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Julia Walther, Lars Kirsten, Edmund Koch

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Optimal processing of Doppler signals in OCT

Julia Walther, Lars Kirsten, Edmund Koch

Technische Universität Dresden, Medizinische Fakultät Carl Gustav Carus,
Klinik für Anästhesie und Intensivtherapie, Klinisches Sensoring und Monitoring,
Fetscherstraße 74, 01307 Dresden, Germany

ABSTRACT

Besides structural imaging, OCT can be used to estimate axial velocities of the sample resolved in depth by Doppler-processing. In Fourier domain OCT (FD-OCT), this is accomplished by measuring the phase difference (i.e. phase shift) between timely separated A-scans at the same depth. In most cases, these data are disturbed by noise caused by intrinsic noise of the OCT system, specified by the SNR, and decorrelation noise caused by the transversal movement of the optical beam relative to the sample. Since the first use of Doppler methods in OCT, many methods to reduce the phase shift noise by averaging have been presented. While all these methods use a fixed set of consecutive A-scans, the best method, exhibiting no bias and having the smallest standard deviation, was questionable. Recently, Doppler processing methods depending on the mentioned noise sources and delivering the most likely phase shift and thereby axial velocity became available. The relation of these methods to previously known methods like the Kasai estimator, maximum likelihood estimator (MLE) and joint spectral and time domain OCT (jSTdOCT) will be discussed.

Keywords: Optical coherence tomography, Doppler processing, flow measurement

1. INTRODUCTION

Optical coherence tomography (OCT) is an interferometric noninvasive high-resolution imaging modality providing cross-sectional images with micrometer resolution [1]. Because of the high speed and increased signal to noise ratio (SNR), Fourier domain OCT (FD OCT) is today preferred to time domain OCT (TD OCT) to acquire tomographic data [2,3]. There, the structural and velocity information is extracted by a Fourier transform (FT) of the spectral interference fringe signal resulting in a complex-valued depth scan. The absolute value is defined as A scan representing one vertical line in a cross-sectional morphological image (B scan). The argument contains the phase information of the light prevalently used for flow measurement in scattering samples, which is based on the Doppler principle. Sample movement in the direction of the incident sample beam results in a frequency shift of the interference fringe signal referred to as Doppler frequency shift. The local Doppler frequency shift at a special depth position can be obtained from the phase change between sequential A-scans known as Doppler OCT (DOCT). The sensitivity of the Doppler measurement is limited by the phase sensitivity of the OCT system, which is fundamentally affected by additive noise like detector and shot noise [4,5] resulting in a reduced SNR [5,6,7], by speckle noise and by decorrelation of adjacent signals due to transverse motion between beam and sample either by beam scanning or sample movement [8,9]. To minimize phase shift noise $\sigma(\Delta\phi)$ and by this velocity noise averaging of phase shifts [8,9,10] is essential. For the extraction of the velocity information from the complex OCT data many attempts have been made. The standard method for extracting the phase information from K sequential A-scans, which has no bias and takes advantage of the higher precision of data with high amplitude, calculates the mean phase by

$$\overline{\Delta\phi(z)} = \arg \left\{ \sum_{j=1}^{K-1} \Gamma_{j+1}(z) \cdot \Gamma_j^*(z) \right\} \quad (1)$$

Some authors call this method the Kasai autocorrelation [11] as well. In the following we will name this averaging method phase-resolved Doppler OCT (PR DOCT) processing.

Alternatively to PR DOCT, the flow velocity can be estimated by using joint spectral and time domain OCT (jSTdOCT), which calculates the Doppler frequency shift $f_D(z)$ occurring between consecutive spectral interference fringes [12]. In jSTdOCT a Fourier transformation of a complex time series $\Gamma_j(z)$ results in a Doppler frequency spectrum. The

* Presenting author: Tel.: +49 351 458 6131; E-mail: Edmund.Koch@tu-dresden.de

frequency of the component (as the data $\Gamma_j(z)$ still form a time series) with the highest amplitude is taken as an estimate for the axial velocity:

$$f_D'(z) = \arg \max \{ \text{FT}[\Gamma_j(z)] \} / K \quad (2)$$

Zero padding of the input series $\Gamma_j(z)$ is used to get a finer grading for the discrete velocity values resulting from this calculation. Some authors have called this method the maximum likelihood estimator, as it can be shown that under the assumption of additive Gaussian noise this frequency is the optimal choice. Because in many cases the main noise source is decorrelation source the requirement for the deduction is often not fulfilled.

More methods for averaging OCT-Doppler data have been presented in the literature.

2. NEW MODELS

In recent years it became evident that due to the decorrelation noise, depending on the transversal velocity, optimal averaging methods will depend on an estimate for the transversal velocity [13]. Decorrelation noise will broaden the peak in the frequency spectrum of the OCT data. Additionally, shot and detector noise, expressed by the signal to noise ratio (SNR), will lead to white noise in the frequency spectrum. Recently, two different methods depending on both parameters have been presented. First, a heuristic method was found, by looking for a common notation for PR DOCT and jSTdOCT evaluation, which differs only in the exponent being two for DOCT and infinity for jSTdOCT. This method, called enhanced jSTdOCT (enhjSTdOCT), chooses an optimal exponent between 0.5 and 8, depending on SNR and transversal velocity, which was numerically found [14]. Compared to PR DOCT the enhanced method reduced the noise in the Doppler data by a factor of up to 1.4 as can be seen in Fig. 1 a). Moreover, enhjSTdOCT may be better by a factor of more than 3 at high transversal velocities and good SNR compared to jSTdOCT.

Figure 1. Relative phase noise of a) PR DOCT and b) jSTdOCT compared to the enhjSTdOCT with the optimized exponent plotted as a function of normalized transversal velocity v_x' and $1/\text{SNR}$. The scale $1/\text{SNR}$ is chosen to show all relevant data on a very limited scale. While PR DOCT is already optimal in a wide range of transversal velocities and SNR, characterized by the large red area, enhjSTdOCT improves the Doppler processing at almost axial movement (top left in a) and at high transversal movement (top right) with very good SNR. jSTdOCT is optimal at nearly axial movement (bottom in b) but can be improved by enhjSTdOCT at larger transversal velocities.

The second method searches for the most likelihood estimate of the Doppler frequency. Earlier work considering only additive Gaussian noise found that the Maximum Likelihood Estimator (MLE) for the Doppler frequency leads to the peak of the power spectral density. Recently, Chan et al. [15] presented a derivation considering decorrelation and white noise resulting in a new maximum likelihood Doppler frequency estimator for this case. Without going into the details of

the derivation, this method does not take the frequency with maximal power like the jSTdOCT, but uses the minimum of the circular convolution of the power spectral density (PSD) with a weighting function Σ^{-1} , which can be estimated from the autocorrelation function of the corresponding data. First, an estimate of the covariance function is calculated from the power spectral density. The Fourier transformation of the covariance function results in the diagonal elements of Σ . The most likelihood Doppler frequency is than found by searching for the minimum of the circular convolution between the power spectral density of the data and Σ^{-1} .

Instead of estimating this weighting function from data, this function can be calculated from the SNR and transversal velocity. White Gaussian noise results in a constant value in Σ . The transversal velocity broadens the peak in the power spectral density and therefore in Σ . Typical forms of Σ are shown in Fig. 2 for several transversal velocities and SNR. These curves have a peak, so that Σ^{-1} has a well as shown by Chan in [15]. To highlight the relationship to previously known methods, we suggest using the negative value of the function Σ^{-1} and search for the maximum, which is mathematically totally equivalent. Due to this inversion the function $-\Sigma^{-1}$ does not have a dip or well but a peak again. In the case of a circular convolution neither a constant value nor a positive factor has an influence on the position of the maximum.

Figure 2. Function Σ for several values of v_x and SNR. The width of the central peak depends on the transversal velocity. Due to the frequency spread the heights of the function reduces with increasing transversal velocity. The noise in the system results in a constant additive value, nicely visible at high transversal velocity and SNR of 1, but nearly invisible at low transversal velocity and a SNR of 20.

Figure 3. Normalized weighting function for different transversal velocities and SNR ratios. From left to right normalized transversal velocity of $v_x' = 0.05, 0.3$ and 0.6 , from top to bottom SNR of 20, 3 and 1

Therefore in Fig. 3 the calculated weighting function is plotted normalized to the range of zero to one for some values of transversal velocity and SNR. The transversal velocity is normalized to $v_x' = v_x / (f_{A\text{-scan}} w_0)$, where $f_{A\text{-scan}}$ is the A-scan frequency and w_0 the beam width (FWHM) of the Gaussian sample beam at the focus position. The data are shown for a set of $K = 32$ samples and zero padding to totally 64 samples. At first sight it might appear strange that the narrow peak for small transversal velocities in Σ results in quite differently broad peaks in $-\Sigma^{-1}$ but this is a consequent of the different constant value in Σ ,

As pointed out by others before the convolution between the power spectral data and $-\Sigma^{-1}$ will result only in as many different velocities as data points used for the Fourier transformation. But, instead of using a high degree of zero padding for a finer grading of the velocity scale, we only double the number of samples by zero padding and then use a quadratic interpolation of the circular convolution around the peak to get a continuous velocity distribution. Doubling the number of samples by zero padding avoids the correlation between the beginning and the end of the list, which will only introduce noise.

For small transversal velocities and low SNR the weighting function is similar to a Dirac-function (lower left). In this limit the method becomes equivalent to jSTdOCT, which takes the position of the maximum of the PSD. For medium SNR and transversal velocity (plots on the diagonal) the weighting function becomes more or less sinusoidal. It can be shown that a sinusoidal convolution is equivalent to PR DOCT [15].

When comparing the two new models it is noted that the standard deviation of both methods is always in a range of 25 % within the numerically tested region of SNR better than one and $v_x' < 0.6$, which is fulfilled in most biomedical applications. The computational speed of the new algorithm seems to be lower than PR DOCT, jSTdOCT and enhjSTdOCT. But, by using the low oversampling and a parabolic maximum estimation, the numerical effort will be similar to jSTdOCT and can efficiently implemented on GPU's.

3. CONCLUSION

Recently, two new methods for averaging Doppler data have been proposed, enhjSTdOCT and MLE under decorrelation noise. First, both methods outperform the classical methods like PR DOCT and jSTdOCT. Secondly, both are at some combinations of SNR and transversal velocity equivalent to the previously known methods PR DOCT and jSTdOCT. At low transversal velocity and low SNR both new methods are very similar to jSTdOCT, by taking the frequency of the maximum of the PSD. Moreover, the comparison shows that PR DOCT is nearly optimal in a large range of parameters, with medium SNR and medium transversal velocity. At good SNR and high transversal velocity the new methods are better than previously known methods.

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