Phase estimation for global defocus correction in optical coherence tomography

2nd CCOCT in Canterbury

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September 8, 2017
Optical coherence tomography
  - The need for defocus correction in OCT

Refocusing
  - Hardware corrections
  - Numerical phase corrections

2-D Phase estimation
  - Direct fitting method
  - Iterative method
  - Sub-aperture method

Conclusion
Optical coherence tomography (SD-OCT)

- In-depth imaging using white light interferometry

![Diagram of SD-OCT setup]

- Broadband source
- Beam splitter
- Reference mirror
- Sample
- Spectrometer
Optical coherence tomography (SD-OCT)

- **In-depth imaging using white light interferometry**

![Diagram of SD-OCT](image-url)

- Broadband source
- Beam splitter
- Reference mirror
- Spectrometer

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Refocusing - How is it done?

- Multiple probe beams
  - Increases system complexity and processing time

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**Equation:**

$$I \propto |E_R(k) + E_S(x,y,k)|^2 = |E_R|^2 + |E_S|^2 + E_S E^* R + E^* S E R$$

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Numerical schemes:
- Numerical wavefront correction

For defocus,
- $\phi_{NL}$ is parabolic

Estimation of $\phi_{NL}$
- Least squares / unifitting
- Iterative methods
  - Sub-aperture method (mimics wavefront sensor)

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2-D phase estimation for defocus correction in OCT

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Refocusing - How is it done?

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![Diagram with components: Broadband source, Beam splitter, Reference mirror, Spectrometer, white text, and an image of an OCT scan with green and red lines.]

Mathematical expression:
\[ I \propto |E_R(k) + E_S(x,y,k)|^2 = |E_R|^2 + |E_S|^2 + E_S^*E_R + E_R^*E_S \]
Refocusing - How is it done?

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![Diagram of Refocusing setup]

- Broadband source
- Beam splitter
- Reference mirror
- Spectrometer

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![Diagram](image_url)

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Interferometry

\[ I \propto |E_R(k) + E_S(x,y,k)|^2 = |E_R|^2 + |E_S|^2 + E_S^*E_R + E_R^*E_S \]

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Conv OCT

Mirror terms

\[ z \]
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\[ \text{Conv OCT} \quad \text{Mirror terms} \]

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- Numerical schemes
  - Numerical wavefront correction
    - \[ \tilde{I}_C(k_x, k_y, z_0) = \tilde{I}(k_x, k_y, z_0) \exp(-i\phi_{NL}(k_x, k_y)) \]
Refocusing - How is it done?

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  - Increases system complexity and processing time

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  \[ I \propto |E_R(k) + E_S(x, y, k)|^2 = |E_R|^2 + |E_S|^2 + E_S E_R^* + E_R^* E_S \]

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Multiple probe beams

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  - For defocus, \( \phi_{NL} \) is parabolic

- Estimation of \( \phi_{NL} \)
  - Least squares fitting
  - Iterative methods
  - Sub-aperture method (mimicks wavefront sensor)
Refocusing - Phase estimation

- Least squares fitting
  - 2-D unwrapping is an over-bound problem
    \[-\pi < \phi < \pi\]

\[ k_x \]
\[ k_y \]
Refocusing - Phase estimation

- Least squares fitting
  - 2-D unwrapping is an over-bound problem
  - LS solution
Least squares fitting
- 2-D unwrapping is an over-bound problem
- LS solution
- Fit
Refocusing - Phase estimation

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  - Variance used as sharpness metric
Refocusing - Phase estimation

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  - Fit
- Iterative method
  - Variance used as sharpness metric
- Sub-aperture method [1]

Refocusing - Cucumber slice
Refocusing - A single *en-face* image

- *En-face* number 33: ~ 330 microns above focus
Refocusing - A single *en-face* image

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Refocusing - A single *en-face* image

- *En-face* number 33: $\sim 330$ microns above focus

Fitting

- $\sim 54\,\mu m$
- $16.2\,\mu m$
- $10.8\,\mu m$
- $6.2\,\mu m$
Refocusing - A single *en-face* image

- *En-face* number 33: ~ 330 microns above focus

![Image of en-face image with measurements](image1.png)

**Iteration**

![Image of iteration with measurements](image2.png)
Refocusing - A single *en-face* image

- *En-face* number 33: \( \sim 330 \) microns above focus

![En-face image](image1.png)

Sub-aperture

![Sub-aperture image](image2.png)
Refocusing - A volume

- Defocus unaffected by sample
- $\phi_{NL} \propto z - z_F$
- Extrapolation from a single *en-face*
Refocusing - A volume

- Defocus unaffected by sample
- $\phi_{NL} \propto z - z_F$
- Extrapolation from a single en-face

390 microns above focus
Refocusing - A volume

- Defocus unaffected by sample
- $\phi_{NL} \propto z - z_F$
- Extrapolation from a single *en-face*

234 microns above focus
Refocusing - A volume

- Defocus unaffected by sample
- $\phi_{NL} \propto z - z_F$
- Extrapolation from a single *en-face*

78 microns above focus
Refocusing - A volume

- Defocus unaffected by sample
- $\phi_{NL} \propto z - z_F$
- Extrapolation from a single en-face

78 microns below focus
Refocusing - A volume

- Defocus unaffected by sample
- $\phi_{NL} \propto z - z_F$
- Extrapolation from a single en-face

234 microns below focus
Refocusing - A different volume

- A bell pepper volume corrected with the previous phase
Refocusing - A different volume

- A bell pepper volume corrected with the previous phase

\[ \sim 300 \text{ microns above focus} \]
Conclusion

- OCT suffers from defocus
Conclusion

- OCT suffers from defocus
- Complicated hardware solutions
  - Multiple probe beams
  - Modifying focus of a single beam

Interferometric nature of OCT allows numerical phase corrections. All three methods give similar improvements. DOF increases from 2–9 microns – factor of ∼2 improvement. Limited by top of sample and multiple scattering.

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- Interferometric nature of OCT allows numerical phase corrections
  - All three methods give similar improvements
  - Diffraction limited
- Phase extrapolated to correct entire volumes
  - Phase estimation is a one-time job
  - Applied continually
Conclusion

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  - Modifying focus of a single beam

- Interferometric nature of OCT allows numerical phase corrections
  - All three methods give similar improvements
  - Diffraction limited

- Phase extrapolated to correct entire volumes
  - Phase estimation is a one-time job
  - Applied continually

- DOF > 550 microns
  - Up from 290 microns – factor of ~2 improvement
  - Limited by top of sample and multiple scattering
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Thank you!

Any questions?