Quantitative phase from defocused color images

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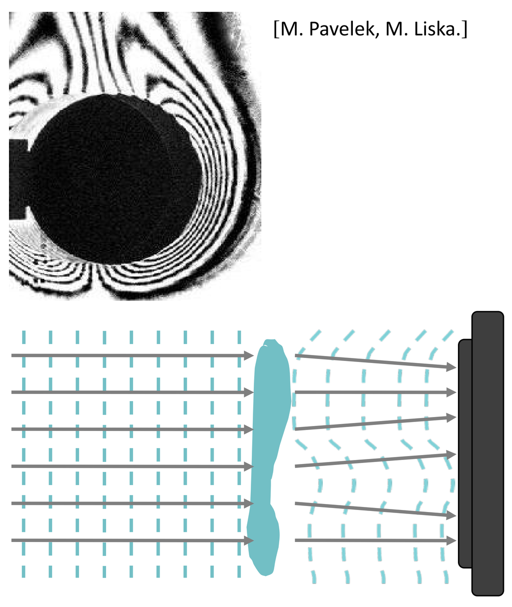
Motivation

GOAL: Simple, inexpensive phase imaging in real-time with white light illumination for height mapping, density fields and visualization of transparent objects.



Light is a wave, having both an amplitude and a phase. However, our eyes and cameras are not fast enough to detect optical phase directly; thus, phase must be measured indirectly. Phase carries information about an object's shape and optical density and is necessary in applications ranging from surface profiling, density measurements and adaptive optics, to biomedical research in cell and tissue visualization. Here we demonstrate a simple method for deriving phase from a single three-colour image. Our technique is fast, accurate, requires no hardware modification and is valid with partially coherent illumination.

Theory

Our approach is inspired by the Transport of Intensity[1] equation (TIE), which states that the derivative of intensity with respect to the optical axis, z, is related to the phase. By taking two images at different z positions the phase of an incident beam may be recovered[2,3]. Limitations include the requirement for either two cameras or motion between sequential capture of multiple images, as well as registration problems[4].

Our equation is derived from the paraxial wave equation after Fresnel propagation[5]. Wavelength λ and distance z are interchangeable – in fact, defocus is the product of the two $\xi = \lambda z$.

Fourier Domain

$$\psi(x) = Ae^{i\varphi} \rightarrow \Psi(u)$$

$$H(u;\xi) = e^{ikz}\exp\left\{-i\pi\xi u^2\right\}$$

$$I(u;\xi) = \mathrm{A}\left\{\Psi H\right\}$$

Small defocus limit (Linearization) →

$$H(u;\xi) = 1 - i\pi\xi u^2 - \frac{(\pi\xi)^2 u^4}{2!} - \ldots \approx 1 - i\pi\xi u^2$$

$$I(u;\xi) = \mathrm{A}\left\{\Psi(1 - i\pi\xi u^2)\right\}$$

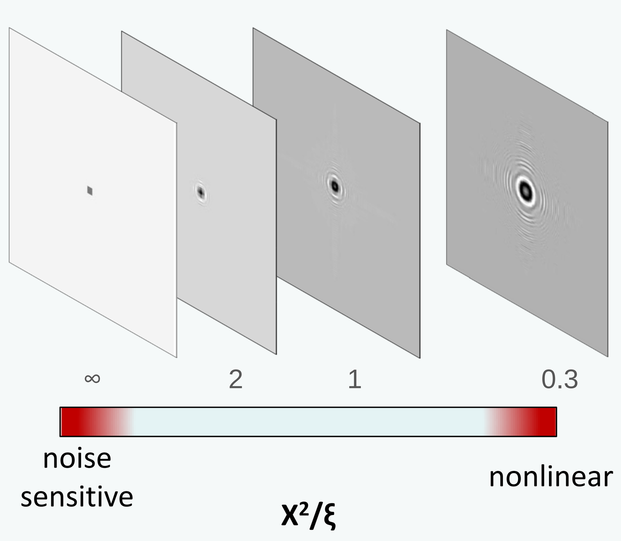
$$i2\pi u \rightarrow \nabla$$

$$I(x;\xi) = \left|\psi + i\xi\frac{\nabla^2\psi}{4\pi}\right|^2$$

$$I(x;\xi) = I - \frac{\xi}{2\pi}\nabla \bullet (I\nabla\varphi)$$

$$\frac{I(x;\xi+\delta\xi) - I(x;\xi)}{\delta\xi} \approx \frac{\partial I}{\partial \xi} = -\frac{\nabla_\perp \cdot \left[I\nabla_\perp\varphi\right]}{2\pi}$$

Validity range



Equation is well-posed, BUT derivative estimate is unstable

$$\frac{\partial I}{\partial \xi} \approx \frac{I_R - I_B}{\Delta\xi} + \frac{noise}{\Delta\xi}$$

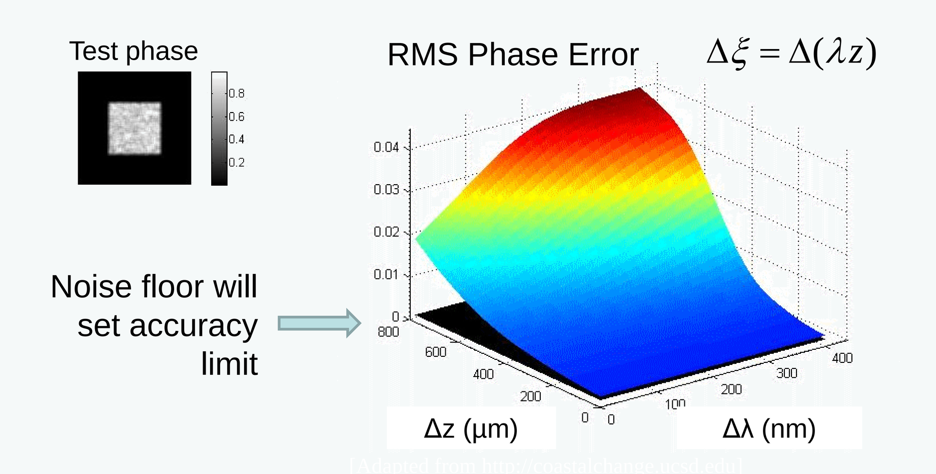
Noise amplified by $1/\Delta\xi$

Large $\Delta\xi$ decreases noise, but compromises accuracy

→ set $\Delta\xi \le x^2$

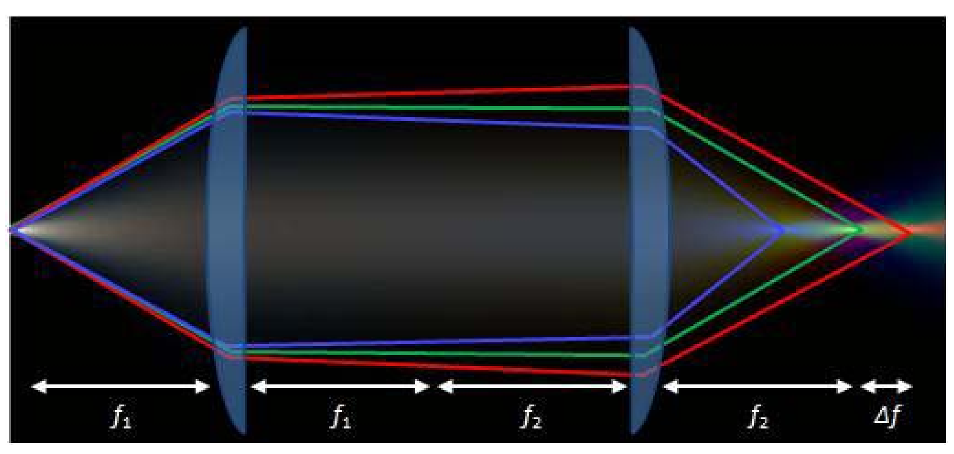
I is intensity, φ is phase, and the gradient operates only in the lateral dimensions. One implementation of this equation allows phase to be recovered by taking images with different wavelengths in a single plane, which has been previously proposed for X-ray imaging with quantified dispersion[6,7] and in diffraction tomography[8]. Since the technique does not require strict temporal coherence, filters may be used to separate the colours. Thus, the defocused colour images can be retrieved simultaneously from the RGB channels of any colour camera, allowing single-shot phase imaging free of registration problems.

Noise-free error analysis



Controlling chromatic defocus

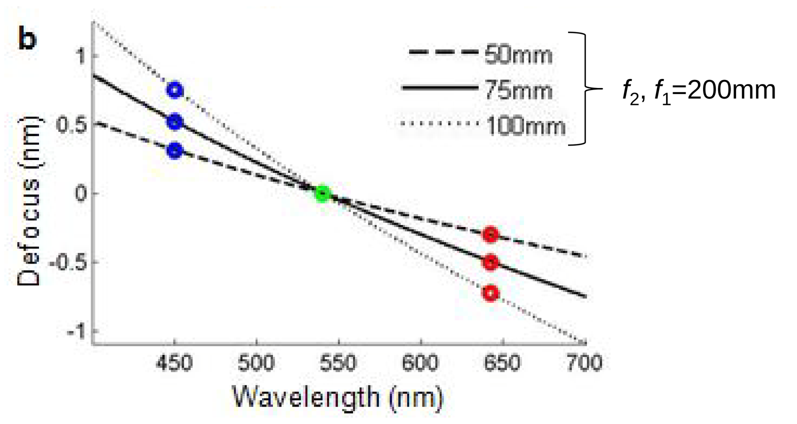
When white light interacts with a dielectric medium, different wavelengths propagate at different speeds, giving rise to chromatic dispersion, often referred to as an aberration[9]. Here we propose a way to use the chromatic dispersion of the imaging system as a mechanism for obtaining phase directly. Controlling dispersion allows optimal in-focus phase imaging.



Single lens: $\Delta f(\lambda) = \frac{n(\lambda_G) - n(\lambda)}{(n(\lambda) - 1)} f_G$

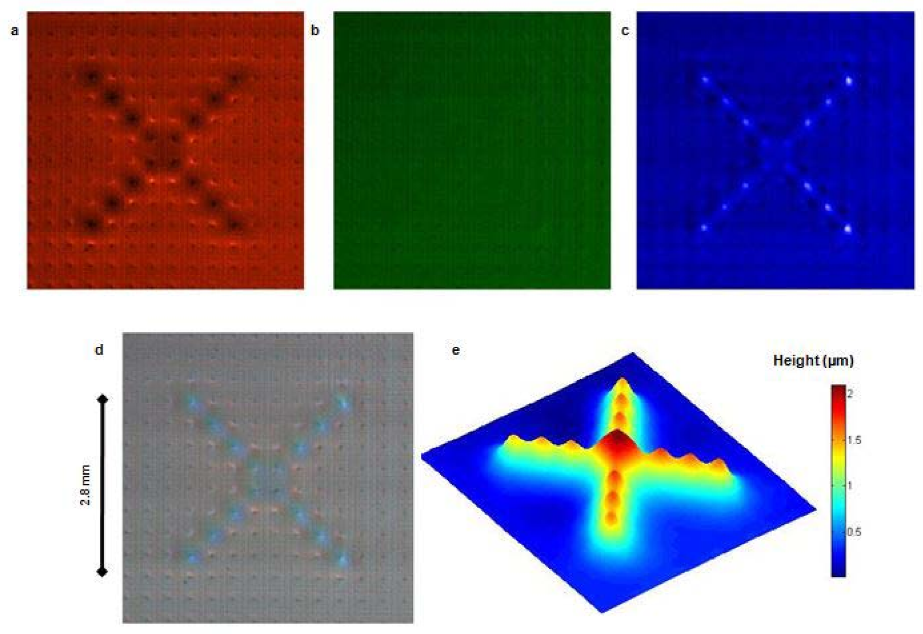
4f system: $\Delta f'(\lambda) = \Delta f_2 + \frac{f_2^2}{\Delta f_1 + \Delta f_2 - (f_1^2/\Delta f_1)}$

Total defocus: $\xi = \lambda \Delta f'(\lambda)$

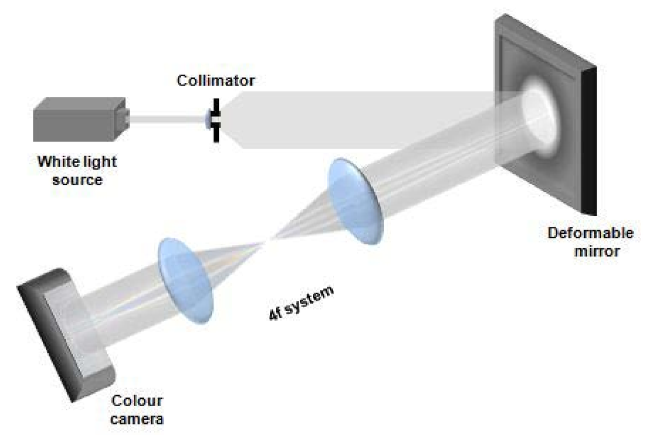


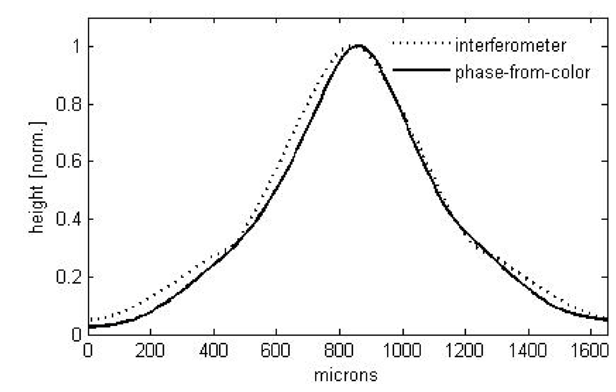
Experimental results

Experiments were done in both a 4f system (f_1=200mm, f_2=75mm), and in a Nikon Eclipse TE2000-U microscope with achromatic objective (20x, NA 0.4). A Boston Micromachines deformable mirror array[10] was used as a test phase object (right). The phase was converted to a surface height measurement, and results were compared with a commercial interferometer. Further experiments in a standard brightfield microscope demonstrated applicability for biological samples and MEMS objects.



Color image Phase (rad)





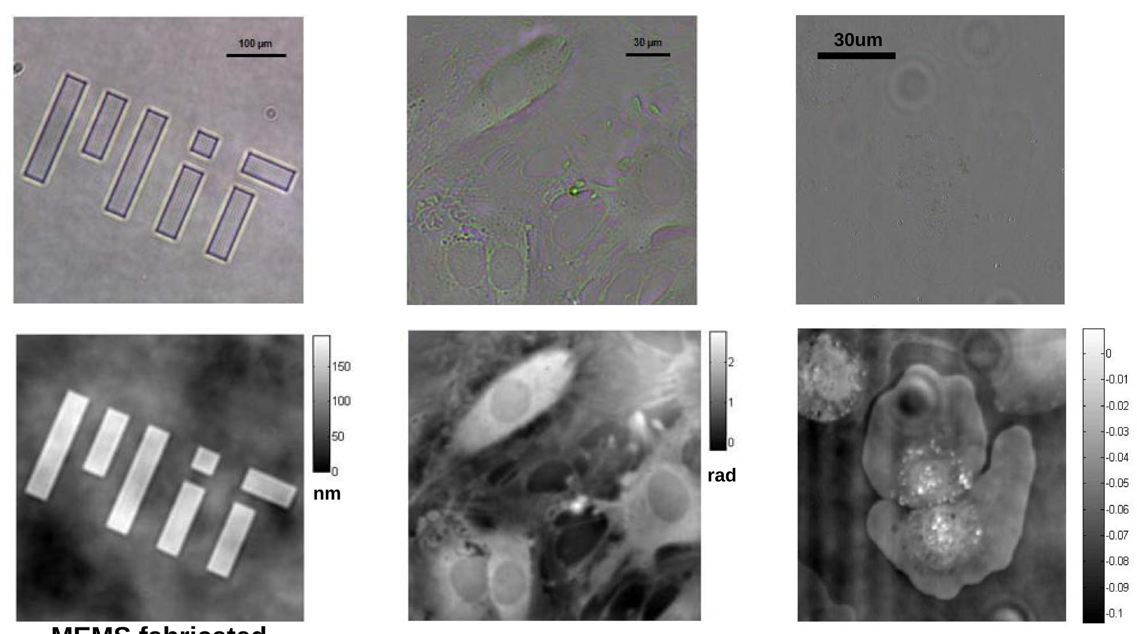
Comparison with interferometer

$$\phi = \frac{2\pi}{\lambda}(\Delta n)2h$$

phase, refractive index, height

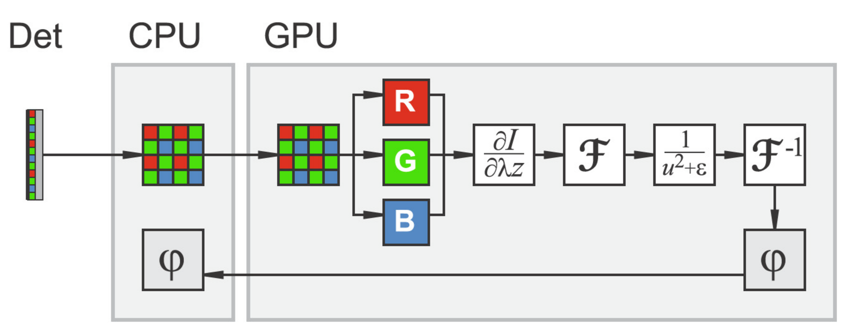
Color image

Phase

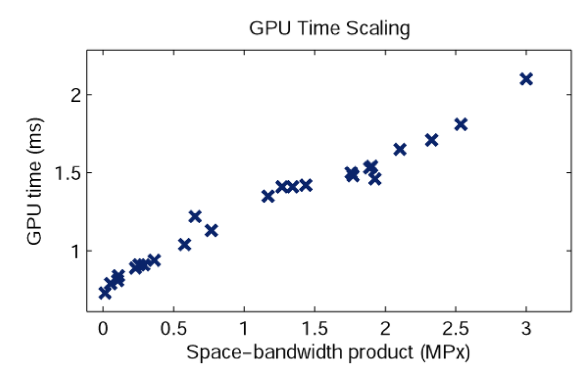


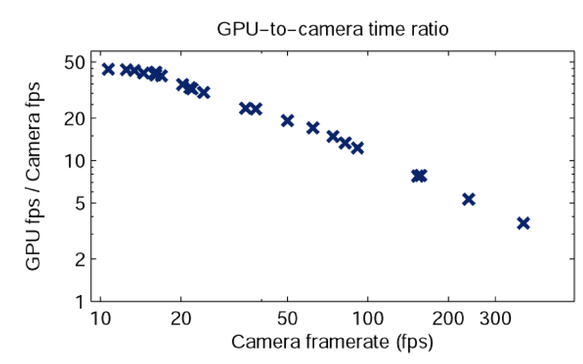
MEMS fabricated object (PMMA) HMVEC cells HeLa cells

Real-time phase imaging and applications



Computations were implemented on a Graphics Processing Unit (GPU) to present real-time phase results to a user.





Measured performance times are shown here. GPU time is linear with the number of pixels and includes fixed overhead from FFT computations. The overhead becomes marginally more significant with faster frame rates, decreasing the relative performance of the GPU – with the GPU falling behind the camera at approximately 2000 fps.

This opens the door to incredibly fast real-time phase recovery with the potential for use in ambient light and large-scale distributions.

Conclusion

High quality phase images are possible in real-time and using white light illumination, using existing optical systems and the processing here described. Current efforts include closed-loop adaptive optics and large-scale density measurements in air.

Acknowledgements

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