Fruit Optical Properties Assessment by means of Spatially Resolved Spectroscopy

E. Madieta *[1], V. Piron [2], A. Flament [1], J.P. L’Huillier[2] and E. MEHINAGIC[1]
[1]PRES L’UNAM, ESA, UPSP GRAPPE, [2] ENSAM Paristech Angers, LAMPA
*Corresponding author: 55 rue Rabelais 49000 Angers, e.madieta@groupe-esa.com

Abstract: Since the invention of laser sources, understanding the interaction between laser and biological tissues has been a subject of great importance especially because of their medical applications for diagnostic purposes. Recently, laser sources have showed a growing interest in the sector of arboriculture to check the fruits quality in a non-destructive way. In this work, we study the interaction between the laser beam and the tissues of apples using different approaches. We establish a FEM model. The outcomes are compared to an analytic solution and an experimental set of data obtained with different varieties of apples.

Keywords: Photon diffusion, fruit, Finite Element Method, Spatially Resolved Spectroscopy**.**

1. Introduction

When the laser sources were conceived at the end of the 1950’s, many researchers realised the value of such a light beam capable of carrying energy non-invasively through biological tissue. This convenience was later improved by the possibility to convey the light with a great flexibility by means of fibre-optics. Consequently, medical applications were thought up in many fields. And, the human tissue had been widely investigated for diagnosis [1], imaging and tomography [2] and surgery.

According to the variable focused on, it is commonly admitted to distinguish three kinds of spectroscopy: time-resolved spectroscopy [3], spatial resolved spectroscopy [4] and frequency domain resolved spectroscopy [5].

All these techniques are non-destructive, non-invasive, and useful for the huge range of biological tissues. Therefore, they applied themselves to the fruit research domain; and today, they are becoming more and more practical alternatives to classical and destructive measurements such as compression and penetrometry test [6, 7]. This results in stating the laser based spectroscopy as promising when dealing with fruit texture assessment. For example, the maturity degree of a fruit was found easy to be estimated by fruit’s light absorption property [8] or by using the size of its laser light image [9]. In addition, the firmness of apples has been correlated to their scattering property [10-12].

However, all these results remain fragmentary. To be adopted as an instrumental measurement by the whole community of fruit researchers and fruit professional workers, the laser based spectroscopy needs to be more investigated. For example, the ranges of optical parameters must be examined; the correlations established must be more convergent in quality, formulation and ranges; their theoretical basis must be more strengthened.

This work falls in this wide objective. We apply the space-resolved spectroscopy to several samples of apple and confront the experimental results with those obtained in a finite element model and an analytical solution.

2. Instrumentation and experimental procedure

A very simple instrumentation is used (Figure 1). A fibre-optic connected to a He-Ne laser source (633nm) illuminates directly the skin of a non-peeled half-apple on its equatorial zone. The radiance emitted in such condition is constant L_0 ($\mathrm{W.m^{-2}.Sr^{-1}}$). Backscattered photons are collected by means of a second fibre-optic. Driven by a micrometer, the latter is connected to a direct reading photometer. This allows to built the curve of the backscattered fluence *R* versus the distance *x*.

Every sample is enlightened in the equatorial zone of the fruit. The receiving fibre-optics is moved on a straight line so allowing recording the backscattered power in twelve equidistant points on a total distance of 8 mm.

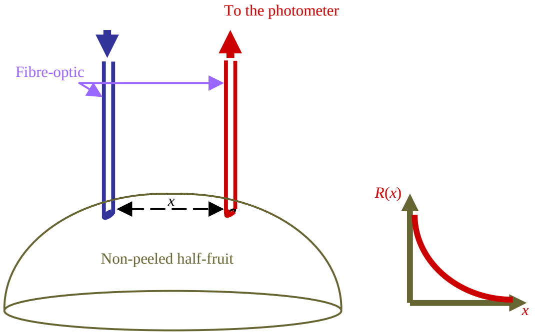

Figure 1 Schematic representation of the measurement setup.

3. Governing equation

Let us consider a biological tissue the optical parameters of which are the following ones. The diffusion coefficient is D, the coefficient of absorption μ_a, the scattering coefficient μ_s and the anisotropy factor g. Frequently termed average cosine scattering angle, the latter ranges from -1 to 1, and serves as a measure of the forward scattering bias, where $g = 0$ corresponds to an uniform scattering. For biological tissues at the visible and near-infrared wavelengths, g turns out to be between about 0.7 and 0.99. It is convenient to define the attenuation coefficient $\mu_t = \mu_a + \mu_s$ and the coefficient of transport $\mu_t' = \mu_a + (1 - g)\mu_s$. In addition, the internal reflection parameter A may be calculated using the relative reflective index *n.* According to Groenhius et *al.*, [13]

$$A = \frac{1 + r_i}{1 - r_i}$$

Where

$$r_i = -1.4399n^{-2} + 0.7099n^{-1} + 0.6681 + 0.0636n\ .$$

As the geometry is axi-symmetrical, a 2D model is built. To simplify the model, the fruit geometry is approximated by a rectangle so that coordinates *x* and *z* are used. In a previous work, we showed that to address this kind of problems, it is useful to take into account the collimated laser beam as a source term which is attenuated as an exponential function of depth. Thus, two sub-domains must be distinguished, the one directly lighted up by to the illuminating fibre and the rest of the biological tissue where there is no source term ($S(x,z) = 0$). Within the first sub-domain, the process follows the Beer's law, and the source photon distribution is therefore proportional to $\exp(-\mu_t z)$. Therefore, the source term is [14]

$$S(x,z) = \mu_s L_0 \left(1 + g\frac{\mu_t}{\mu_t'}\right) e^{-\mu_t z}$$

Thus, the convenient steady conservation equation is:

$$-D\nabla^2 u + \mu_a u = -S$$

The appropriate boundary equations are given in Figure 2. The flux vanishes along the external limit *BB'* as the fruit's dimensions are much higher than fibre diameter. In the same way, it is null along the axial limit *OO'*. In order to take into account the light beam, additional fluxes are used in Robin boundary conditions along *OA* and *0'A'*.

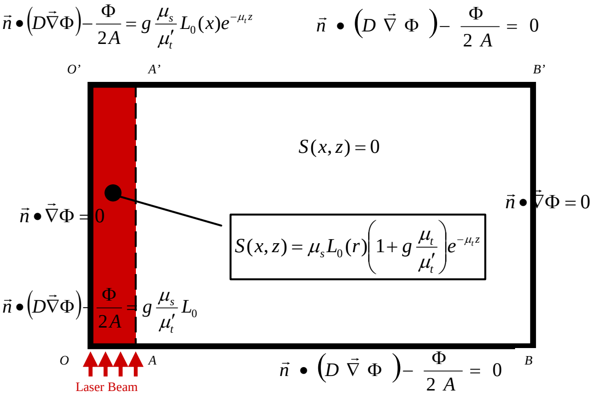

Figure 2. Source terms and boundary conditions

4. The analytical solution

This solution is due to Farrell et al. [15]. The beam, assumed to be pencil-like lights up the biological tissue that is supposed to be homogeneous and semi-infinite. In such conditions, it is fruitful to incorporate a photon dipole source, the first source located at a depth of one transport mean free path (mfp). Thus, the reflectance at the distance ρ is calculated by using the expression:

$$R(\rho)=\frac{C}{4\pi\mu_t^{'}}\left((\mu_e+\frac{1}{r_1})\frac{e^{-\mu_e r_1}}{r_1^2}+(\frac{4}{3}A+1)(\mu_e+\frac{1}{r_2})\frac{e^{-\mu_e r_2}}{r_2^2}\right)$$

Where C is a constant,

$\mu_e=\sqrt{3\mu_a\mu_t'}$, $r_1=\sqrt{\left(\frac{1}{\mu_t^{'}}\right)^2+\rho^2}$ and

$$r_2=\sqrt{\left(\frac{\frac{4}{3}A+1}{\mu_t^{'}}\right)^2+\rho^2}.$$

5. The FEM scheme

A 2D finite element code is used to calculate solution of steady photon diffusion together with boundary conditions. Two sub-domains are useful to take into account the directly illuminated region. The mesh used in the simulations is shown in Figure 3.

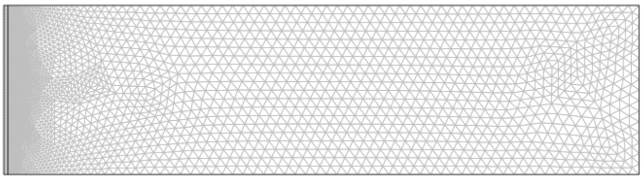

Figure 3. Mesh used consisting of a total of 7728 elements.

6. The global procedure

For each sample, the global procedure consists on first performing experiments following the operating mode. The analytical solution is then used to fit the experimental data. Trust-region method is utilised for this purpose. This is achieved when R^2 maximised and Root Mean Squared Error (RMSE) minimised. The available values of μ_e and μ_t' are then obtained. Thus, the parameters μ_a and μ_s' are deduced by means of $\mu_a=\mu_e^2/3\mu_t'$ and $\mu_s'=\mu'_t-\mu_a$. The FEM simulation is then performed on basis of these optical parameters. The outcomes are compared to analytical solution and experimental data. The values of R^2 and RMSE are estimated for this aim.

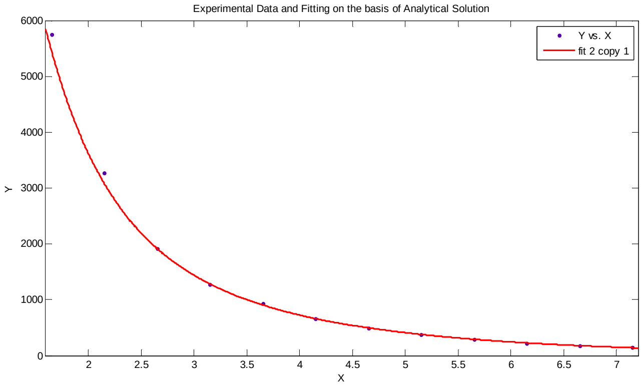

Figure 4. Experimental data (.) and Fitting curve on the basis of analytical solution

7. Results

A set of 40 apples of commercial quality of the variety Dalinbel was investigated. The results obtained for all this lot are substantial and convergent. For all samples, when fitting experimental data by means of analytical solution, less than 400 iterations were necessary to obtain the convergence of the method "Trust-Region ".

However, it beforehand required estimating the adequate initial values. For the whole lot, the coefficient R^2 ranged from 0.987 to 0.999.

For illustration’s sake, we present here results corresponding to one sample. Figure 1 represents the experimental data as well as the fitting curve thanks to analytical solution. The decrease in reflectance leads to an almost negligible fluence at a distance of 7 mm. In the present case, R^2 value was 0.99 and RMSE, 19.83. The fitting procedure brought $\mu_e =$ 0.2513 mm^{-1} and $\mu_t' =$ 1.0159 mm^{-1}. Therefore, μ_a and μ_s' values were deduced (μ_a=0.0207 mm^{-1}, μ_s' = 0.9952 mm^{-1}). For apple tissue, it is common to assume n = 1.4 and $g = 0.98$. On the basis of this set of optical parameters values, FEM simulation was carried out. The bounded domain of size was set to 75 mm × 20 mm. To avoid grid size effects, mesh density over the collimatation area was increased by means as two refinements. In Figure 5 and 6, the 3D surface solution and the profile of the reflectance are represented.

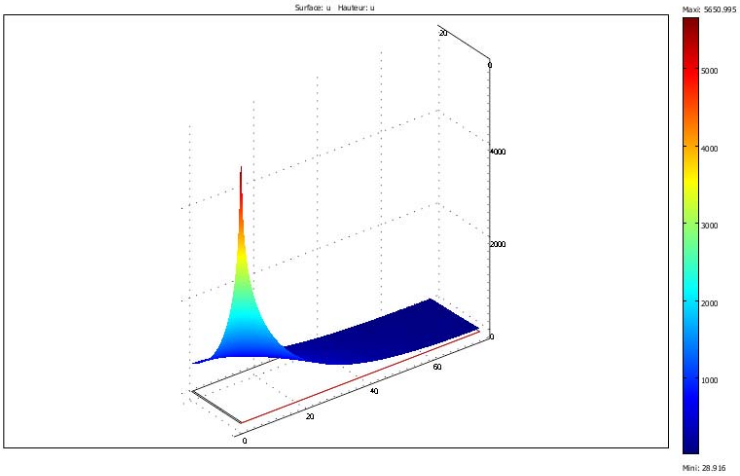

Figure 5. 3D surface of the FEM solution

Good accordance between this outcome and the analytical solution is observed since R^2 value is 0.98. In the same way, FEM solution complies

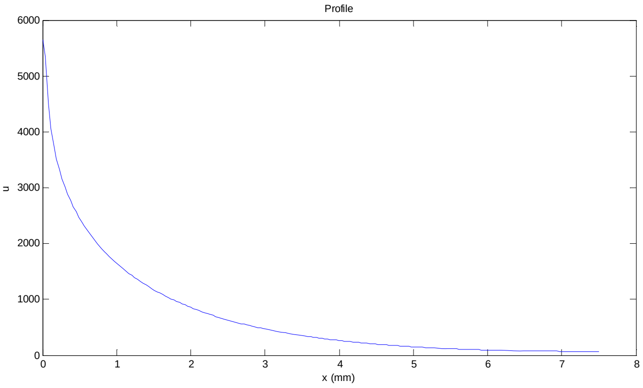

Figure 6 Profile of the reflectance deduced from the FEM solution

with experimental data (R^2 = 0.98 and RSME = 15.7).

8. Conclusions

This work aimed at studying the diffusion of photons in apple tissue. Solution from numerical scheme has been compared firstly to a very well known analytical solution and, secondly to experimental data. The results lend support to some assumptions we made to simplify the approach. Instead of the Boltzmann transfer equation, the diffusion equation has proven to be valid. In fact, for all the studied fruits, scattering was more important than absorption ($\mu_a >> \mu'_s$).The diffusion approximation is known to work best with high scattering albedos, i.e., when the absorption coefficient μ_a, is less than the reduced scattering coefficient μ'_s. Furthermore, the diffusion equation has been deliberately treated in Cartesian coordinates in spite of the axi-symmetric geometry. In addition, a plane geometry has been preferred, thereby neglecting the curvature of the fruit

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9. References

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