# Earth's atmosphere and LSST photometry

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# Chapter 1

# Introduction

**Introducing the lab**
APC (AstroParticle and Cosmology) is a new Institute in Paris devoted to particle astrophysics and csomology. At a time where one expects a large amount of data in this— active field, it seemed apropriate to create a place where the different communities involved (astrophysicists, particle physicists and theorists) would work in close collaboration.

The group "Cosmology" is devoted to the study of the evolution of the universe through the observation of the extra-galactic medium : detailed investigation of the cosmic microwave background, study of dark energy and dark matter.

**Introducing the experiment**
The Large Synoptic Survey Telescope (LSST) is a proposed ground-based 8.4-meter, 10 square-degree-field telescope that will provide digital imaging of faint astronomical objects across the entire sky, night after night. In a relentless campaign of 15 second exposures, LSST will cover the available sky every three nights, opening a movie-like window on objects that change or move on rapid timescales: exploding supernovae, potentially hazardous near-Earth asteroids, and distant Kuiper Belt Objects. The images from the LSST will also be used to trace billions of remote galaxies and measure the distortions in their shapes produced by lumps of Dark Matter, providing multiple tests of the mysterious Dark Energy.

Traking events that would give us more details on the nature of dark energy requires very accurate measurments. Photometric redshifts require better than 2% absolute photometric precision. The tracking of image quality and rapid response to changing observing conditions requires that we find various ways to constrain all the time-changing parameters.

**Introducing the subject**
One of the purpose of my internship was to quantify the impact of atmospheric absorption and fluctations on the observations, in order to determine how the data would be affected. Knowing the atmospheric conditions above the telescope at a given time, we should be able to predict its variations over a certain period of time. This is developped in chapter 2.. An auxiliary telescope will probably be used to immediately get the atmospheric parameters above the telescope.
Part of my internship was also spent trying to rebuild the evolution of the atmospheric extinction using a random gaussian field. This is described in chapter 3.

# Chapter 2

# Atmospheric extinction

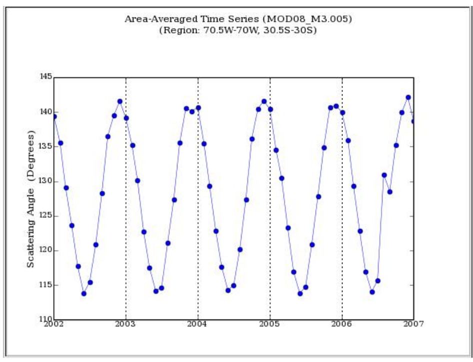
The LSST will be based in Cerro Pachón. As other telescopes are already located there, a large amounts of data on atmospheric conditions have already been collected [2].

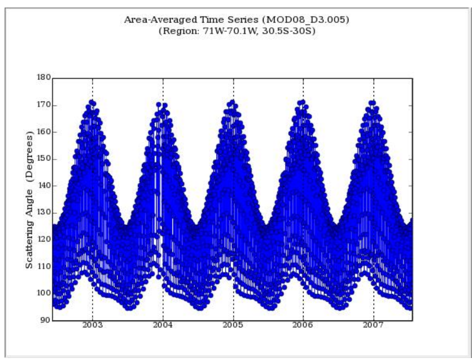
Our first goal is to find a way to describe best the way electromagnetic radiations are attenuated as they pass through the atmosphere. In order to do that, we will base our modelisation on the "Beer-Lambert law", whic is commonly used to describe this phenomenon.

$$I = I_0 * exp^{-\epsilon(k_a+k_m+k_r)} \tag{2.1}$$

Therefore $T = \frac{I}{I_0} = exp^{-\epsilon(k_a+k_m+k_r)}$ is the percentage of the transmitted radiation. $k$ are called *extinction coefficents.*
* r is the Rayleigh scattering
* m refers to molecular gas absorption (H20, 03, 02, C02, NO2).
* a refers to aerosols (that absorb and scatter - includes clouds) - process is called Mie scattering

$\epsilon$ is the airmass factor : $\epsilon \approx \dfrac{1}{cos\theta}$
Shown below is, on the left the scattering angle in degrees monthly-averaged and on the right the same data shown on a daily basis. As we can see the airmass factor fluctuates around 125 with an amplitude of more than 40% day after day and with even a larger amplitude in summer (January). The monthly- average graph shows us that the variation is cyclic.





## 2.1 Rayleigh scattering

The Rayleigh scattering is the most commonly known, and the main extinction channel for small values of $\lambda$ because it varies as $\lambda^{-4}$ :
It can be descrbied by the following equation :

$$k_r = \alpha_r * (\frac{\lambda_0}{\lambda})^4 \tag{2.2}$$

where $\alpha_r(\mu, d)$ is a parameter for a given atmosphere

## 2.2 Molecular absorption

The molecular absorption paramets takes the form as shown below :

$$k_m = \alpha_m f(\frac{\lambda}{\lambda_0}) \tag{2.3}$$

where $\alpha_m$ is a parameter for a given atmosphere. The absoprption spectra of any molecule can be described by a Lorentzian function .

$$f(\frac{\lambda}{\lambda_0}) = \frac{\Gamma}{2\pi} \frac{1}{(\frac{\Gamma}{2})^2 + (\frac{\lambda}{\lambda_0} - \frac{\lambda_{mol}}{\lambda_0})^2} \tag{2.4}$$

where $\lambda_{mol}$ is the absorption peak(s) for a given molecule.

## 2.3 Aerosols - Mie scattering

The commonly used modelisation for *aerosols* is the following $\lambda^{\alpha_{p0}}$ where $\alpha_{p0}$ ranges from $[-1.5; -1]$ ; for clouds, the parameter is a little different : $\lambda^{\alpha_{p1}}$ where $\alpha_{p1} \in ]-1; 0]$.

Hence we can wite the general formula :

$$\alpha_a(\frac{\lambda}{\lambda_0})^{\alpha_p} \tag{2.5}$$

with $\alpha_a$ a parameter for a given atmosphere, and $\alpha_p$ ranging between 0 and 1.5 (in absolute value).

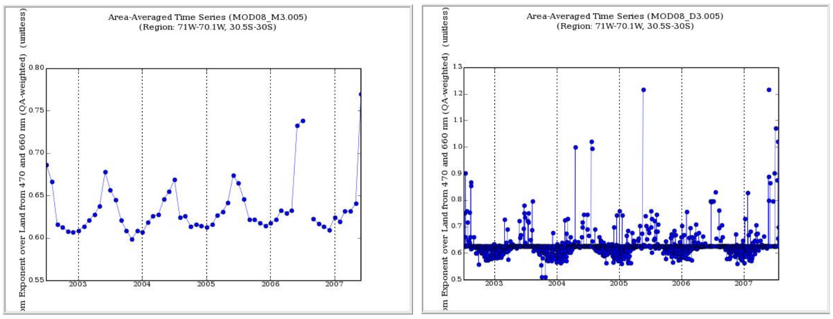



Figure 2.1: This graph shows the value of $\alpha_p$ on a monthly-averaged (left) and daily-averaged basis (right). Mean value : $\alpha_p = 0.65$ with 10% fluctuations (except for a few extreme datapoints.)

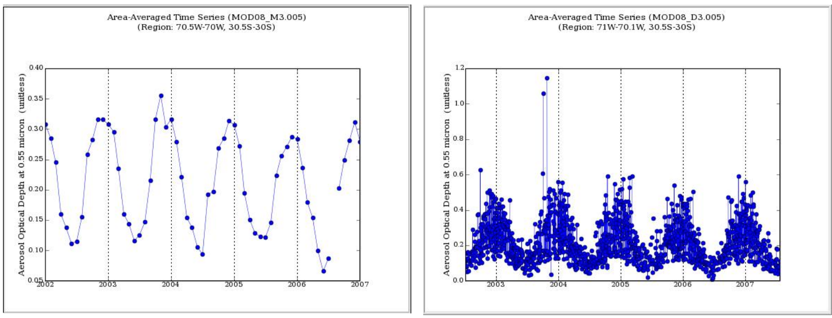



Figure 2.2: This graph shows the aerosols optical depth on a monthly (left) and daily basis (right).This parameter fluctuates around the value 0.20+/-0.10. Again in summer the daily fluctuations seem to be much more important (up to 100%) compared to the ones in winter time (less that 50%).

The graph clearly illustrates that the cloud fraction of Cerro Pachon varies from 10% in summer to around 60% in winter. The cloud effective radius shows how the particle size in the clouds varies with time (influencing the lambda-dependance and therefore the value of the $\alpha_a$ parameter.

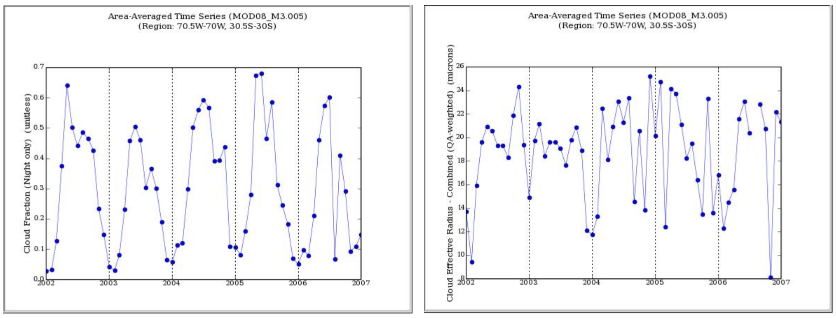



Figure 2.3: This graph shows the cloud fraction (left) and their effective radius (right).

## 2.4 Atmospheric Profile

The idea is now to create a realistic atmospheric profile for the Cerro Pachon area and see how the atmospheric extinction varies when some of the parameters are changed. There was a precedent study about atmospheric extinction that was made by another student[1]. Scaling parameters of equation (2.1) to fit with their graph, we get the following values :
$\alpha_p = -1$ :
$\alpha_r = 1.113$
$\alpha_a = 0.0765$
$\epsilon = 1$
Below is shown the atmospheric attenuation profile for their atmosphere:

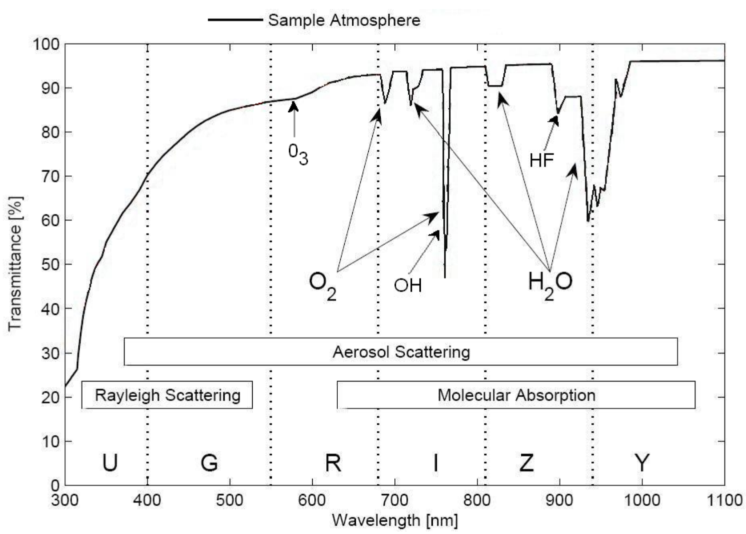



Figure 2.4: Transmission of light through Earth's atmopshere as shown on another document

But those datas are shown to be wrong, as those values are not the correct values for Cerro Pachon. Here is the graph with the **correct value for Cerro Pachon area**. The parameters being : $\alpha_p = -0.65$ :
$\alpha_r = 1.113$
$\alpha_a = 0.2$
$\epsilon = 1.75$
As we can the resulting global atmospheric extinction is much less than the one given in the previous document (see formula in the appendix).

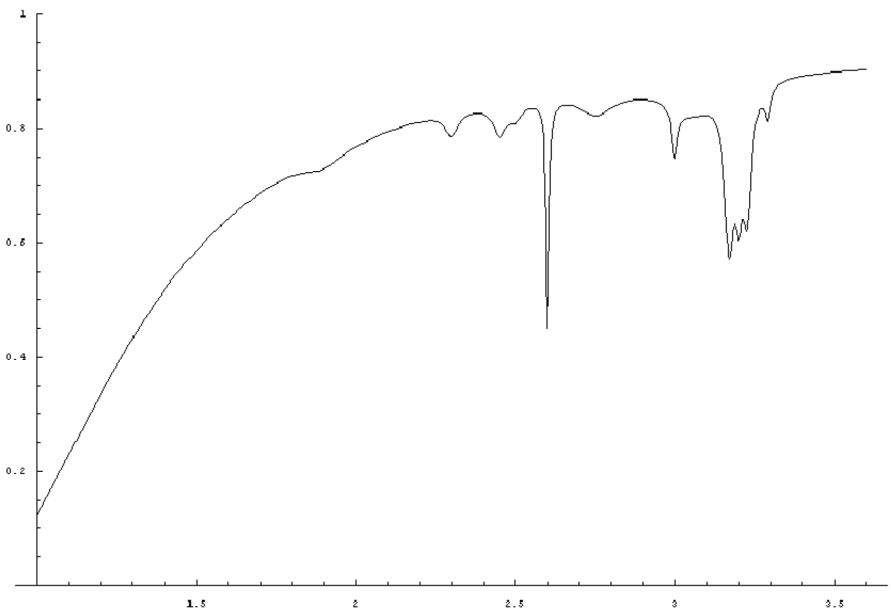



Figure 2.5: Transmission of light through Earth's atmopshere - Model (x axis : $x = \frac{\lambda}{\lambda_0}$ and $\lambda_0 = 300nm$) All in all, we can quantify the variation of the different parameters, and therefore compute the theoretical change in the atmospheric attenuation. The worst case scenario would be if there is no auxiliary telescope that could take datas in live. Therefore, we will assume that the parameters can have extreme variations and compute the change in the intensity. The worst case scenario leads to a change in the parameters in the following way : $\alpha_p = -0.7$ $\alpha_r = 1.113$ $\alpha_a = 0.35$ $\epsilon = 1.3$ which leads to a change of 10% in the atmospheric attenuation.However, this was a very extreme case (assuming that all the parameters would have their maximal variations). In reality it turns out the intra-day overall fluctuation of the atmospheric extinction will not be more than 5%.

# Chapter 3

# Atmospheric model : random field and spherical harmonics

During my internship, I also tried to study how we could predict the evolution of the atmospheric conditions, describing aerosols as a random field. The idea is to see the different layers of the atmosphere as a random density field that fluctuates over time. Therefore, it is convenient to simulate it in spherical harmonics to build up anisotropies and then let this field evolve over time to see what happens.

Our goal will then be to build up those harmonics in order to create a field that will have a realistic spatial and temporal correlation function, and therefore a realistic behavior over space and time. Using spherical harmonics to simulate anisotropies is a widely spread technique, used for example for the CMB of for planet topography, so we will be able to apply some of the work done in these field to our study.

## 3.1 Spherical harmonics

$$\tau(\vec{r}, t) = \frac{\delta\rho}{\rho} = \sum_{l,m} a_l^m(t) Y_l^m(\vec{r}) \tag{3.1}$$

Here $\vec{r}$ represents the angular spearation $\alpha$ between two points on the field. The correlation function is given by :

$$C(\alpha, t) = \langle \tau(\vec{r_1}, t)\tau(\vec{r_2}, t)\rangle = \sum_l C_l(t)\frac{2l+1}{4\pi}P_l(cos(\alpha)) \tag{3.2}$$

$C(\alpha, t)$ is the correlation function, $C_l(t) = \langle |a_l^m(t)|^2\rangle$ is the power spectrum. The lack of any preferred direction requires that there is no dependence on m.

## 3.2 Application to aerosols

The following graph [3] shows spatial and temporal correlation for aerosols. We will extract datapoints from those graphs to get the power spectrum, which then can be related to the atmospheric attenuation.

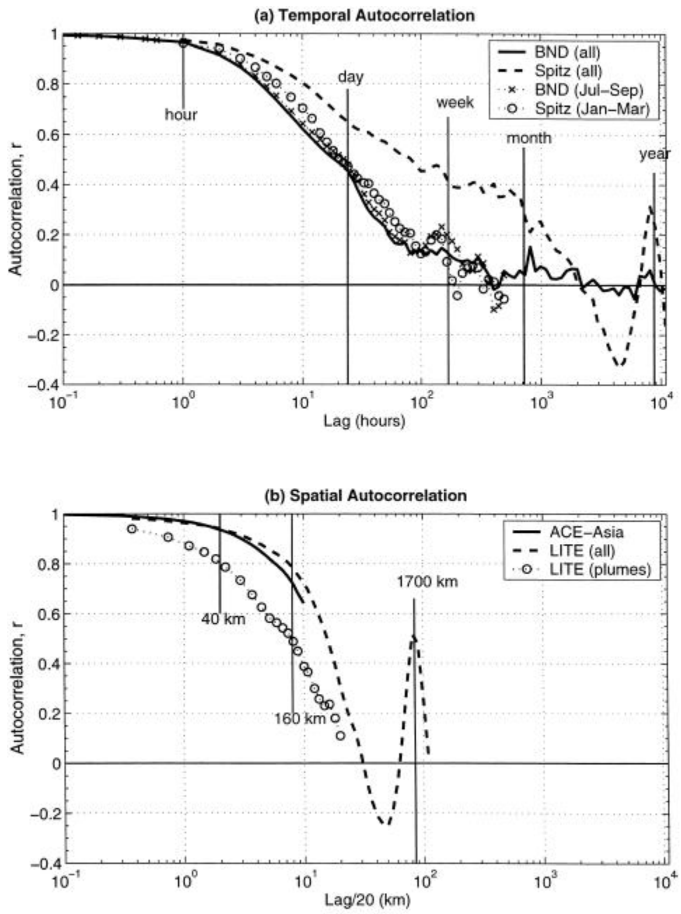



Figure 3.1: Spatial and temporal correlation. Full Sky : $\alpha = \frac{160}{180}\pi \Rightarrow d = \frac{160}{180}2\pi h \approx 350km$ therefore $C(\frac{160}{180}\pi, t) = \sum_l C_l(t)\frac{2l+1}{4\pi}P_l(cos(\frac{160}{180}\pi)) = 0.82$

| $l$ | $C_l(t_0)$ | $S_l$ |
|---|---|---|
| $l = 0$ | 6.33 | 0 |
| $l = 1$ | 1.73 | 0.52 |
| $l = 2$ | 0.10 | 0.22 |
| $l = 3$ | 0.09 | 0.29 |
| $l = 4$ | 0.03 | 0.23 |
| $l = 5$ | 0.02 | 0.22 |
| $l = 6$ | 0.003 | 0.10 |

Rebuilding the power spectrum:

$$\frac{\delta\rho}{\rho} = S_l = \sqrt{\frac{l(l+1)}{4\pi}\sum\langle|a_l^m(t)|\rangle^2} = \sqrt{\frac{l(l+1)}{4\pi}|C_l|} \tag{3.3}$$

A high power spectrum coefficient indicates a significant contribution to the overall field.

Knowing the correlation for a given time lag or distance lag allows us to rebuild the atmospheric extinction profile.

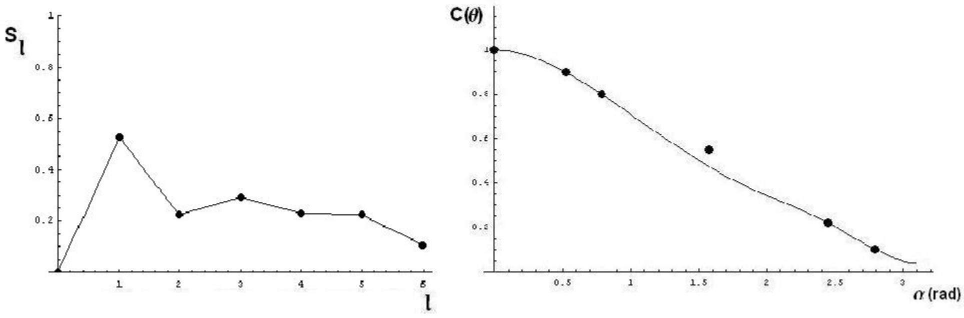



Figure 3.2: Power spectrum for l=6 ; $\lambda = \frac{\frac{160}{180}\pi h}{l}$ therefore $\lambda = 350km, 170km, 110km, 85km, 70km, 55km$.

Temporal correlation :
Below is shown the time-correlation function. We can extract from it the typical time after which the correlation becomes obsolete.

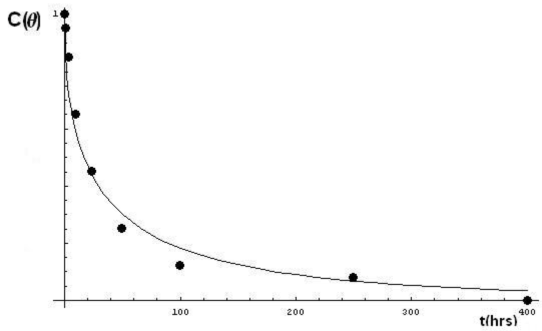



Figure 3.3: Correlation : $C(\alpha) = \sum_l C_l \frac{2l+1}{4\pi} P_l(cos\alpha)$

$$C_l(t) = C_l(t_0)e^{-0.17\sqrt{t}} \tag{3.4}$$

with t in hours therefore

$$C(\alpha, t) = \sum_l C_l(t_0)\frac{2l+1}{4\pi}P_l(cos\alpha)e^{-0.17\sqrt{t}} \tag{3.5}$$

Therefore the typical time lag is around 30 hours. Knowing the temporal and spatial correlation function for an aerosol cloud allows us to recreate its power spectrum. Hence, if we have enough datapoints (which means having much more than 6 harmonics to recreate the field), it should be possible to rebuild its density profile (by looking how the different harmonics add up) and therefore get the atmospheric extinction for that aerosol cloud.

# Conclusion

In this document, I tried to understand how the atmosphere of the Cerro Pachon site could be described and how its fluctuations could be predicted and quantified.

I first based my work on a precedent study by a student, but it turned out that the datas they had been using were not correct for the Cerro Pachon site. Using datas on the Nasa website, I was able to determine the different parameters that should be taken into account for a proper modeilsation of the atmosphere. After having created a typical realistic profile, I was able to try different values for each parameter in order to see how large the fluctuations of the atmospheric attenuation could get. It turned out that the maximum intraday extinction variation would be of around 5%.

I also tried to find a way to recreate the evolution of an aerosol using a random gaussian field ; using the correlation function of an aerosol cloud, I was able to recreate its power spectrum and therefore extract some of the atmospheric parameters. However a good prior knowledge of the the correlation function is required, otherwise you do not have enough datapoints (so you can rebuild enough harmonics) to extract enough information (as in my study).

We obtained some interesting results concerning the evolution of the atmospheric extinction for the Cerro Pachon site ; the use of an auxiliary telescope together with what was developped in this study should help predict the evolution of the intensity of the flux received at different lenghtwaves, therefore allowing us to make much more precise observations.

**Acknowledgments**

I would like to thank all the researchers and all the personnel that work in the APC for their great reception and for all the documents and material they put at my disposition for my work, and for all the meetings of the Cosmology group that made me discover the various experiments and projects all the teams were working on. I would like to thank in particular Jim Bartlett, my traineeship supervisor, that gave me many useful indications that helped me work in the best conditions. I really enjoyed working on that subject, which made me learn a lot on how complicated the modelisation of the atmosphere could be, and helped me better understand what the work of a researcher consist in.

# References


1 The Effect of Eath's Atmosphere on LSST Photometry, Alexandra S. Rahlin - August 25, 2006

2 Nasa Website :

`http://disc1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MODIS_MONTHLY_L3`

3 Mesoscale Variations of Tropospheric Aerosols, THEODORE L. ANDERSON AND ROBERT J. CHARLSON, DAVID M. WINKER, JOHN A. OGREN, KIM HOLME´N - July 15, 2002

Other documents used :

1. The Physics of CMBR Anisotropies, Kandaswamy Subramanian - September 12, 2006
2. Cours sur la modélisation atmosphérique :

   `http://www.ifremer.fr/droos/cours_teledetection/cours.html`

3. Modtran Infrared Radiation Code :

   `http://geosci.uchicago.edu/~archer/cgimodels/radiation.html`

# Appendix

Formula for the correct atmospheric profile :

```
Exp[-1.113*x^-4-0.0765*
      x^-1-(1/100)*(0.01/(2*Pi)*1/((0.01/2)^2+(x-2.6)^2))-(1/
          100)*(0.17/(2*Pi)*1/((0.17/2)^2+(x-1.9)^2))-(1/
          250)*(0.05/(2*Pi)*1/((0.05/2)^2+(x-2.3)^2))-(1/
          200)*(0.05/(2*Pi)*1/((0.05/2)^2+(x-2.45)^2))-(1/
          400)*(0.05/(2*Pi)*1/((0.05/2)^2+(x-2.50)^2))-(1/
          250)*(0.1/(2*Pi)*1/((0.1/2)^2+(x-2.75)^2))-(1/
          250)*(0.2/(2*Pi)*1/((0.2/2)^2+(x-2.75)^2))-(1/
          250)*(0.2/(2*Pi)*1/((0.2/2)^2+(x-2.78)^2))-(1/
          290)*(0.02/(2*Pi)*1/((0.02/2)^2+(x-3)^2))-(1/
          50)*(0.2/(2*Pi)*1/((0.2/2)^2+(x-3.05)^2))-(1/
          60)*(0.03/(2*Pi)*1/((0.03/2)^2+(x-3.17)^2))-(1/
          90)*(0.03/(2*Pi)*1/((0.03/2)^2+(x-3.20)^2))-(1/
          80)*(0.03/(2*Pi)*1/((0.03/2)^2+(x-3.227)^2))-(1/
          500)*(0.02/(2*Pi)*1/((0.02/2)^2+(x-3.29)^2))]
```

where $x = \frac{\lambda}{\lambda_0}$ and $\lambda_0 = 300nm$