PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

# Phase estimation for global defocus correction in optical coherence tomography

Mikkel Jensen, Niels M. Israelsen, Adrian Podoleanu, Ole Bang

Mikkel Jensen, Niels M. Israelsen, Adrian Podoleanu, Ole Bang, "Phase estimation for global defocus correction in optical coherence tomography," Proc. SPIE 10591, 2nd Canterbury Conference on OCT with Emphasis on Broadband Optical Sources, 105910Q (5 March 2018); doi: 10.1117/12.2292547

Event: Second Canterbury Conference on Optical Coherence Tomography, 2017, Canterbury, United Kingdom

# Phase estimation for global defocus correction in optical coherence tomography

Mikkel Jensen[a], Niels M. Israelsen[a], Adrian Podoleanu[b], and Ole Bang[a]

[a]Technical University of Denmark, DTU Fotonik, Ørsteds Plads 343, 2800 Kongens Lyngby, Denmark

[b]School of Physical Sciences, University of Kent, CT2 7NH Canterbury, England

## ABSTRACT

In this work we investigate three techniques for estimation of the non-linear phase present due to defocus in optical coherence tomography, and apply them with the angular spectrum method. The techniques are: Least squares fitting the of unwrapped phase of the angular spectrum, iterative optimization, and sub-aperture correlations. The estimated phase of a single *en-face* image is used to extrapolate the non-linear phase at all depths, which in the end can be used to correct the entire 3-D tomogram, and any other tomogram from the same system.

**Keywords:** Optical coherence tomography, angular spectrum method, defocus correction

## 1. INTRODUCTION

Optical coherence tomography (OCT)[1] is a well established optical imaging technique, which utilises white light interferometry in a Michelson interferometer to obtain a non-invasive depth scan (A-scan) of the backscattering coefficient of the imaged medium. A three dimensional (3-D) tomogram is constructed by assembling adjacent A-scans obtained e.g. by scanning the beam laterally. In conventional microscopy, the axial (depth) and lateral resolutions are linked through the numerical aperture (NA), which is a measure of the tightness of focus of the illuminating beam. In OCT, the axial resolution is determined by the coherence length of the optical source, and there is thus no need to axially scan the the sample or the probe beam. Therefore the NA can be chosen small to enlarge the depth of focus (DOF) and increase the penetration depth without sacrificing the axial resolution. The penetration depth is typically close to 10 times larger than the DOF, so only a small portion of the obtained tomogram is in focus. This issue can be mitigated by either employing several illuminating beams focused at different depths,[2] or by introducing a movable lens that adjusts the focus.[3] Both methods require a complex and expensive set-up as well as post processing in terms of fusion of the in-focus axial segments. As an alternative, numerical methods which use the phase information of the complex valued tomogram for defocus correction have been proposed, of which interferometric synthetic aperture microscopy (ISAM)[4] is the most profiled. ISAM requires solution of the inverse scattering problem for the full 3-D tomogram, but other methods promise to correct a single axial position at a time, utilising e.g sub-aperture correlations[5] or iterative optimisations.[6] We propose to use the defocus correction obtained at a single depth to extrapolate the correction at other depths. In this work we compare the performance of three different methods for phase estimation for use by the angular spectrum method to perform *en-face* corrections: Direct unwrapping of the phase and least squares fitting, iterative focus optimisation, and sub-aperture correlations, and we apply the resulting phase corrections to correct defocus for an entire volume of data.

Because OCT is an interferometric imaging modality, the phase of the tomogram is proportional to the phase of the electric field. By adding a paraboloid phase factor with the opposite sign of the defocus aberration in the angular spectrum, defocus can be corrected. The task is then to identify the strength of the defocus aberration to perform the most precise correction. The phase is estimated and applied in the 2-D spectral domain of the *en-face* image.

Further author information: (Send correspondence to M.J)
M.J.: E-mail: mikkje@fotonik.dtu.dk

2nd Canterbury Conference on OCT with Emphasis on Broadband Optical Sources,
edited by Adrian Podoleanu, Ole Bang, Proc. of SPIE Vol. 10591, 105910Q
 · doi: 10.1117/12.2292547

## 2. METHODS

Direct unwrapping of 2-D phase values of is an overdetermined problem without an exact solution, and the least squares solution to the unwrapping problem can be found by solving Poisson's equation.[7] The iterative method changes the applied paraboloid phase such that the sharpness metric (here the variance of the pixel values are used) is maximised. The sub-aperture correlation method splits the Fourier transform of the *en-face* image into sub-apertures that are cross-correlated to yield the local wavefront slope, mimicking a Shack-Hartmann wavefront sensor. The phase factor estimated from all three methods are added to the angular spectrum, which is then inversely Fourier transformed back to the physical domain.

The optical set-up used employ a supercontinuum source, superK Extreme EXR-9 OCT (NKT Photonics, Denmark), and a longpass filter to select wavelengths 1000 nm - 1750 nm. A customized 50/50 fibre coupler (Goosch and Housego, Netherlands), split the light into the interferometer arms. Standard achromatic lenses collimate the light in both arms, and a pair of galvano scanners perform the lateral scanning. The spectrometer used, C-1070-1470-GL2KL (Wasatch, USA), provide a 400 nm bandwidth, and operate at a line rate of 76 kHz. Laterally, the system is able to resolve features down to a size of 6 microns.

## 3. RESULTS AND DISCUSSION

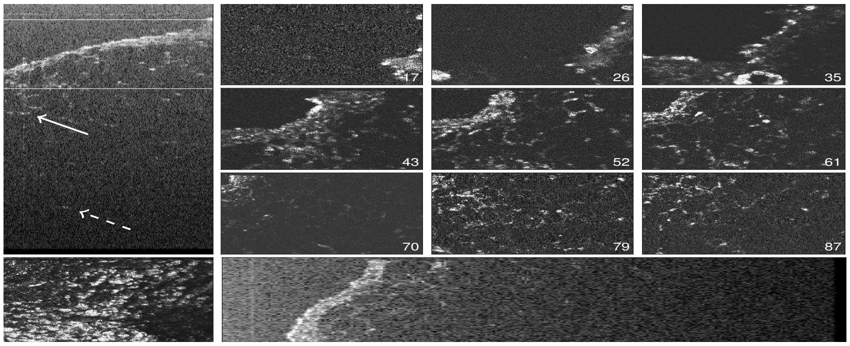
A cucumber slice was imaged and an overview of the 3-D tomogram is seen in figure 1(a). In the top left corner a B-scan along the fast axis is shown, and to the bottom right a B-scan along the slow axis is shown. The nine images to the top right are *en-face* images linearly spaced between the white lines in the B-scan of the fast axis with the numbers being the pixel position in depth, and 7.8 microns per pixel. The bottom left is a psuedo confocal image that shows the maximum pixel value through depth at all lateral positions. The *en-face* images for pixel 17 - 52 are blurred by defocus, but the remaining images are in focus. The focal point is estimated to be at pixel 75 (586 microns OPD). The *en-face* image at pixel 33 (258 microns OPD) is used for phase estimation, and the raw image is seen in figure 1(b). Figures 1(c-e) show the corresponding corrected images for the direct unwrapping, the iterative method and the sub-aperture method, respectively. All three images show significant improvements, and the inset show a zoom-in of a separate feature used to assess the resolution. The larger feature to the left in the inset is reduced by a factor of 4-5 from 54 microns to 10.8 - 14.8 microns, and the smaller feature to the right in the inset 6.2 or 6.1 microns in all three cases, being in the order of the lateral resolution. The obtained non-linear phase is used to extrapolate the phase for all depths, and it is seen applied in figure 1(f). All the displayed *en-face* images now show a similar sharpness despite the distance of 548 micron OPD between them, and the psuedo confocal image is also sharper in figure 1(f) than in figure 1(a). This suggests that the phase estimated at a single depth can be used to correct an entire volume, and that the volume correction can also be applied to any other tomogram obtained with the same system. This is demonstrated in figure 2, where the raw 3-D image is seen in figure 2(a) and the corrected image in figure 2(b). The correction is applied based on the extrapolated phase extracted from a single *en-face* image from the cucumber, verifying that the defocus error, can in fact be corrected without continuous re-optimization of the applied phase. The white arrows in figure 2 point to features that are sharpened by the correction, and we can appreciate the focal region being extended to the top *en-face* image shown here.

## 4. CONCLUSION

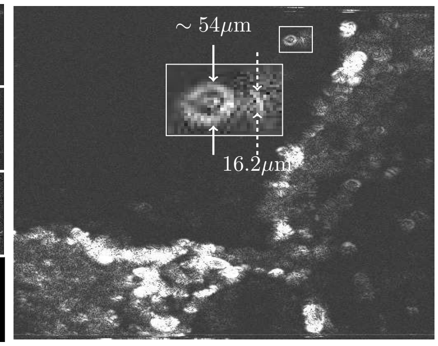
Single *en-face* defocus correction of a cucumber slice by the angular spectrum method was demonstrated using three different methods for phase estimation: A direct unwrapping, an iterative procedure and a sub-aperture correlation method, which all gave similar results with the smallest feature size of 6.1 and 6.2 microns, similar to the lateral resolution. The estimated phase factor from the iterative method was used to extrapolate the phase required to correct the entire volume, and the depth of focus was increased to at least 550 microns. Furthermore, a bell pepper was imaged and defocus was corrected in the entire volume by applying the phase extracted from the cucumber image.

## ACKNOWLEDGMENTS

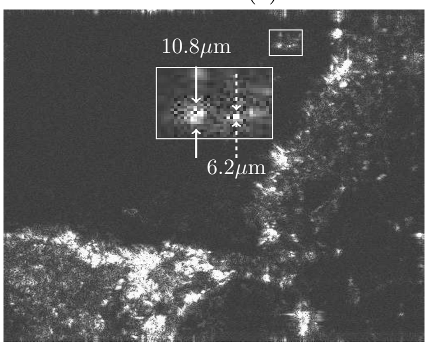
All authors acknowledge support from Innovation Fund Denmark through the Shape OCT grant No. 4107-00011A.



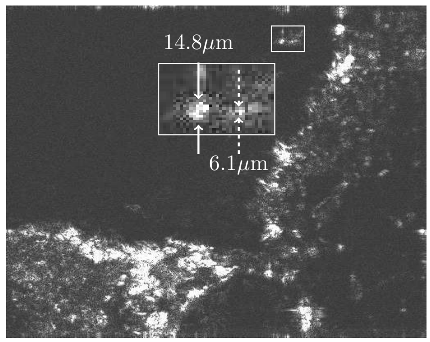

(a) Overview of cucumber volume



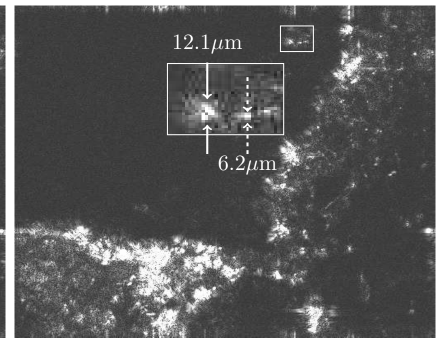

(b) Raw image



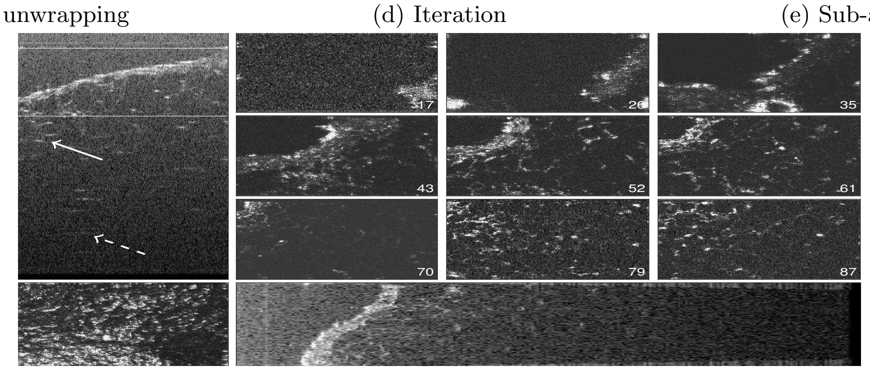

(c) Direct unwrapping




(d) Iteration




(e) Sub-aperture




(f) Corrected volume

Figure 1: OCT image of a cucumber slice. (a) shows an overview of the raw data, (b) shows a raw *en-face* image, (c)-(e) shows correction with direct unwrapping, iterations, and sub-aperture correlations, respectively. (f) show an overview of the corrected volume.

## REFERENCES

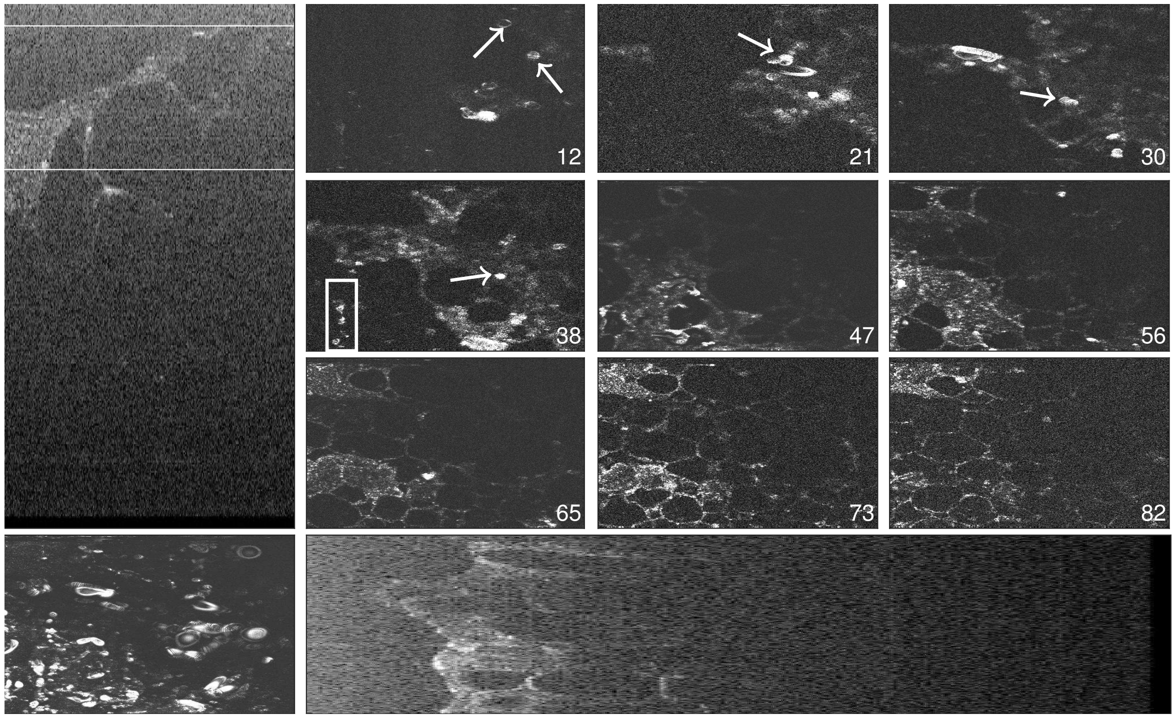
[1] Huang, D., Swanson, E. A., Lin, C. P., Schuman, J. S., Stinson, W. G., Chang, W., Hee, M. R., Flotte, T., Gregory, K., Puliafito, C. A., Et, A., and al., E., "Optical coherence tomography.," *Science* **254**(5035), 1178–81 (1991).

[2] Zhou, C., Wang, J., and Jiao, S., "Dual channel dual focus optical coherence tomography for imaging accommodation of the eye.," *Optics express* **17**, 8947–55 (may 2009).

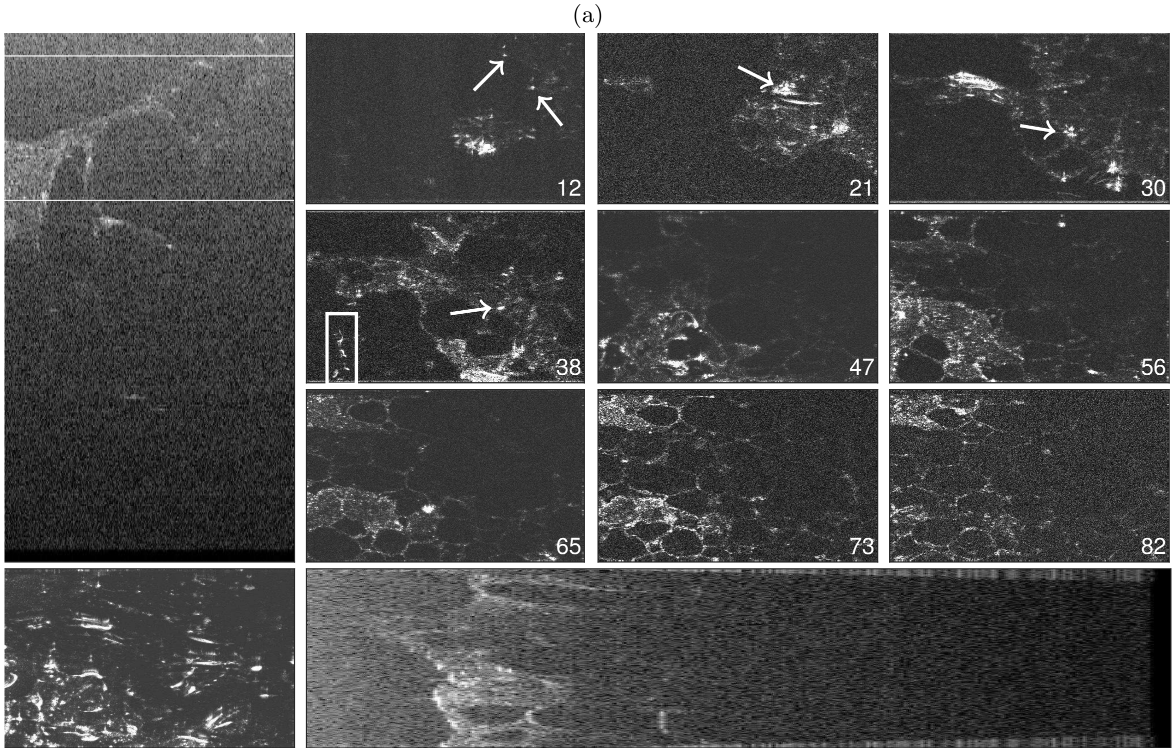
[3] Rolland, J. P., Meemon, P., Murali, S., Thompson, K. P., and Lee, K.-s., "Gabor-based fusion technique for Optical Coherence Microscopy," *Optics Express* **18**, 3632 (feb 2010).

[4] Ralston, T. S., Marks, D. L., Carney, P. S., and Boppart, S. A., "Interferometric synthetic aperture microscopy," *Nature Physics* **16**(4), 2555–2569 (2007).

[5] Kumar, A., Drexler, W., and Leitgeb, R. A., "Subaperture correlation based digital adaptive optics for full field optical coherence tomography," *Optics Express* **21**(9), 10850 (2013).




(a)




(b)

Figure 2: Overview of a 3-D image of a bell pepper with (a) being the raw image and (b) the corrected image. (b) is corrected with the phase estimated with the fitting method from a single *en-face* image of the cucumber.

[6] Adie, S. G., Graf, B. W., Ahmad, A., Carney, P. S., and Boppart, S. A., "Computational adaptive optics for broadband optical interferometric tomography of biological tissue," *Proceedings of the National Academy of Sciences* **109**(19), 7175–7180 (2012).

[7] Ghiglia, D. C. and Romero, L. A., "Robust two-dimensional weighted and unweighted phase unwrapping that uses fast transforms and iterative methods," *Journal of the Optical Society of America A* **11**, 107 (jan 1994).