Deep neural networks for aberrations compensation in retinal imaging acquired by digital holography

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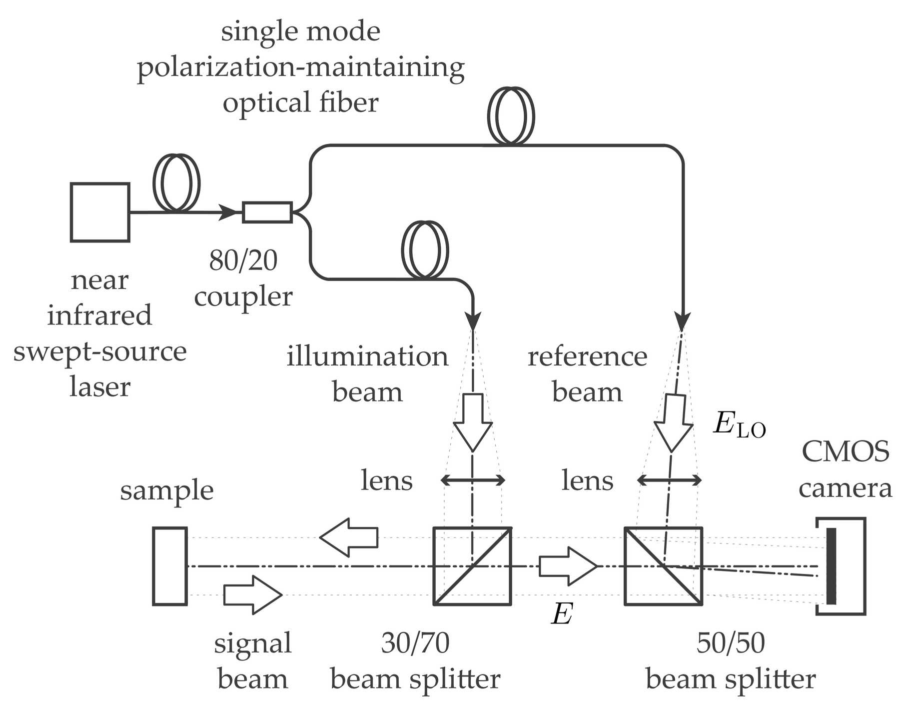
Abstract

Optical Coherence Tomography (OCT) is one of the most widely available technology for retinal imaging. It is commonly used to monitor and study eye diseases like glaucoma, macular degeneration and diabetes. We develop computational imaging approaches based on wide-field interferometric measurements for OCT imaging in order to increase the imaging throughput. With our setup and our home-made software Holovibes, we can reconstruct 3D holographic images in real-time, at 10 billion voxels per second.

In computational imaging by digital holography, **lateral resolution** of retinal images is **limited by the aberrations of the eye** to about 20 microns. To overcome this limitation and improve lateral resolution up to the diffraction limit, eye's aberrations have to be canceled. We are investigating **new digital aberration compensation schemes** to circumvent the limitations of aberrations correction algorithms of the state of the art.

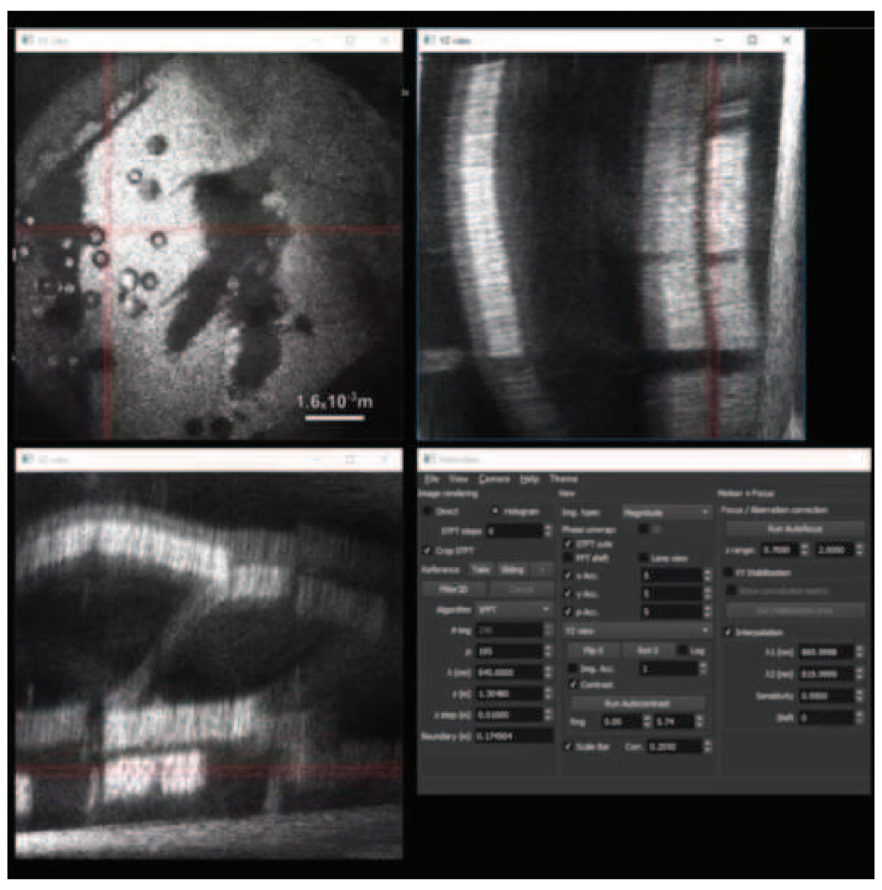
Setups

OCT Setup



OCT setup: the source is a tunable laser whose wavelength varies linearly from 870 nm to 820 nm in 0.5 s. The CMOS camera records 1024×1024 pixel images at a frame rate of 512 Hz with 16 bit/pixel quantization.

OCT images



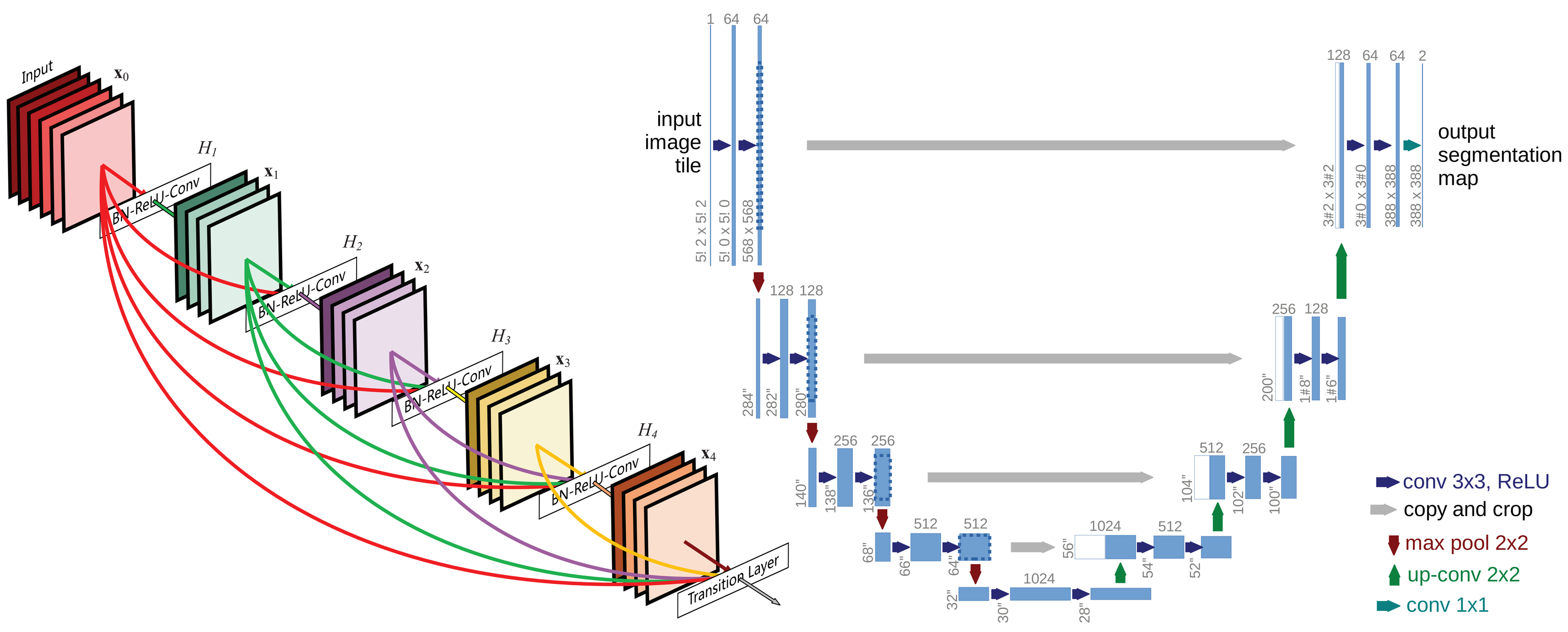
Real-time holographic tomography of a semi-transparent sample of 400-800 microns silica beads wrapped with tape.

Our setup provides en-face and axial images at the same time. It is still a prototype. Imaging in the eye was demonstrated at much faster acquisition rates (60 kHz) to circumvent physiological motion [5].

Axial field of view is about 1.8 mm, with a resolution of **14 microns**.

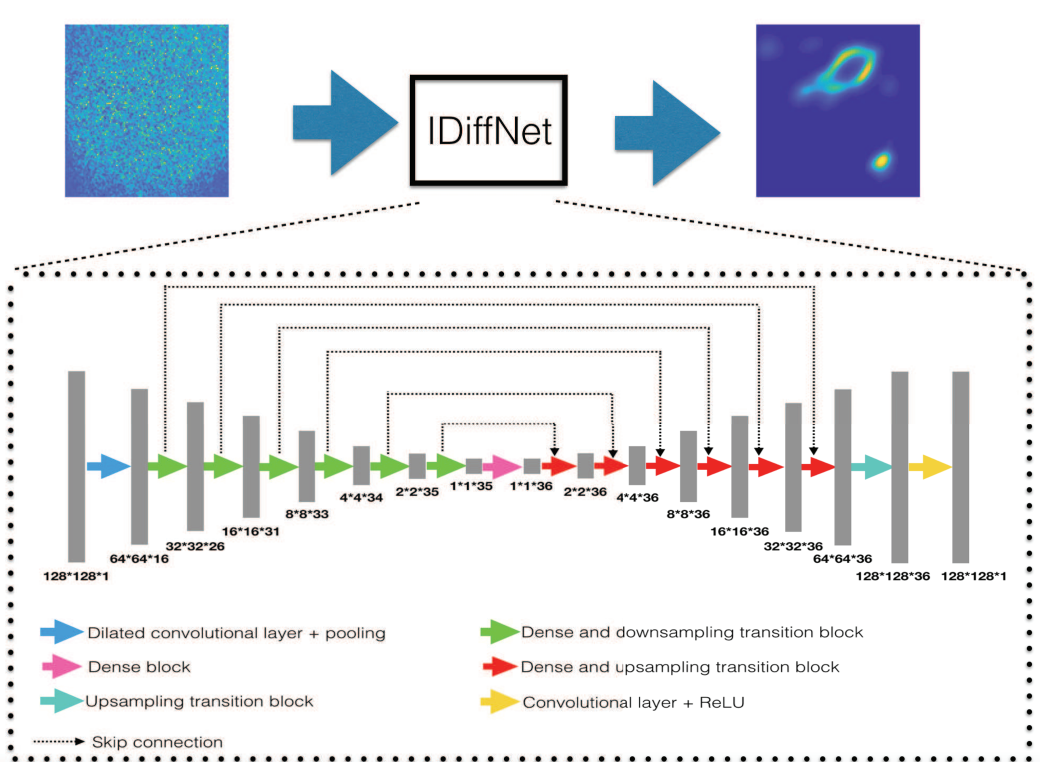
Input throughput: 512 Mega bytes per second.
Output throughput: 10 billion voxels per second.
Real-time images are obtained with **Holovibes**.

Deep neural networks for aberrations compensation

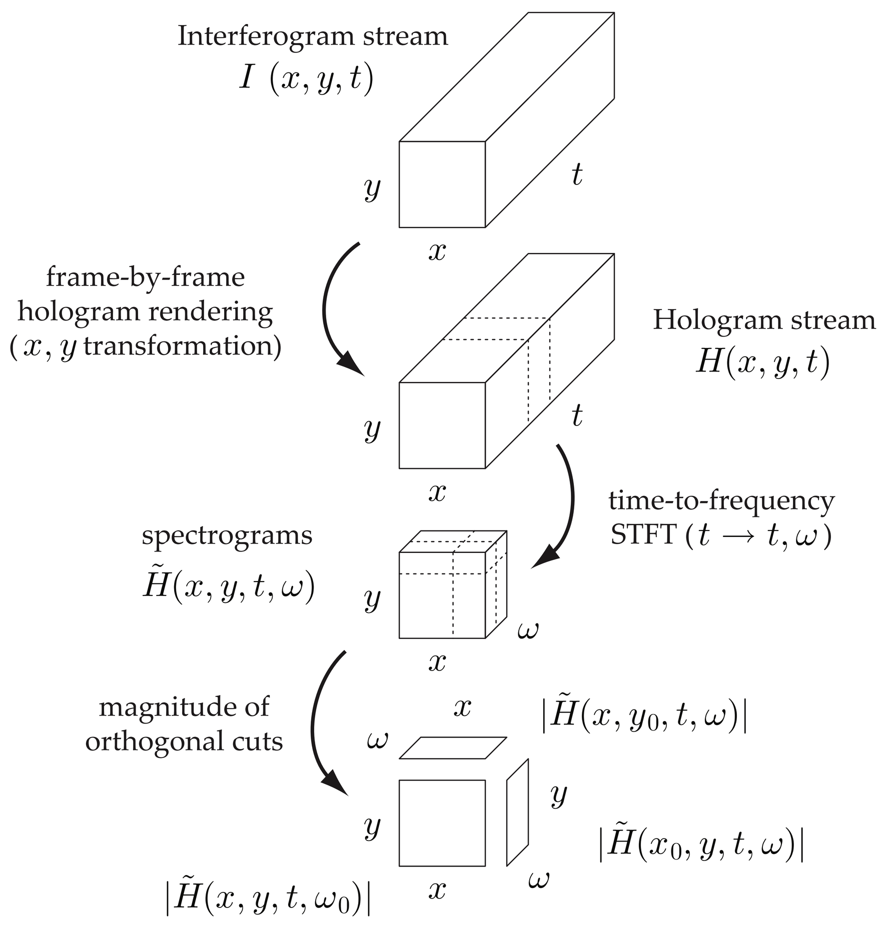


A 5-layer denseblock (left) and U-net (right).

IDiffNet [1] is able to reconstruct phase images propagated through a scattering medium. It succeeds in computational image generation from interferogram measurements. It uses denseblocks from Densenet [2] and skip connections from U-Net [3], improving features propagation in the network. We are adapting this type of network in order to reconstruct intensity images of retina's layers. The network will be trained on the eye fundus database from the 15-20 hospital in Paris.



Digital image formation



To obtain retinal images, fields corresponding to interferograms acquired with the CMOS camera are digitally propagated from camera plane to image or reconstruction plane. Considering camera plane corresponds to $z = 0$, and the distance between both planes is z, field in image plane can be expressed as:

$$E(x, y, z) = E(x, y, 0) * h(x, y, z), \tag{1}$$

where $h(x, y, z)$ is the impulse response of free space propagation:

$$h(x, y, z) = \frac{e^{ikz}}{i\lambda z} e^{i\frac{k}{2z}(x^2+y^2)}. \tag{2}$$

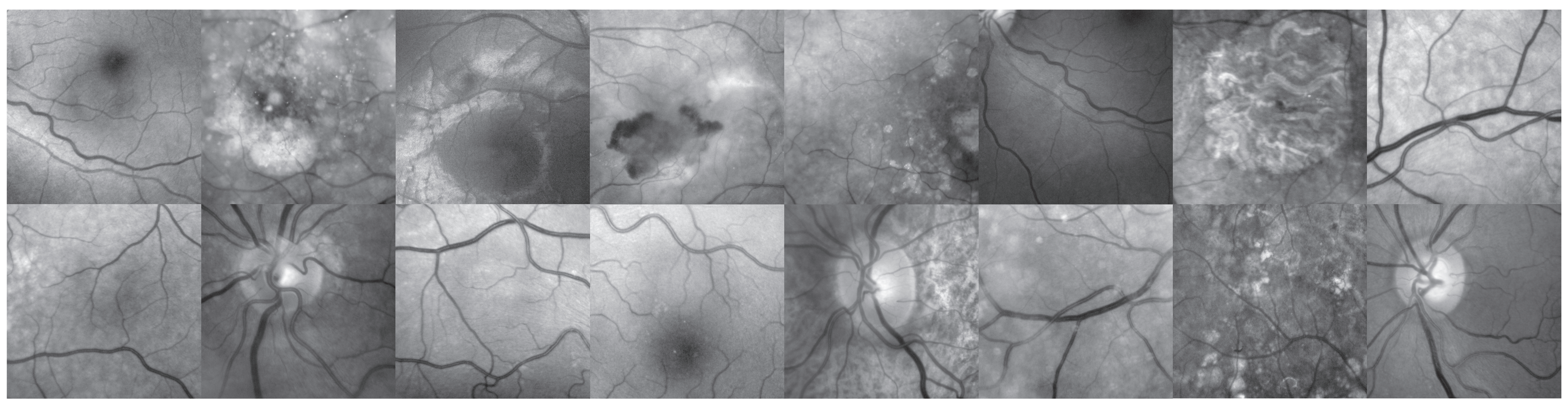
Intensity interferogram acquired can be related to the field with $I(x, y, 0) = |E(x, y, 0)|^2$. In the same way, $H(x, y, z) = |E(x, y, z)|^2$. The same relation Eq. 1 exists between interferogram and hologram:

$$H(x, y, z) = I(x, y, 0) * h(x, y, z). \tag{3}$$

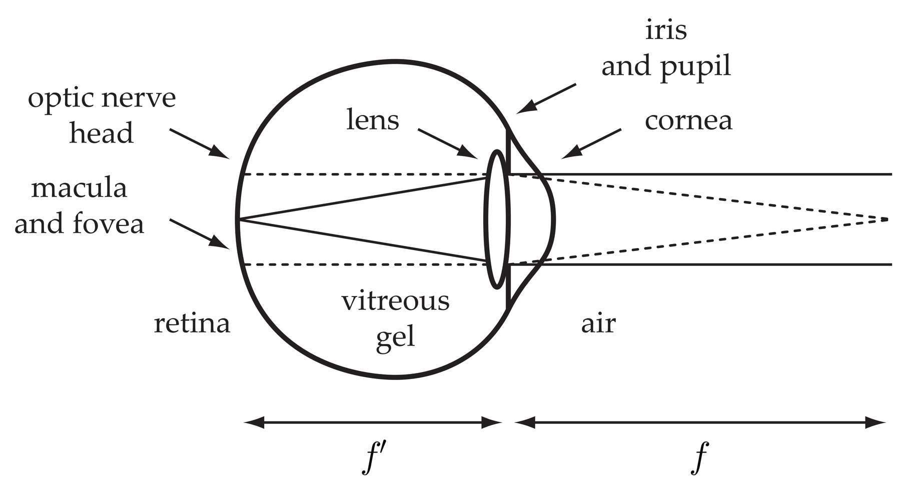
Time Fourier transform is then applied to get frequency and depth dependency.

Aberrations compensation

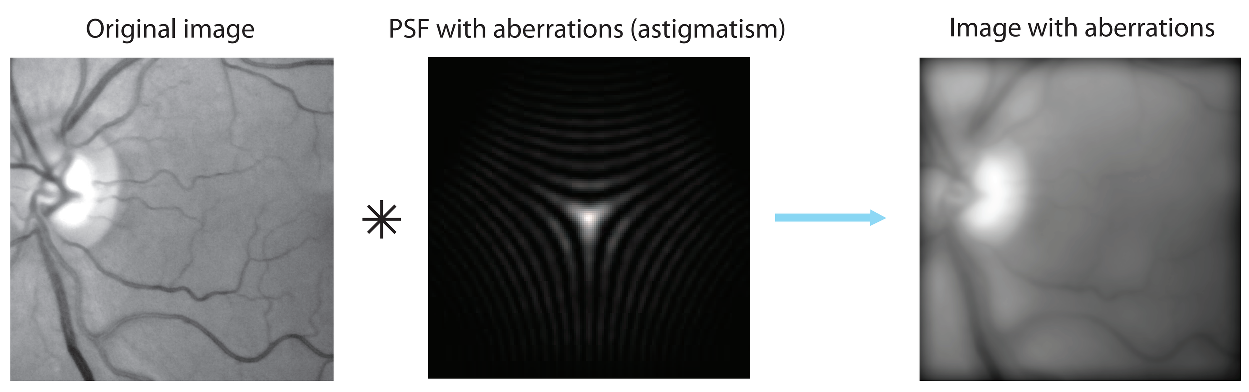
1 Simulation



Images extracted from eye fundus database, collected at the 15-20 hospital in Paris.

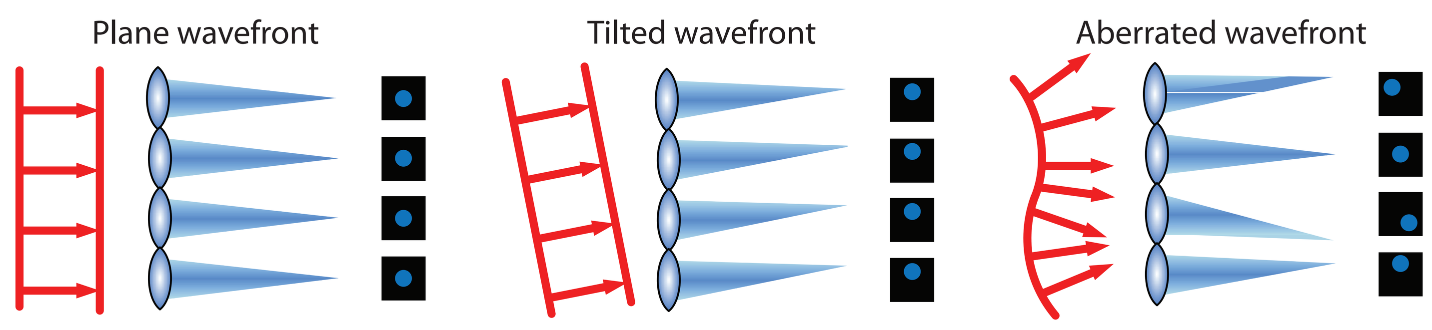


Sketch of the optical configuration.



Intensity images are convoluted to a point spread function (PSF) corresponding to the impulse response of the eye's optical system which light beam crosses. If there is no aberration, the wavefront will not be distorted, the PSF will be a point and the image will stick to the original one. If there are aberrations, created by cornea, the PSF will not be a point anymore, which means the wavefront will be distorted. The resolution of resulting image will decrease.

2 State of the art



Shack-Hartmann wavefront sensor principle.

The focal plane of the lens is divided into multiple sub-lenses. Each of them provides PSF for some parts of the plane. If the wavefront is not aberrated, each PSF will be in the middle of each sub-image in the focal plane. If the wavefront is distorted, each PSF will be shifted according to the wavefront's slope. The relation between wavefront and PSF is defined by $PSF = FFT\{\Gamma_{wavefront}\}$, where FFT means Fast Fourier Transform, and $\Gamma_{wavefront}$ is the autocorrelation of the wavefront in the focal plane.

Aberration compensation methods:
Reconstruction of digital holograms in subapertures: wavefront measurement, lateral phase correlation analysis and non-iterative aberration compensation of retinal holograms [4].
Iterative digital aberration compensation: minimization of the local entropy of speckle-averaged tomographic volumes [5].

Further reading

References

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