

# OCT wavenumber calibration with simple reference arm modification

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**Abstract:** FD-OCT systems with non-uniform wavenumber sampling require calibration and resampling routines to achieve optimal axial resolution. We present a simple calibration procedure and provide all necessary algorithmic components for wavenumber resampling. © 2021 The Author(s)

## 1. Introduction

The essential processing step in Fourier-domain optical coherence tomography (FD-OCT) is the inverse Fourier transform which relates wavenumber to distance. If the acquired interference signal is not sampled linearly in wavenumber the resulting depth scan has a decreased axial resolution compared to the theoretically possible resolution. To address this issue one of two strategies can be used. Either the interference signal is already acquired linearly in wavenumber, e.g. with k-clocking in swept source OCT or with a linear-in-wavenumber spectrometer in spectral domain OCT [1], or the signal is resampled after acquisition which is also called k-linearization. The second strategy usually requires a calibration measurement but in most cases the k-linearization approach is easier to implement from the hardware side and reduces the complexity and cost of the optical setup. Various k-linearization techniques have been published [2-7]. However, most of these have a complicated calibration routine and/or require significant amount of time to implement the necessary algorithms that are part of the procedure. Here we present an extremely simple calibration setup that can be adapted for every FD-OCT system with a free-space optics reference arm. We also describe the required processing scheme and provide an open source implementation of it.

## 2. Methods

Figure 1 shows a simplified version of our optical setup with emphasis on the modified reference arm. It includes a movable glass window that, in combination with the reference arm mirror, acts as a Fabry-Perot interferometer with variable cavity length. When placed at the right distance from the mirror, an autocorrelation signal is generated that does not suffer from dispersion imbalance and is used for the wavenumber calibration procedure.

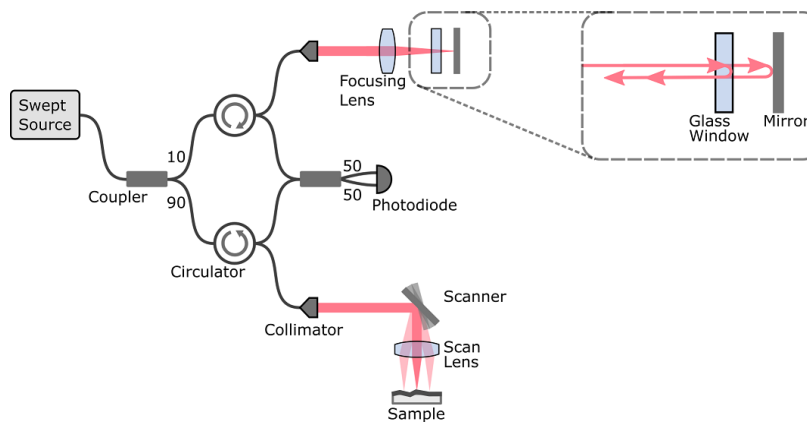


Fig. 1. Fiber based swept source OCT setup with a glass window in the reference arm. The light reflected from the back side of the glass window and the light reflected from the mirror create an autocorrelation signal that is not affected by dispersion imbalance and is used for wavenumber calibration.

Three different autocorrelation signals with different origins can occur with this setup:

- Reflections from front surface of the glass window and its back surface
- Reflection from front surface of glass window and reflection from mirror
- Reflection from back surface of glass window and reflection from mirror

Only the autocorrelation signal from case c) is used for the calibration routine. To avoid signals from case a) and b) a wedged window can be used. Alternatively a glass window can be used with an optical thickness that is larger than the imaging depth of the OCT system.

Once a signal is acquired with this method, the instantaneous phase, which is used to generate a remapping function, needs to be extracted. The remapping function assigns every index of the OCT interference signal a fractional index. The signal value at this fractional index needs to be interpolated and resampled to the index position given by the remapping function to obtain a wavenumber linearized signal. Figure 2 shows the processing steps that are used to retrieve the instantaneous phase from the autocorrelation signal. First, several hundred signals are acquired and averaged. Then a fast Fourier transform (FFT) is performed which results in a “pre A-scan” since the magnitude is not calculated. A multiplication by a rectangular window function is then performed to remove everything but the autocorrelation signal. This, in combination with the initial averaging, makes it possible to use the calibration routine even with a sample present in the sample arm. For the next step the inverse FFT is applied on the windowed autocorrelation signal. The resulting complex signal is then used to extract the wrapped phase with the two-argument variant of the arctangent function. Finally, phase unwrapping is performed. This extraction method is very similar to the one described by Gora et al. [8], but differs in a simple but crucial step. Gora et al. use the Heaviside function to remove complex conjugate and DC signal instead of a rectangular window that encloses the calibration signal. This means that the entire signal may only consist of the calibration signal and the light from the sample arm needs to be blocked or the sample needs to be removed.

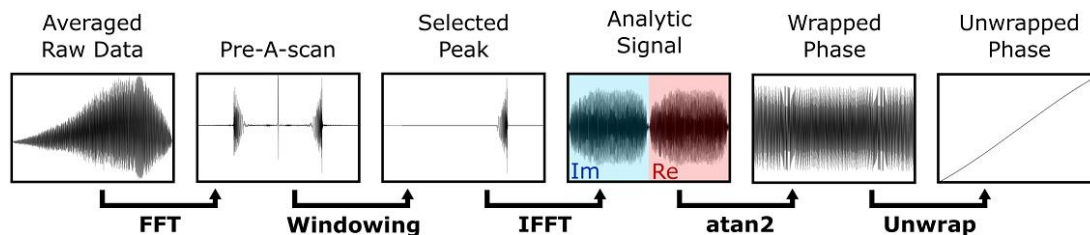


Fig. 2. Extraction process to obtain the instantaneous phase of the autocorrelation signal. FFT: fast Fourier transform, IFFT: inverse FFT, Im: imaginary part, Re: real part, atan2: two-argument variant of arctangent function

For an autocorrelation signal that is already sampled linearly in wavenumber the unwrapped phase is a straight line. This fact can be used to derive a remapping function from the retrieved non-straight unwrapped phase. The exact algorithm, including the steps described previously, can be found in the source code of the *Phase Extraction Extension* which we provide together with the OCT processing software OCTproZ [9].

The goal of the calibration routine is to obtain the remapping function which is used for k-linearization. It needs to be performed only once and is valid as long as the non-linear wavenumber sampling remains unchanged. After the calibration is done, the glass window in the reference arm can be removed. It is also possible to leave the window in the setup and just slightly move it to increase the cavity length such that no autocorrelation signal is visible in the OCT acquisitions.

### 3. Results

Figure 3 shows OCT images with simultaneous acquisition of sample signal and calibration signal from the modified reference arm. A laminated IR detector card is used as sample. When k-linearization is performed axial resolution drastically improves which can be seen on the sample (middle part of Fig. 3b) as well as on the calibration signal itself (bright horizontal line in Fig. 3b). To get the best image quality the glass window is moved within the reference arm such that the calibration signal is not visible anymore and further processing steps are applied. These include numerical dispersion compensation and fixed-pattern noise removal.

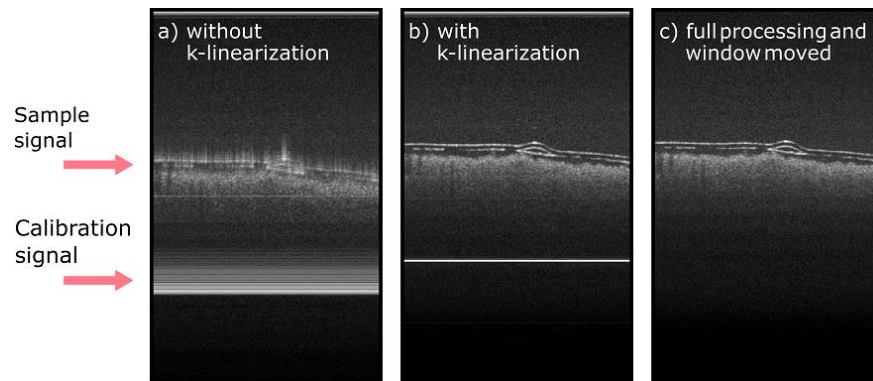


Fig. 3. Simultaneous acquisition of sample signal and calibration signal. A laminated IR detector card is used as sample. a) k-linearization is not performed. b) k-linearization is performed. c) Numerical dispersion compensation and fixed-pattern noise applied. Glass window is moved within reference arm to increase cavity length and calibration signal is not visible any more.

### 4. Acknowledgements

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