Partially Coherent Phase Recovery by Kalman Filtering

Zhong Jingshan,[1,2] **Lei Tian,**[2] **Rene A. Claus,**[3] **Justin Dauwels,**[1] **and Laura Waller**[2]

[1]*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798*
[2]*Department of Electrical Engineering and Computer Sciences, University of California, Berkeley*
[3]*Applied Science and Technology, University of California, Berkeley*
jingshanzhong@gmail.com

Abstract: We demonstrate a Kalman filtering method to recover the phase of a thin object illuminated by partially coherent light. Our method is fast, efficient, robust to noise, and able to handle arbitrary source shapes when used in a microscope with Köhler illumination.

Quantitative phase imaging has become an important tool in biology and surface metrology [1,2], since objects of interest often do not absorb much light, but cause phase delay. Phase retrieval methods [3-5] that use a stack of intensity images taken through focus are particularly attractive because they are experimentally simple. We have previously shown that Kalman filtering can be used in such schemes [6], providing information theoretic near-optimal phase solution. However, this method was computationally expensive and could only handle fully coherent (laser) illumination. By using a sparse Kalman filter [7], the computational complexity was reduced to $\mathcal{O}(N \log N)$, where N is the number of pixels in the phase construction. Here, we extend this method to the case of spatially partially coherent illumination [8]. The new Kalman filtering method is fast, efficient, robust to noise, and able to handle arbitrary source distribution when used in a microscope with Köhler illumination.

To include partially coherent illumination into Kalman filter model, we assume an incoherent extended source in the Köhler configuration that is typical in most microscopes (see Fig. 1). The intensity $I(x, y; z)$ defocused by z can be written as a convolution between the intensity from coherent illumination $I^{Coh}(x, y; z)$ and a scaled source intensity distribution $S(x, y)$:

$$I(x, y; z) = I^{Coh}(x, y; z) \otimes S\left(-\frac{f}{z}x, -\frac{f}{z}y\right), \qquad (1)$$

where f is the focal length of the condenser lens. A state-space model for Kalman filtering can be derived following the procedure in [6]. The sparse model in [7] is also adopted to reduce the computational complexity to $\mathcal{O}(N \log N)$.

The experimental setup is shown in Fig. 1(a). An incoherent white light source, filtered by a narrow-band color filter with center wavelength 650 nm is placed at the front focal plane of the condenser. The spatial coherence of the illumination is adjusted by the size of an iris placed immediately behind the color filter. A $4f$ system images the object onto the camera, by which a through focus intensity stack is taken by moving the sample along the optical axis.

We first demonstrate the proposed method by simulating a phase and amplitude object illuminated by a circular incoherent source (2mm in diameter, and the focal length of the condenser is 10mm). An intensity stack [in Fig. 1(b)] consisting of 101 images were calculated by defocusing the object symmetrically about the focus with 10μm step size. The data was further corrupted by white Gaussian noise with variance 0.0015. To demonstrate the effect of partial coherence, we first process the data using the fully coherent model in [7], shown in Fig. 1(c). Significant blur present in the phase reconstruction result is caused by the intensity

smearing due to off-center source points. The phase reconstruction by incorporating partially coherent illumination, successfully eliminates the blurring artifact, as shown Fig. 1(d).

Next, we test out our method experimentally in a microscope. A cheek cell sample was defocused symmetrically about the focus at 81 z-planes ranging from -2.5 mm to 2.5 mm, shown in Fig. 2(a). Each image contains 701×625 pixels. The circular iris has a 2mm diameter and the light is collimated by a 100mm focal length condenser. In Fig. 2(b) and (c), we compare the result using the method in [7] and the new partial coherence method. The phase recovered by the partial coherence Kalman filtering method has higher contrast and shows much more detail inside the cell. We expect further improvement with less coherent illumination.
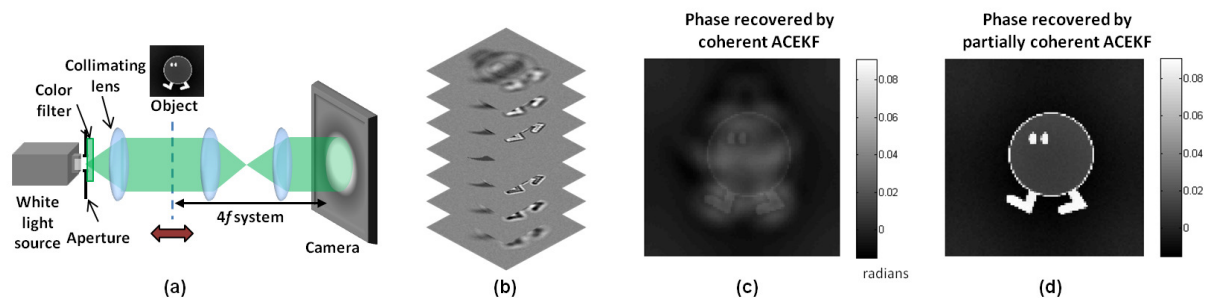

Fig.1 (a) Experimental setup for capturing intensity images. (b) Simulated noisy intensity images with partially coherence illumination. (c) Recovered phase by sparse ACEKF which ignores partially coherence, and (d) Recovered phase by the proposed Kalman filtering method which includes partial coherence.
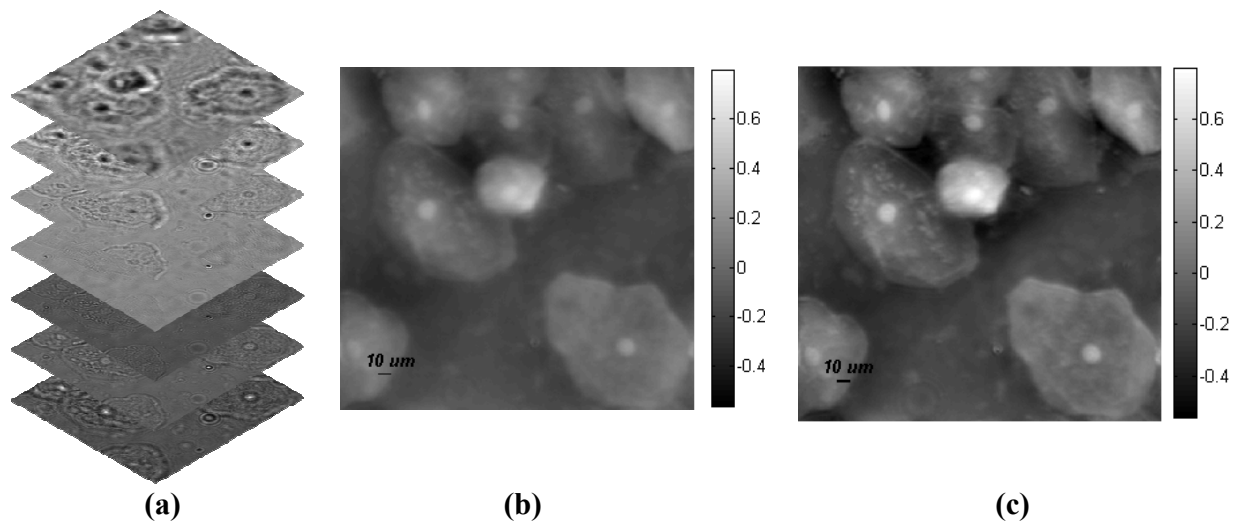

Fig.2 (a) Experimental intensity images through focus, with partially coherent illumination. (b) phase recovered by sparse ACEKF assuming fully coherent illumination, and (c) phase recovered by the proposed Kalman filtering method with knowledge of the source intensity distribution.

References

[1] G. Popescu, Quantitative phase imaging of cells and tissues. New York: McGraw-Hill (2011).
[2] K. Nugent, D. Paganin, and T. Gureyev. "A Phase Odyssey." Physics Today 54.21(2001).
[3] J. Fienup, "Phase retrieval algorithms: a comparison," Appl. Opt. 21, 2758–2769 (1982).
[4] N. Streibl, "Phase imaging by the transport equation of intensity," Opt. Commun. 49, 6–10 (1984).
[5] L. Waller, L. Tian, and G. Barbastathis, "Transport of Intensity phase-amplitude imaging with higher order intensity derivatives," Opt. Express 18, 12552-12561 (2010)
[6] L. Waller, M. Tsang, S. Ponda, S. Yang, and G. Barbastathis, "Phase and amplitude imaging from noisy images by Kalman filtering," Opt. Express 19, 2805–2814 (2011).
[7] Z. Jingshan, J. Dauwels, M. A. V´azquez, and L. Waller, "Sparse ACEKF for phase reconstruction," Opt. express 21, 18125-18137 (2013).
[8] J. Petruccelli, L. Tian, and G. Barbastathis "The transport of intensity equation for optical path length recovery using partially coherent illumination," Opt. Express 21.12, 14430-14441 (2013).