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Signal processing with unequally spaced data in Fourier-Domain Optical Coherence Tomography

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ABSTRACT

Different algorithms for performing Fourier transforms with unequally sampled data in wavenumber space for Fourier-domain optical coherence tomography are considered. The efficiency of these algorithms is evaluated from point-spread functions obtained with a swept-source optical coherence tomography system and from computational time. Images of a 4-layer phantom processed with these different algorithms are compared. We show that convolving the data with an optimized Kaiser-Bessel window allowing a small oversampling factor before computing the fast Fourier transform provides the optimal trade-off between image quality and computational time.

Keywords: Optical Coherence Tomography, Swept Source OCT, Nonlinear optical signal processing

1. INTRODUCTION

In Fourier-domain optical coherence tomography (FD-OCT), one often has to deal with unequally spaced data in wavenumber space (k -space). In swept-source OCT (SS-OCT) it is caused by the nonlinear sweep of the source in wavenumber. In spectral-domain OCT (SD-OCT), it is caused by the combination of spectrometer and CCD detector array. This can be compensated with hardware modifications by using a linear in wavenumber swept-source¹ or by providing k -triggering in SS-OCT and by using a specially designed detection unit in SD-OCT.^{2,3} These hardware modifications bring additional challenges in the fabrication of an OCT system. This is why one normally compensates for the unequally spaced data by interpolating to obtain evenly spaced data in k -space prior to performing a fast Fourier transform (FFT). In this paper, we explore different algorithms to process the unequally spaced data. The efficiency of each algorithm is evaluated from the point-spread function (PSF) measured at various depths. Computational times are also compared to identify the algorithm which offers the best trade-off between image quality and computational time.

2. ALGORITHMS USED

The different algorithms used in our study are based on:

- the Vandermonde matrix;
- a linear interpolation + FFT (abbreviated as LIFFT _{α});
- a spline interpolation + FFT (abbreviated as SIFFT _{α});
- a convolution by a Kaiser-Bessel window of a length M + FFT (abbreviated as KBFFT _{M,α});

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where α is the oversampling factor in the k -space: it corresponds to the number of points involved in the FFT operation so that $N' = N\alpha$ where N is the number of acquired points.

These different methods are fully described in Vergnole et al.⁴ Here we only present the Kaiser-Bessel method since we will show that it is the optimal method. This method, known as gridding in MRI,⁵ can be advantageously used for the data inversion of the SS-OCT data. In this method, OCT data is convolved in the k -space with a Kaiser-Bessel window, followed by the use of conventional FFT. Very recently, such a method was proposed in OCT using an integer oversampling factor and was applied only to simulated data.⁶ Our approach uses a small fractional oversampling factor which lies between 1 and 2 allowed by an optimized β value. This implies that smaller vectors are used, insuring small processing time while maintaining high accuracy. The k vector is in the range $k_{\min} < k < k_{\max}$. The step sizes in wavenumber domain is defined as $\delta k = (k_{\max} - k_{\min})/N\alpha = 2\pi/N'\delta z$ and in the optical path domain as $\delta z = 2\pi/(k_{\max} - k_{\min})$. The convolution of OCT data is made on N' center values of k using the optimal Kaiser-Bessel window as:

$$U_k = \sum_{j=1}^M U_j C_{kj} \quad (1)$$

where

$$C_{kj} = I_0 \left(\beta \sqrt{1 - (2\kappa/M)^2} \right) / M, \quad \kappa = \left| \frac{k - k^j}{\delta} \right| \leq \frac{M}{2} \quad (2)$$

where I_0 is the zero-order modified Bessel function of the first kind, and k^j 's are the neighboring points around the center value k . The optimized design parameter β is defined as:⁷

$$\beta = \pi \sqrt{\frac{M^2}{\alpha^2} \left(\alpha - \frac{1}{2} \right)^2 - 0.8} \quad (3)$$

This choice of β makes possible the use of an oversampling factor α smaller than 2 while maintaining a good accuracy. For one-dimensional data such as in OCT and M typically between 3 and 8, the C_{kj} are calculated once for processing all SS-OCT signals. The convolution of the data with a Kaiser-Bessel window requires a correction after the FFT operation, multiplying the result with the vector c_n given by:⁷

$$c_n = \frac{\sqrt{(n\pi M/N')^2 - \beta^2}}{\sin \left(\sqrt{(n\pi M/N')^2 - \beta^2} \right)} \quad (4)$$

where n is the index (linked to the optical path) and complex arithmetics is allowed. The overall scheme has a complexity of $O(N' \log N')$.

3. EXPERIMENTAL RESULTS

Measurements were performed with a custom-built Mach-Zehnder SS-OCT interferometer using a Santec swept source with a repetition rate of 30 kHz, a bandwidth of 110 nm and a center wavelength of 1310 nm. For each A-scan, the number of acquired points is $N=1666$. The point spread functions (PSF) were obtained from a mirror located at various depth positions from the zero-delay position of the SS-OCT system. The data was post-processed using the different algorithms stated in section 2 and the PSFs are plotted in Fig. 1. Table 1 gives the computational time of each method.

Table 1. Computational time for 1000 A-scans (ms) evaluated on a PC with an Intel Core2 Duo CPU T7700 @ 2.4 GHz and 3.5 GB RAM and running of one processor.

Vandermonde	LIFFT ₂	SIFFT ₁	KBFFT _{5,1.2}
3052	137	230	129

The Vandermonde method is the more exact method and gives a good quality PSF with low variation of noise

level but it is also the slower method. LIFFT₂ shows low computational time but the signal at deeper positions is quite noisy. SIFFT₁ exhibits huge noise level variation at deeper positions and the SIFFT method would require an oversampling factor of 2 to get better image quality which results in a larger computational time. Finally, the convolution with a Kaiser-Bessel + FFT method offers the best trade-off between PSF quality and computational time. Indeed, the PSF are almost as good as what was obtained with the Vandermonde method and the computational time is the lowest of all the methods proposed here.

Figure 1. PSF for different signal processing methods.

The previous results are further confirmed by imaging a custom-built 4-layer phantom using a variation of the technique described in Bisailon et al.⁸ Figure 2 shows the measurement on this phantom.

Figure 2. OCT images of a 4-layer phantom using different signal processing methods. Images are 6.5 cm wide by 6.5 cm deep. Each axis tic mark corresponds to 1 mm.

The images obtained with the Vandermonde and KBFFT_{5,1.2} methods present the nicer results: the four different layers are very well delineated. On the other hand, LIFFT₂ and SIFFT₁ methods provide images with artifacts which could lead to misinterpretation: indeed, one can believe that there are more than 4 layers in the images processed with these methods.

4. DISCUSSION AND CONCLUSION

A comparison of various methods to process the data in SS-OCT was performed by evaluating PSFs and by imaging a structured phantom. These methods include non-uniform discrete Fourier transforms with Vandermonde matrix, resampling with linear interpolation or spline interpolation prior to FFT, and resampling through convolution with a Kaiser-Bessel function followed by FFT. The latter method with a small fractional oversampling factor of 1.2 was shown to provide similar results as the reference method using the Vandermonde matrix, but with a much smaller processing time.

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