Simultaneous spectral calibration and dispersion compensation using a thin piece of glass

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ABSTRACT

The behavior of the signal elements in a quantum-mimic OCT is modelled to provide coefficients for simultaneous spectral calibration and dispersion compensation. The method allows to obtain the correction vectors based on a single spectrum and in an almost fully automatic way.

1. INTRODUCTION

Raw spectra acquired in Spectral Optical Coherence Tomography (OCT) possess two types of nonlinearity. One originates in the spectrometer as a consequence of linear-in-λ operation of the diffraction grating. The second one comes from the unbalanced chromatic dispersion in the interferometer, mostly due to a non-symmetric amount of glass in the interferometer arms.

Because these nonlinearities lead to a degradation of the axial resolution, it is important to remove them as efficiently as possible. There are methods for compensating either one type in the presence of the other or both at the same time. The latter ones make use of different mechanisms behind each type of nonlinearity: while the spectrometer-related one is depth-dependent, the one connected to unbalanced dispersion remains constant. By measuring two spectra [1,2] corresponding to the mirror placed at two different depth and subtracting their phases, one removes the constant contribution of unbalanced dispersion and can calculate the correction vector for spectral calibration in the spectrometer. Once the spectrometer's nonlinearity is removed, one of the measured spectra is used to generate a dispersion-compensating vector.

Here, we present a method for simultaneous spectral calibration and dispersion compensation based on the acquisition of just one spectrum, which corresponds to a low-dispersion, thin piece of glass, i.e. a cover glass. This method uses the signal obtained in quantum-mimic OCT [3] and analyses the behavior of its components in response to nonlinearities originating from the spectrometer and the unbalanced dispersion. Modeling of this behavior allows to extract parameters necessary to generate the correction vectors and coarsely linearize spectra, as shown on both synthetic and experimental data. We provide the theoretical background of our approach and discuss the observed limitations.

2. THEORY

Since the grating in the spectrometer disperses light linearly in wavelengths, wavenumber $k = \frac{2\pi}{\lambda_1 + i\Delta\lambda}$, where λ_1 is the wavelength of light illuminating the first pixel of the camera in the spectrometer, $\Delta\lambda$ – the wavelength portion between two adjacent camera pixels, and $i = 0,1,2,\ldots,N-1$ enumerates the pixels (N – total number of pixels in the camera).

The phase is expanded in the Taylor series around $a = N/2 - 1$:

$$\cos(kZ) = \cos\left(\frac{2\pi}{\lambda_1 + i\Delta\lambda}Z\right) = \cos\left(\frac{2\pi}{\lambda_1 + a\Delta\lambda}Z - \frac{2\pi\Delta\lambda}{(\lambda_1 + a\Delta\lambda)^2}Z(i-a) + \frac{2\pi\Delta\lambda^2}{(\lambda_1 + a\Delta\lambda)^3}Z(i-a)^2 - \frac{2\pi\Delta\lambda^3}{(\lambda_1 + a\Delta\lambda)^4}Z(i-a)^3\right) \quad \textbf{(1)}$$

where Z is twice the distance between 0 optical path difference in the interferometer and the position of the reflector. In quantum-mimic OCT, the cosine argument is doubled and the elements with even powers are removed. The position of a peak is incorporated in the factor in front of $(i-a)$: $\frac{2\pi\Delta\lambda}{(\lambda_1 + a\Delta\lambda)^2}Z\frac{N}{2\pi}$, where $N/2\pi$ is added to obtain the pixel position of the peak in the Fourier transform.

FFT stack is built from fragments of the spectrum with m enumerating the pixels in the fragments. The formula is rewritten to account for it and then expanded into a Taylor series around $b = M/2 - 1$ (M – total number of fragments):

$$\frac{2\pi\Delta\lambda}{(\lambda_1 + a\Delta\lambda)^2}Z\frac{N}{2\pi} := \frac{2\pi\Delta\lambda}{(\lambda_1 + a\Delta\lambda + m\Delta\lambda)^2}Z\frac{N}{2\pi} = \frac{2\pi\Delta\lambda}{(\lambda_1 + a\Delta\lambda + b\Delta\lambda)^2}Z\frac{N}{2\pi} - 2\frac{2\pi\Delta\lambda^2}{(\lambda_1 + a\Delta\lambda + b\Delta\lambda)^3}Z\frac{N}{2\pi}(m-b)$$

$$= A - 2A\frac{1}{\lambda_R + a + b}(m-b) = F(m) \quad \textbf{(2)}$$

where $A = A(Z) = \frac{2\pi}{(\lambda_R + a + b)^2}Z\frac{N}{2\pi}$ and $\lambda_R = \frac{\lambda_1}{\Delta\lambda}$.

For two reflectors placed at Z_1 and Z_2, the corresponding peak position functions, F_1 and F_2, will be equal to $A(Z_1) - 2A(Z_1)\frac{1}{\lambda_R + a + b}(m-b)$ and $A(Z_2) - 2A(Z_2)\frac{1}{\lambda_R + a + b}(m-b)$, and their difference, $\Delta F = F_1 - F_2 = \Delta A - 2\Delta A\frac{1}{\lambda_R + a + b}(m-b)$, where $\Delta A = A(Z_1) - A(Z_2)$. Division of ΔF by ΔA gives

$$\frac{\Delta F}{\Delta A} = 1 - 2\frac{1}{\lambda_R + a + b}(m - b) = 1 + D(m - b) \qquad \textbf{(3)}$$

Fitting a linear function to $\frac{\Delta F}{\Delta A}$ lets us obtain the parameter D, from which the unknown λ_R can be calculated:

$$\lambda_R = -\frac{1}{2D} - (a + b) \qquad \textbf{(4)}$$

and used to generate the correction vector for converting the spectrum from λ-space to k-space, based on eq. 1:

$$(kZ)/B = 1 - \frac{1}{\lambda_R + a}(i - a) + \left(\frac{1}{\lambda_R + a}\right)^2 (i - a)^2 - \left(\frac{1}{\lambda_R + a}\right)^3 (i - a)^3 \qquad \textbf{(5)}$$

where $B = \frac{2\pi}{\lambda_1 + a\Delta\lambda} Z$ and, being a constant, does not influence the interpolation process used for λ to k recalculation.

In the case of unbalanced dispersion, the cosine argument is expanded in the Taylor series around 0:

$$kZ \coloneqq kZ + C_2k^2 + C_3k^3 \quad \textbf{(6)}$$

Substituting $k = k_0 + i\Delta k$ in (6), where k_0 is the index of the first camera pixel (here: $-N/2$) and Δk is the size of the pixel (here equal to 1), and ordering the elements by powers of i let us write the expression for peak positions:

$$F^{(\mathrm{disp})} = (2Z + 4C_2k_0 + 6C_3k_0^2)\Delta k \frac{N}{2\pi} \qquad \textbf{(7)}$$

For a spectral fragment indexed by m, k_0 becomes $\left(-\frac{N}{2} + m\right)$ and the coefficients next to m^2 and m equal to $6C_3\frac{N}{2\pi}$ and $4C_2\frac{N}{2\pi}$. Fitting a polynomial to $F^{(\mathrm{disp})}$ lets us obtain C_2 and C_3 needed to generate a phase correction vector for compensating dispersion: $\exp\left(-\mathrm{i}(C_2i^2 + C_3i^3)\right)$, where "i" is the imaginary unit.

3. NUMERICAL RESULTS

A 2048-element-long spectrum representing a one-layer object was computer generated, with the thickness of 50 µm and Group Velocity Dispersion (GVD) of 33 fs^2/mm in the spectral range from 770 to 934 nm. The unbalanced dispersion is set to a GVD of 4,000 fs^2/mm and Third Order Dispersion of 5,000 fs^3/mm. This spectrum was used to calculate the quantum-mimic OCT signal called an FFT stack [3] comprising Fourier transforms of several autocorrelated fragments of the spectrum (Fig. 1a). The peaks' positions on each stack line are determined (Fig. 1b) and the curve corresponding to $\frac{\Delta F}{\Delta A}$ in (3) is obtained (Fig. 1c). λ_R calculated based on the fit equals 9410 (the ideal value is 9625). A more accurate estimate, 9840, is obtained by changing this value so that the slope coefficient of the fit for both interfaces is the same. λ_R is used to generate the correction vector as in (5) which is applied to the spectrum (FFT stack in Fig. 1d). Finally, dispersion compensation is done with a correction vector built from coefficients calculated based on a polynomial fit to one of the peak position plots (as in (7), Fig. 1e). FFT stack corresponding to a fully linearized spectrum is presented in Fig. 1f.

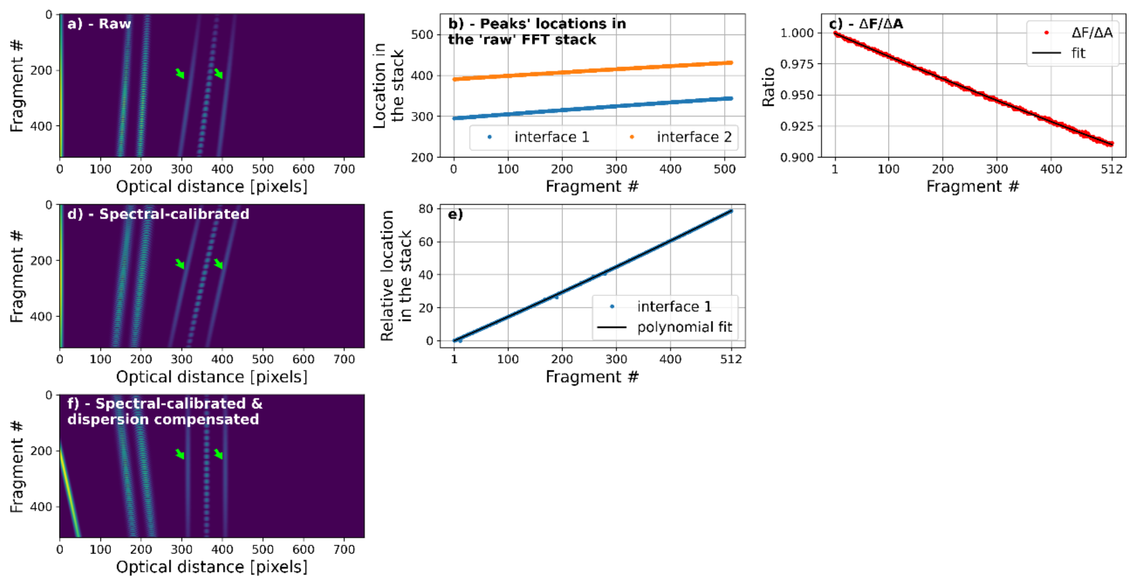

Figure 1. Synthetic data: from **(a)** FFT stack made from a raw spectrum, **(b)** interfaces' locations are extracted **(c)** and based on them, $\Delta F/\Delta A$ is calculated (red dots) and fitted (black line). The fit's coefficients are used in spectral calibration. **(d)** FFT stack of the spectrally calibrated spectrum, **(e)** the first interface's locations (blue dots) together with a fit (black line), based on which dispersion compensation is performed. **(f)** FFT stack made from the fully linearized spectrum. Green arrows indicate elements representing glass interfaces.

17 spectra representing a reflector at different depths (Fig. 2a) were generated to assess the goodness of the linearization. Whereas the dispersion compensation was performed in a successful way (blue and orange lines in Fig. 2bcd), spectral calibration was not perfect and resulted in a slight resolution decrease at depths above 400 µm (green lines in Fig. 2bcd).

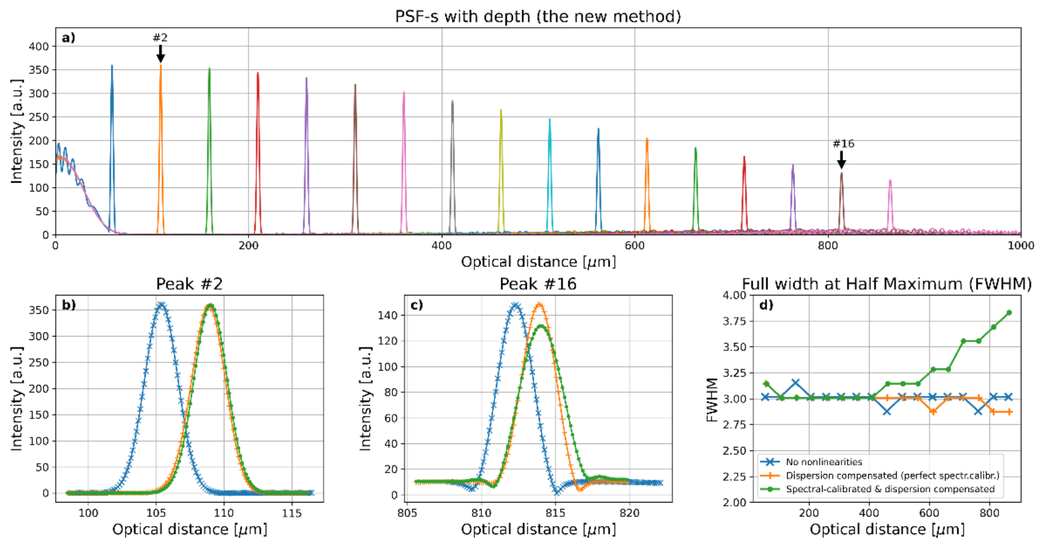

Figure 2. (a) 17 A-scans of a mirror at different depths, linearized with the proposed method. **(b)** Peak 2, **(c)** peak 16 and **(d)** FWHM for perfectly linear data (blue), only dispersion compensated (orange) and after applying the proposed method (green).

4. EXPERIMENTAL RESULTS

A spectrum corresponding to a 50-µm cover glass was acquired with an OCT system with an unbalanced dispersion and uncalibrated spectrometer. The correction vectors for spectral calibration and dispersion compensation were calculated using a glass slide in the same way as for the synthetic object. Next, 20 spectra representing a mirror at different depths were measured and the calculated correction vectors were applied. For comparison, correction vectors obtained with a standard method were applied as well. Just as in the previous case, dispersion compensation is performed well, but the spectral calibration is not perfect, although provides good results in the useful imaging range.

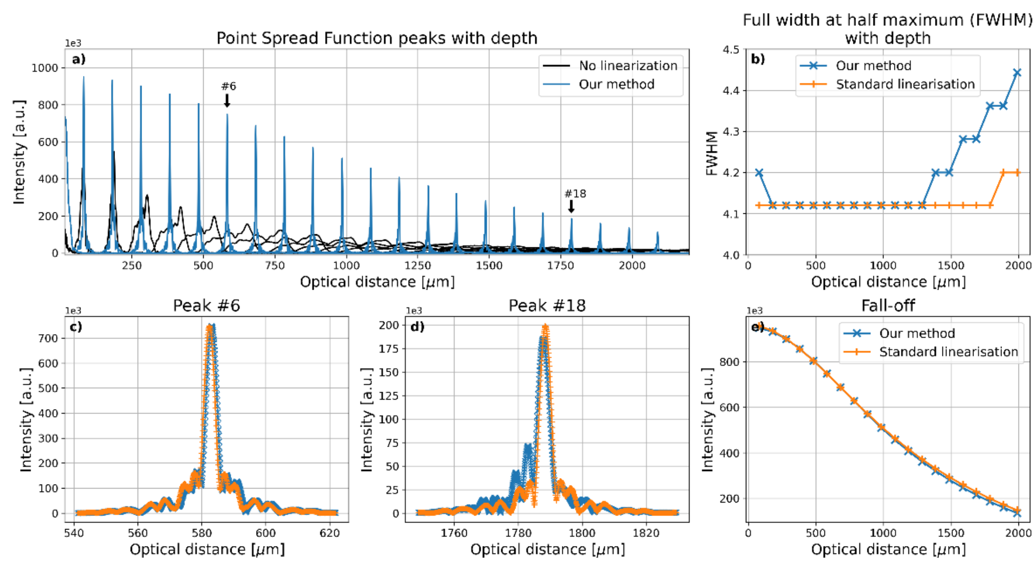

Figure 3. (a) 20 A-scans of a mirror at different depths, linearized with the proposed method (blue) and not linearized (black). **(b)** FWHM, **(c)** peak 6, **(d)** peak 18 and **(e)** fall-off for traditionally linearized data (orange), and after applying the proposed method (blue).

5. SUMMARY AND FUTURE WORK

Spectral calibration and dispersion compensation are performed based on a single spectrum representing a thin piece of glass. The presented method is almost fully automatic – the only user input it needs is information about the location of the peaks. Its limitations are connected to the non-zero dispersion of the used glass, as shown in the numerical example. Also, the goodness of the spectral calibration correction vector may be limited by the imperfections in the spectrometer, e.g. aberrations which change the positions of wavelengths on the camera and lead to a demand for slightly different coefficients. Our future work will focus on developing automatic methods for fine-tuning the correction vectors, for example using the height of the peaks as feedback.

6. REFERENCES

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