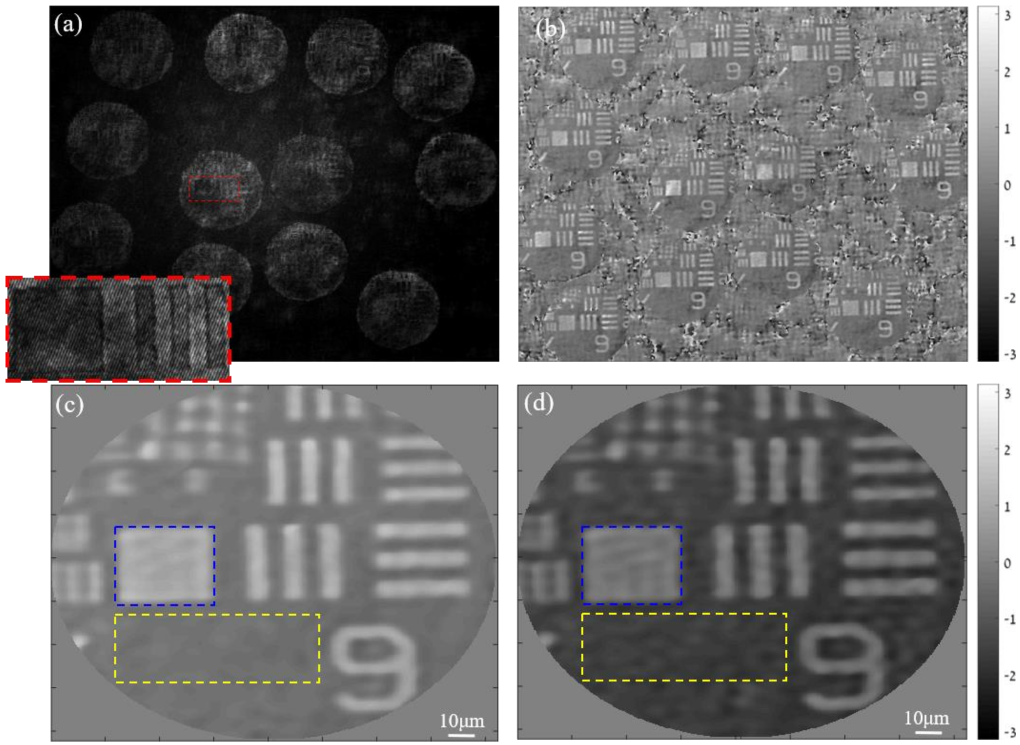


N. Hai, and J. Rosen, "Coded aperture correlation holographic microscope for single-shot quantitative phase and amplitude imaging with extended field of view," Opt. Express **28**(19), 27372-27386 (2020).

Quantitative Phase Microscopy using Coherent Sparse COACH

Off-axis hologram recorded using Coherent Sparse COACH containing image replications

The phase of its filtered signal after phase background subtraction.



Quantitative phase imaging of USAF pure phase resolution chart using Coherent Sparse COACH

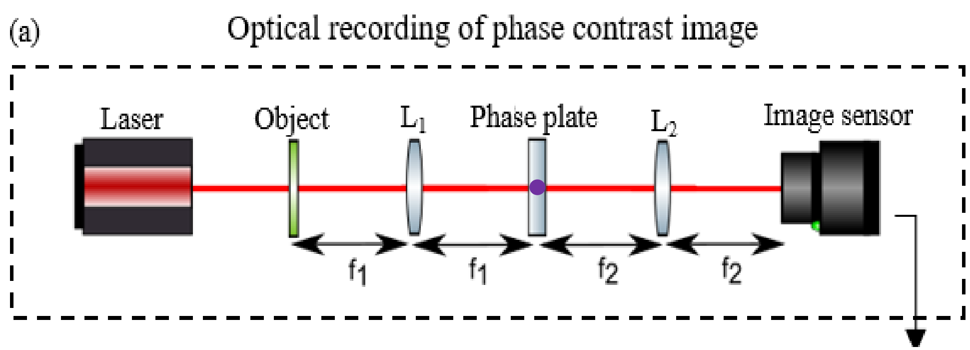
Quantitative phase imaging of USAF pure phase resolution chart using standard open aperture holography

	Open aperture	CS-COACH
Phase element MSE (blue dashed square)	1.97e-3	1.92e-3
Substrate MSE (yellow dashed square)	10.86e-4	7.06e-4
Phase element height [nm]	273	267

Quantitative Phase Imaging

<u>Goal:</u> Quantitative Phase imaging by a single shot on-axis system

Optical configuration used to record a phase contrast image of pure phase objects

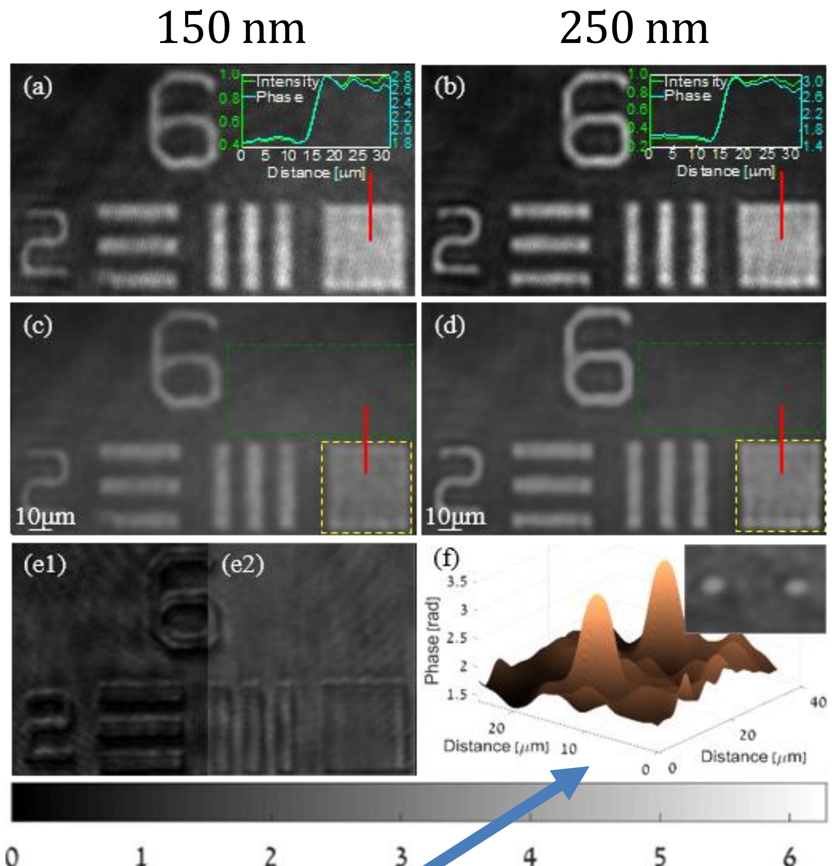


Quantitative Phase Imaging

Phase-contrast images of phase targets captured by the camera

Quantitative phase images obtained from the modified GSA output after initialization with the corresponding phase contrast images

(e1) Intensity image captured by the camera without the phase contrast operation and (e2) the corresponding phase reconstruction by using the modified GSA.



Phase plot of the 6 µm diameter Polystyrene microspheres reconstructed in a similar method

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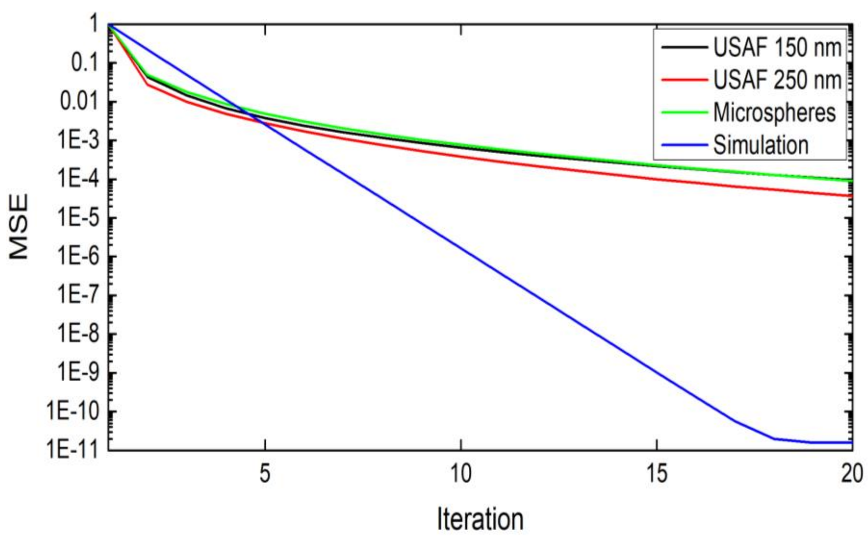
Quantitative Phase Imaging



Quantitative analysis

Phase object	Phase contrast-based phase retrieval		Holography
USAF 1951 phase target (150 nm)	161 nm		170 nm
USAF 1951 phase target (250 nm)	244 nm		267 nm
Polystyrene microspheres (6 µm diameter)	6.04 µm		5.78 µm

Convergence plots of the recovered phase distribution from the modified GSA. Normalized (to the initial MSE) mean square error (MSE) in log scale as a function of the iteration number in linear scale, for the three examined objects and a simulated object shows that convergence to MSE<10^{-3} is achieved within a maximum of 10 iterations.

N. Hai, and J. Rosen, “Phase contrast-based phase retrieval: a bridge between qualitative phase contrast and quantitative phase imaging by phase retrieval algorithms,” Opt. Lett. **45**(20), 5812-5815 (2020).

Conclusions and Challenges

- **Inventions can sometimes be nothing more than a new and unexpected combination of well-known and unrelated ideas. Therefore, it is essential to read about other close or far studies and to stay open-minded to as many as possible influences from others.**
- **Incoherent imaging with synthetic aperture imaging should be explored further. Instead of working with a baseline interferometer, a method based on local detection should be studied.**
- **Better methods should be explored in the areas of image sectioning, tomography, and imaging through a scattering medium.**

Acknowledgment

ELECTRO-OPTICS LABORATORY
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Thank you for your attention

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