LIDAR-like equation model for Optical Coherence Tomography signal solution

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ABSTRACT

The objective of this work was to develop a LIDAR-like equation model to analyze the measured Optical coherence tomography (OCT) signal and determine the total extinction coefficient of a scattering sample. OCT is an interferometric technique that explore sample backscattering feature to acquire in depth cross-section images using a low coherence light source. Although, almost of the OCT applications are intended to generate images for diagnostic, similar to histological images, but the backscattering signal carries much more information. The backscattering problem is similar to those found on LIDAR (Light Detection And Ranging) problem, this similar situation indicate a path that should be followed to solve the OCT problem. To determine the total extinction coefficient three inversion methods was used: the slope, boundary point and optical depth methods solutions. These algorithms were used to analyze the OCT signal of a single and double layer dentist resin polymer. The total extinction coefficient variations along the optical path were obtained in order to evaluate the potential of this technique to differentiate structures with different optical properties. The sample optical characteristics extracted from OCT signal can be use as an additional quantitative method to help clinical diagnoses when applied on biological tissues among others.

Keywords: Optical Coherence Tomography, OCT, LIDAR equation, Total Extinction Coefficient, OCT image enhancement

1. INTRODUCTION

Optical Coherence Tomography (OCT) is a relatively new technique which relies on low coherence length interferometry [1]. The OCT technique derives from studies of optical fibers faults location [2] in 1987.

However, the breakthrough occurred when this methodology was applied to perform tomographic images of delicate live structures, such as eyes structures [3-5] and other biological tissue [6-8]. Despite the fact that OCT can be considered as an established diagnostic tool, especially by biomedical areas, the technique has less than two decades of conception and still are under development.

This technique, known as a biological tissue image technique, can also be used to imaging another delicate samples like some kinds of ceramics, polymers, resin, textile products or papers for example.

The most common OCT setup uses a Michelson interferometer to provide a cross section image of a scattering samples with noninvasive and no contact parts. In this setup, the light is conducted by an optical fiber to a 2x2 coupler and in this way the light is divided in two beams: one part of the light goes to a reference mirror and the other part goes to sample (Figure 1).

Biomedical Applications of Light Scattering V, edited by Adam P. Wax, Vadim Backman,
Proc. of SPIE Vol. 7907, 790714 · © 2011 SPIE · CCC code: 1605-7422/11/$18 · doi: 10.1117/12.875572

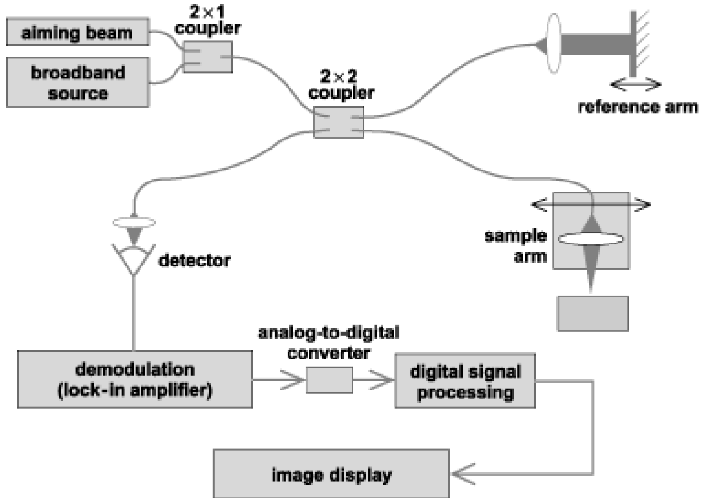


Figure 1: Schematic representation of OCT system.

The mirror and sample backscattering radiations are recombined to form an interferometric pattern in the detector. Because light source have low coherence length, broad spectral band, the interference occurs in the detector only when the optical path length difference between sample's arm and reference arm is shorter than the coherence length, i.e., only the photons once scattering have the information necessary to generate the interferometrics pattern.

Nowadays, OCT is mainly used as an image technique, but the backscattered signal has more information about sample than those explored. OCT system explores the media backscattering feature to make a cross-section image. For this reason, understand the scattering process, and how the media influences the image formation, is very important not just to construct an image but also to determine some media optical properties. The knowledge of tissue optical properties, for example, can be used as an auxiliary tool to differentiate health from a pathological tissue.

2. OCT and LIDAR

LIDAR (Light Detection And Ranging) is a remote sensing technique, mainly used in atmospherics studies, that explore the atmospheric backscattering features to measure optical properties and extract information about it, like pollutants monitoring or aerosols profile mapping, for example. In the LIDAR technique, a laser beam is directed to the atmosphere and the backscattering radiation is collected by a telescope and recorded based on time of photon flight and, in the other hand, OCT is based on coherence length. The backscattering process found on LIDAR is the same found on OCT. Basically the electromagnetic radiation that propagates through a media can be attenuated by absorption or scattering.

The light scattering occurs in all direction and the scattering intensity depends on the wavelength, the angle between the incident and scatter beam, the physical features and density of the scatters following Mie theory. In a similar way, the absorbed radiation depends on the presence of absorbers on the pathway. The backscattering sample propriety used in OCT image formation is similar to those found on LIDAR problem, this similar situation indicate the path that should be followed to solve OCT signal.

A light beam propagating through a scattering medium is attenuated along way [9], in each interaction with molecular or particle present in de medium. The scattered radiation is emitted in all directions, but only a portion of radiation return to system in the same direction and back way, it is known as backscattering. It can be demonstrated [9] that the backscattering can be written as equation 1, knowing also as LIDAR equation due to its use on LIDAR experiments.

$$F(r) = C_0 T_0 \frac{\beta_\pi(r)}{r^2} exp\left[-2\int_{r_0}^{r} \kappa_t(x)dx\right] \quad (1)$$

$\beta_\pi(r)$ is the total backscattering coefficient, $\kappa_t(r)$ is the total extinction coefficient and C_0 is a constant that only depends the system. In this scenario the aim of this work was to develop a LIDAR-like equation model to analyze the measured OCT signal and determine the total extinction coefficient of a sample and show that is possible to use this correlation for image enhancement.

3. SOLUTION METHODS

The advantage of do this correlation between LIDAR and OCT problem is that LIDAR have a number of solution methods well established. At this point we propose to use three different inversion solution methods to determine the total extinction coefficient, knowing in LIDAR [9] area as: slope, boundary point and optical depth method solution.

3.1 Slope method solution

The first method can be applied when the medium total extinction coefficient and backscattering coefficient can be assumed constant over the path. Then taking the logarithm of equation 1 it can be reduced to a linear equation (equation 2).

$$\ln\left(\frac{P(r)r^2}{T_0\,C_0}\right) = \ln(\beta) - 2\kappa_t r \quad (2)$$

When the total extinction coefficient and backscattering coefficient change along the path, and assuming that the ratio between they is constant (known as LIDAR ratio), the other two methods must be applied, but is necessary know, or measure, some parameter, as shown below.

3.2 Boundary point method solution

This method can be used when the total extinction coefficient changes along the path, but is necessary to know it value in some position. Knowing or measuring this value in the r_b position the solution reduces to equation 3.

$$\kappa_t(r) = \frac{Z_r(r)}{\frac{Z_r(r_b)}{\kappa_p(r_b)} + 2\int_r^{r_b} Z_r(r')dr'} \quad (3)$$

Were

$$Z_r(r) = \frac{F(r)r^2}{T_0\,C_0}$$

$\kappa_p(r_b)$ and $Z_r(r_b)$ are the total extinction coefficient and $Z_r(r)$ in the r_b position.

3.3 Optical Depth method solution

As the previous method, this solution assumes that the LIDAR ratio is a constant, but in this method is necessary to measure de sample transmittance (T_{max}), so the total extinction coefficient can be determinate using the equation 4:

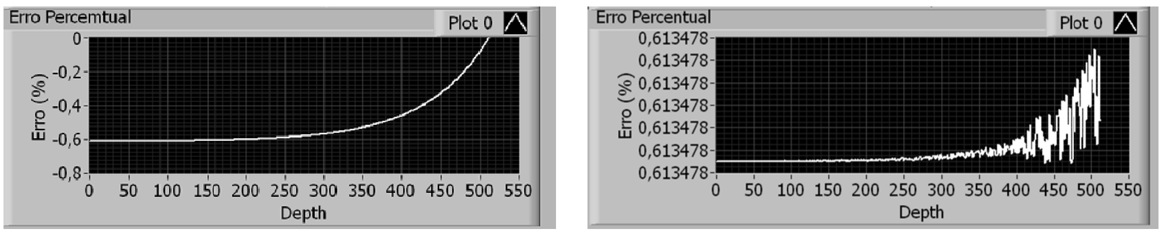
$$\kappa_t(r) = \frac{0{,}5\,Z_r(r)}{\frac{I_{r,max}}{1-T_{max}^2} + 2\int_{r_0}^{r} Z_r(r')dr'} \quad (4)$$

The three solutions methods algorithms were implemented on LabVIEW® environment.

4. Analyses

4.1 Algorithm Error Evaluation

To evaluate the performance of the three method algorithms used to solve LIDAR equation, the computational error were evaluated using a simulated backscattering signal, obtained with equation 2.
In the slope method no computational error were performed, in the Boundary Point and Optical Depth method solution the associated computational error were less than ~0.6%, as can be seen on Figure 2 (a) and (b) respectively.



(a) (b)

Figure 2: Computational error of (a) Boundary Point and (b) Optical Depth solution method.

4.2 1D image analyze

After perform the algorithm error evaluation, a dentist polymer resin sample (Z250 B1, 3M) was measured using commercial SS-OCT (Figure 3) operating at 1300nm. This image signal was introduced on the three method solution program used to determine the total extinction coefficient.

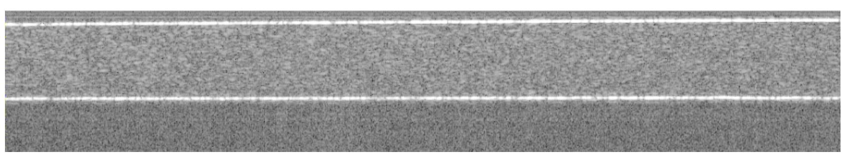


Figure 3: OCT image of a polymer resin sample.

The image was first analyzed by integrating all a-scans to obtain its profile (Figure 4) and analyze it on 1-dimesion.

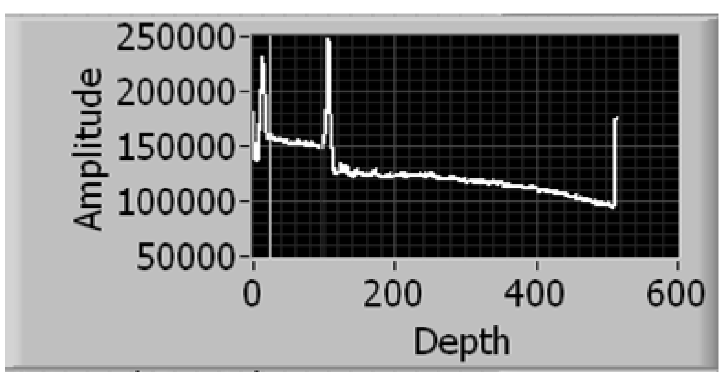
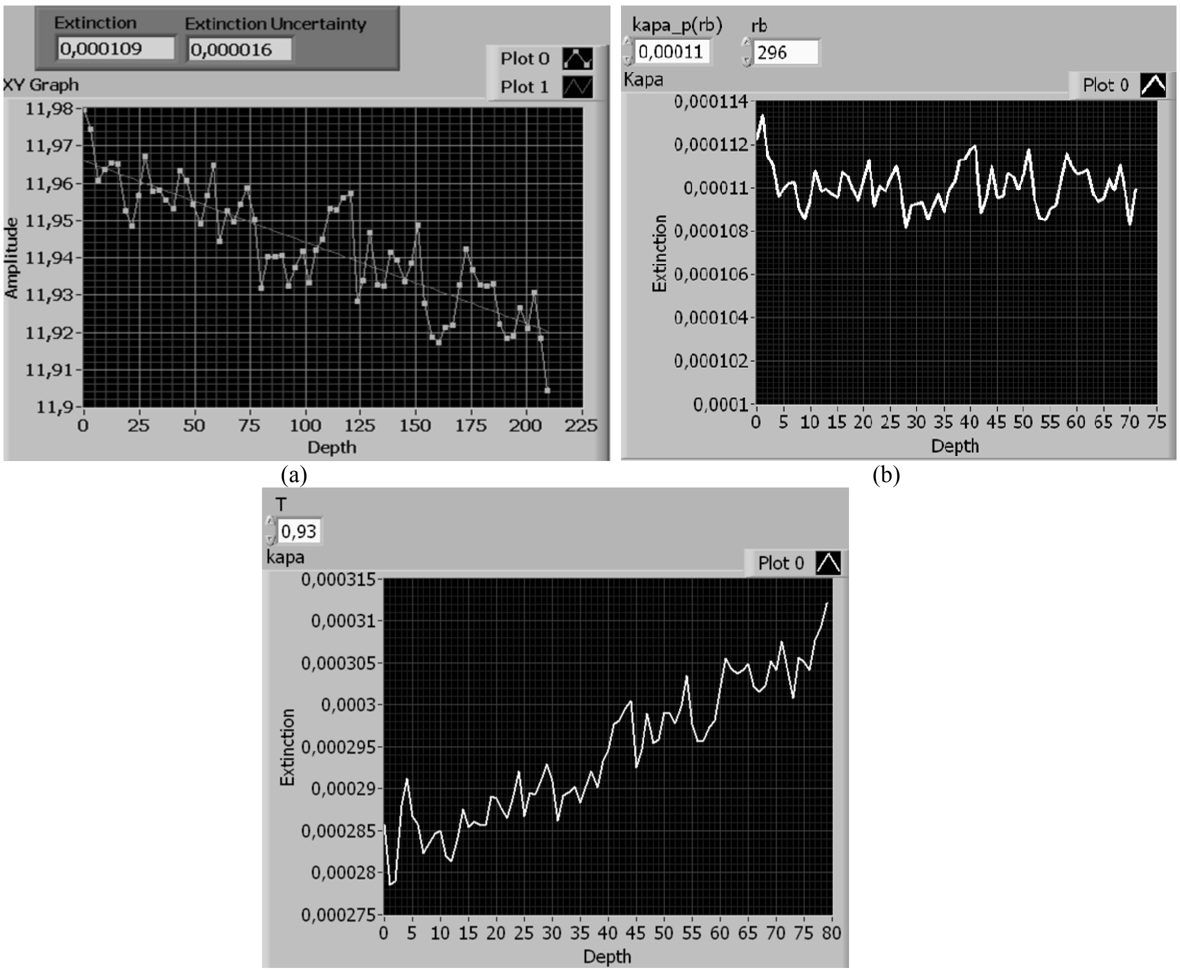


Figure 4: Polymer resin sample 1D image profile

The Figure 5(a) shows the linear fit to calculate the total extinction coefficient, the Figure 5 (b) and (c) show the program screen graphics of total extinction coefficient along the path.

To determine the total extinction coefficient using the Optical Depth method solution the transmittance of the sample was measured using an integration sphere, and the transmittance value is equal to 93% at 1300nm.



(a) (b) (c)

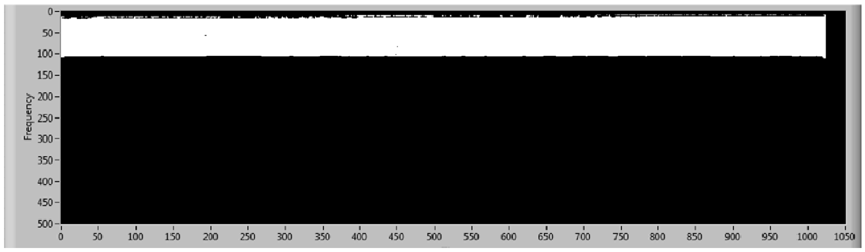
Figure 5: (a)Slope, (b) Boundary Point, (c) Optical Depth solution method applied to the dentist polymer resin sample backscattering signal.

The total extinction coefficient obtained with the slope method was 1,09(16)x10^{-3} μm^{-1}. This value is statistically similar with the Boundary Point profile values. The optical depth method differs by a factor of 2, form the other two, in fact we still do not understand this and this is still under investigation.

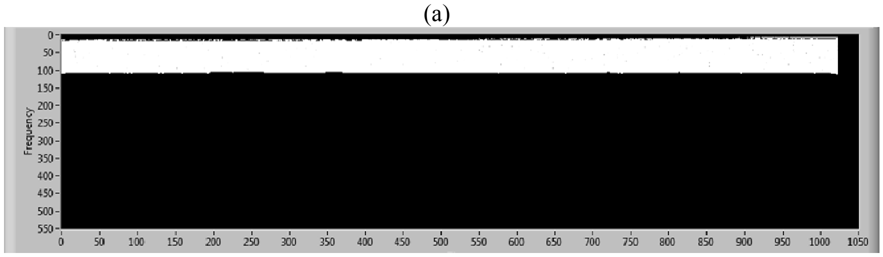
4.3 2D image analyze

After perform the 1D analyze this methodology was applied to each column of the image in order to acquire a total extinction coefficient image.

The slope method is a method to homogeneous media, and it is not possible to get extinction in depth image. The other two methods were applied after an image noise treatment on the image, this proceed were applied due to the strong variation observed caused by background noise. The Figure 6 (a) and (b) show the Figure 3 enhanced by the difference between air and resin extinction coefficient.



(a)



(b)

Figure 6: (a) Boundary Point (b) Optical Depth methods solution image enhancement

In the Figure 6 the white color corresponds to the resin polymer and black correspond to the air. It is important to note that a background noise image treatment is very important to get this differentiation.

After evaluate this single layer sample, a resin double layer sample with air between the two layers was imaged and used on the boundary point and optical depth solution. The Figure 7 show the double layer OCT image and the enhance resin image using the optical depth solution. The image for boundary point solution is very similar to Figure 7 and for this reason was omitted.

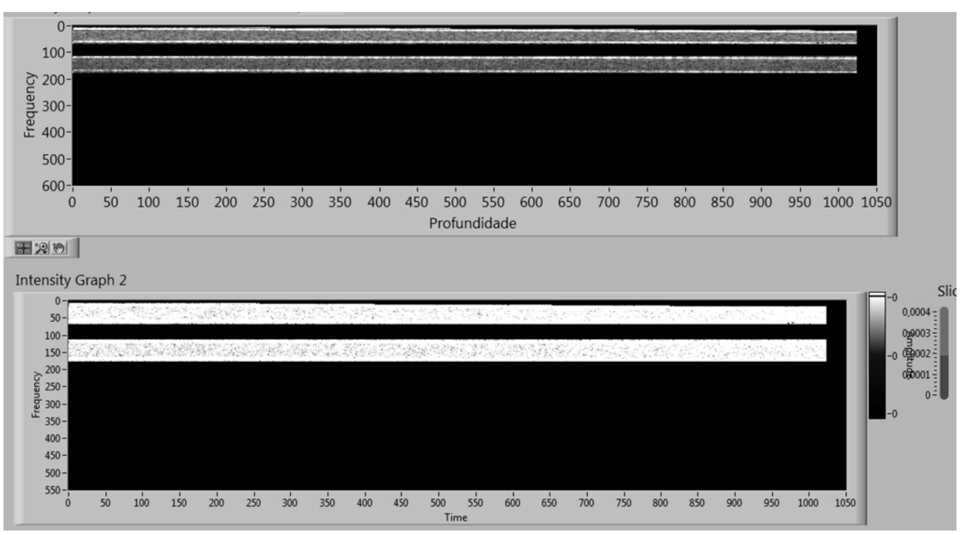


Figure 7: Resin double layer OCT image (first image) and enhanced image (second image).

5. Conclusions

Sample backscattering signal used in OCT to generate image cross-section is similar to LIDAR backscattering signal. Due to the similarity of these two problems, LIDAR equation could be, *a priori*, used as a model to determine extinction coefficient in OCT images. The three most used LIDAR solution algorithm was implemented in LabVIEW® and a simulated OCT signal was used to quantify the computational error introduced when the extinction coefficient is determine.

Due to the feature of the method, the Slope Method Solution showed the best agreement with extinction coefficient used to generate the simulated signal, but the method assumes that the extinction coefficient is a constant over range. This is not always true for every sample and this is a limitation of the slope method, but the method is a very nice tool when we need to know the extinction coefficient of a region of unknown sample.

The other two methods (Boundary Point and Optical Depth) present a computational error of about 0.6% between extinction coefficient determinate and the simulated signal. These methods can be applied when the sample extinction coefficient changes along the pathway. This is an advantage over the slope method.

The main disadvantages of boundary point and optical depth solution methods is that these are methods very sensible to the boundary condition (to know the extinction coefficient at a point in the boundary point solution and the sample transmittance in the optical depth solution) and, of course, also the fact that we have to know this parameters, that is no always simple to get.

These methodologies were applied to a dentist resin polymer and an enhanced image was acquired, for a single and double layer. It shows the potential of this technique to differentiate structures with different optical properties.

This work was important to understand the LIDAR solution behavior for OCT signal, both computational error and application on real scattering sample. The correlation between this two problems open a different way to look how solve it and extract information of the image, but it is far to be totally understood and a lot of work is still needed before this became a validated methodology, same problems can be solved, like background noise treatment. But the sample optical feature, extracted from OCT signal, can be used in the future as an additional quantitative method to help clinical diagnoses when applied on biological tissues among others.

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