IMPLEMENTATION OF A BIO-OPTICAL MODEL IN IDL

by

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ABSTRACT

This report presents the implementation of a bio-optical model for the determination of the water leaving radiance given the inherent optical properties and the bottom reflectance. The bio-optical model developed by Zhongping Lee was implemented in the Interactive Data Language (IDL). The model implementation is described and a description of how to use the software is given. The implementation is validated against a model implementation in excel provided by Dr. Lee. Comparisons between the implemented model and Lee's model are done using linear regression. Validation results show that the developed implementation produce the same numerical results as Lee's implementation.

RESUMEN

Este reporte presenta la implementación de un modelo bio-óptico para determinar la radianza que sale del agua dada las propiedades ópticas inherentes y la reflectancia del fondo. Se implementó el modelo desarrollado por Zhongping Lee utilizando el Lenguaje Interactivo de Data (IDL por sus siglas en inglés). Se presenta la implementación del modelo y se da una descripción de cómo utilizar el mismo. La implementación es validada utilizando una implementación del modelo provisto por el Dr. Lee en Excel. Las comparaciones entre ambos se hacen utilizando regresión linear. Los resultados de la validación muestran la implementación desarrollada produce los mismos resultados numéricos que la implementación de Lee.

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CHAPTER 1 INTRODUCTION

Benthic habitats are places on or near the sea floor where aquatic organisms live. These beds of sea grass, areas of mud and sand, and coral reefs provide food and shelter to a rich array of animals. The preservation of this ecosystem, especially its coral reefs, is a National priority. In addition, this ecosystem is an attractive environment for many recreational, commercial and scientific activities, and is critical to the tourist economy. There is a need to establish an ongoing and consistent national database of coastal benthic data that document changes and trends over time. Satellite hyperspectral remote sensing technology has the potential to provide the required information to achieve these objectives.

For decades inherent optical properties have affected sea life. The inherent optical properties specify the optical properties of natural waters in a form suited to the needs of radiative transfer theory [15]. Hyperspectral imagery is a technology that has great potential for the monitoring of coastal environments. The main goal of this project was to implement and validate the bio-optical model of Z. Lee in the IDL environment to use in the estimation of properties of benthic habitats. A bio-optical model is used for the determination of inherent optical properties from reflectance data. It is usually used in applications to remotely sensed data from case I and case II waters. Case I waters is know as natural waters, or not sea water; case II waters are known as salt water. Many efforts have been made to study the effect of such properties by estimating the amount of these in water. In the last decades remote sensing imagery is a method widely used. Through hyperspectral and multispectral remote sensing we can study these optical properties through remotely sensed images. This project discusses an implementation of a model to relate satellite water leaving radiance to estimate inherent optical properties.

When monitoring underwater environments using satellite remote sensing, the signal received by the satellite sensor consists of the sum of the contribution of the atmosphere, the water column, and the signal from the sea floor. Atmospheric correction codes remove from the measured satellite signal the contribution of the atmosphere leaving the water leaving radiance which is processed using bio-optical models to retrieve the inherent optical properties of the water as well as the bottom reflectance.

This project presents the implementation and validation of the bio-optical model of Z.P. Lee [14] in IDL. IDL was chosen is because of its wide use in remote sensing. Lee's model is widely studied in the literature but no IDL implementation is available for use by CenSSIS researchers.[1] Validation for this implementation and the methods for the validation are presented in the report.

1.1 Report Outline

In chapter 2, we discuss Zhongping Lee's bio-optical model. Each subcomponent of the model is explained in detail. In chapter 3, we discuss the methods for implementation and the implementation. We also describe how to access and run the program. Finally, in chapter 4, we present our validation of the implementation using simulated data. Chapter 5 presents conclusions and suggestions for future work.

CHAPTER 2 ZHONGPING LEE'S BIO OPTICAL MODEL

In this chapter we will review the bioptical model implemented in the program[14]. All components are specified with each respective sub-component and their meaning.

There are various bio-optical models described in the literature[1,2,14]. For this project we decided to use Zhongping Lee's bio-optical model because of its wide use in the bio-optical oceanography.

Bio-optical models can be used to predict the penetration of spectral irradiance in the water column. They take as input the spectral irradiance above the air-water interface, compute the transmittance through this interface, and permit the estimation of biologically effective irradiance as a function of depth in natural waters. Inherent optical properties of water are a key element in these models.

2.1 Radiative Transfer Equation (RTE):

Most photons descending from the atmosphere over an ocean or lake eventually reach the water surface. The surface reflects some of these photons back to the sky, and transmits the remainder into the water body. Likewise, photons within a water body occasionally strike the air-water surface from below; some of these photons pass through the surface into the air and some are reflected back into the water body. This activity is provided partly by the *interaction principle* of radiative transfer theory written for the air-water surface[15].

In remote sensing of coastal environments, the radiance leaving the water surface is determined among other factors by the surface state, the optical properties of water, and in the case of shallow water by the depth and reflectance of the sea-bottom. Figure 1 illustrates the basic components of the satellite measured signal for coastal remote sensing[11].

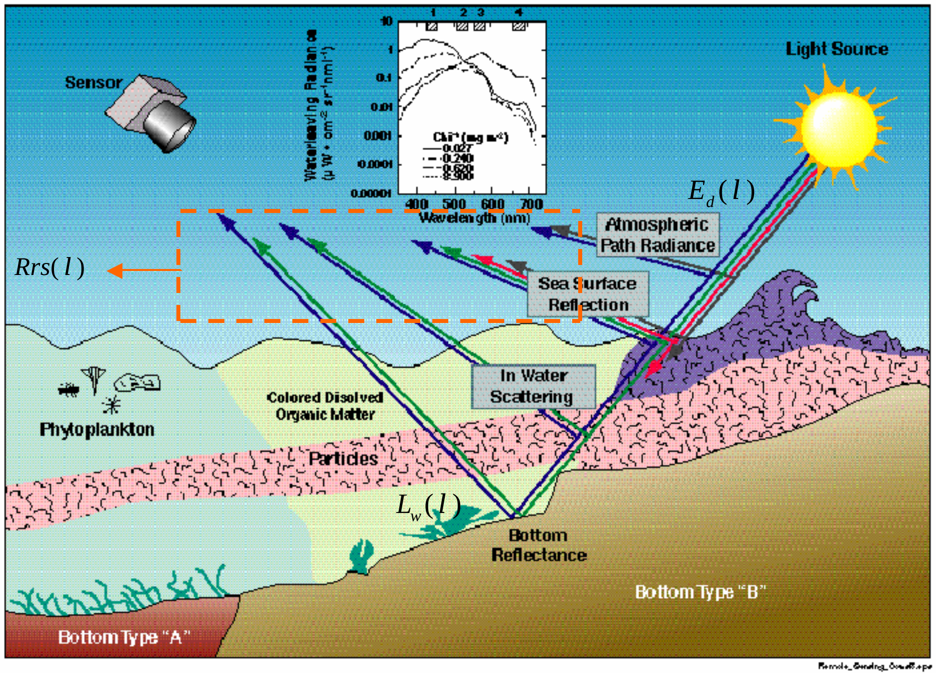

Figure 2-1 Basic components of the satellite measured signal [14]

As described in Lee et al.[7], the information about water IOP and bottom reflectance is extracted from the remote-sensing reflectance, R_{rs}, which is defined as, the water-leaving radiance, L_w, (light scattered back up through the surface of the ocean water) divided by the downwelling irradiance (just above the sea surface), E_d at wavelength l. The water leaving remote sensing reflectance can be used in conjunction with bio-optical models to retrieve water inherent optical properties (IOP), bathymetry and bottom reflectance.

$$R_{rs} = \frac{L_w}{E_d}$$

A common bio-optical model used to relate the inherent optical properties of the water and bottom reflectance with the measured remote sensing reflectance R_{rs} is Lee's bio-optical given by[14]:

$$R_{rs} = \frac{0.5 r_{rs}}{1 - 1.5 r_{rs}}$$

where

$$r_{rs} = r_{rs}^{\ dp}\left(1 - \exp\left\{-\left[1 + \frac{D_u^C}{0.92}\right]kH\right\}\right) + \frac{1}{p}\, r\, \exp\left\{-\left[1 + \frac{D_u^B}{0.92}\right]kH\right\}$$

$$u = \frac{\mathrm{b_p}}{\mathrm{a} + \mathrm{b_p}}$$

$$r_{rs}^{\ dp} = (0.084 + 0.170u)u$$

$$k = \mathrm{a} + \mathrm{b_b}$$

$$D_u^C = 1.03(1 + 2.4u)^{0.5}$$

$$D_u^B = 1.05(1 + 5.5u)^{0.5}$$

r_{rs} is the subsurface remote sensing reflectance, $a(l)$ is the absorption coefficient, $b_b(l)$ is the backscattering coefficient, $r(l)$ is the bottom albedo, H is the bottom depth, q_w is the subsurface solar zenith angle, q is the subsurface viewing angle from nadir. Table 2-1 summarizes the terminology.

Coefficients	Description	Units
a	total absorption coefficient	m^{-1}
a_w	pure water absorption coefficient	m^{-1}
a_f	absorption coefficients of phytoplankton	m^{-1}
a_g	absorption coefficient for gelbstoff	m^{-1}
b_{bp}	backscatter coefficient for particles	m^{-1}
b_{bw}	backscatter coefficient for pure water	m^{-1}
b_b	Total backscatter coefficient	m^{-1}
L_w	Water-leaving radiance	$W / m^2 / nm / sr$
E_d	Downwelling radiance	$W / nm / m^2$
R_{rs}	Above-surface remote sensing reflectance	sr^{-1}
r_{rs}	Subsurface remote sensing reflectance from water-column scattering	sr^{-1}
D_u^C	Optical path-elongation for scattered photons from the water column	
D_u^B	Optical path-elongation for scattered photons from the bottom	
?	Waveband in nanometers (390nm-710nm)	nm
k	Viewing azimuth angle from solar plane	m^{-1}
q	Subsurface viewing angle from nadir	rad
q_w	Subsurface solar zenith angle	rad
H	Bottom Depth	m

Table 2-1 Symbol Description

Every radiometric variable has its diffuse attenuation coefficient. The most commonly used is the downwelling irradiance. For coastal remote sensing the Water Column is referred to as the attenuation coefficients which by Lee are defined as:

2.2 Inherent Optical Properties of Water Equations

Inherent Optical Properties (IOP's) specify the optical properties of natural waters in a form suited to the needs of radiative transfer theory. These are the properties that depend only on the medium, and therefore are independent of the ambient light field within the medium.

The two fundamental IOP's are the absorption coefficient and the volume scattering function or backscatter. Other inherent optical properties include the index of refraction, the beam attenuation coefficient and the single-scattering albedo.

2.3 Absorption:

The determination of the spectral absorption is difficult because it absorbs only and very weekly in the near-UV and blue wavelengths. The equation for *total absorption* as expressed by Lee et al.[6] is as follows:

$$a = a_w + a_f + a_g$$

where a_w is the coefficient of pure water absorption (which is well-known), a_f is the coefficient for the absorption of phytoplankton and the coefficient for the absorption of gelbstoff. The absorption of pure water is well known. These values are taken by Smith & Baker[13]. The absorption of gelbstoff is given by[14]:

$$\mathrm{a}_g = G(\exp[0.014(440 - l)])$$

where $G = 0.06(\mathrm{chl\ -\ a})^{0.65}$, chl-a=0.4, S = 0.014 is the spectral slope, and l the wavelength.

The concentration of phytoplankton and detritus is difficult to separate. However, phytoplankton cells are strong absorbers. For this reason the absorption of phytoplankton and detritus are assumed one by Zhongping Lee and is described by:

$$\mathrm{a}_f = \{(a_0(l) + a_1(l)\ln[P])P\}$$

$$P = a_f(440)$$

where a0 and a1 are empirically determined and are shown in Table 3.

Wavelength (nm)	$a_0(l)$	$a_1(l)$
390	0.5813	0.0235
400	0.6843	0.0205
410	0.7782	0.0129
420	0.8637	0.006
430	0.9603	0.002
440	1.0	0
450	0.9634	0.006
460	0.9311	0.0109
470	0.8697	0.0157
480	0.789	0.0152
490	0.7558	0.0256
500	0.7333	0.0559
510	0.6911	0.0865
520	0.6327	0.0981
530	0.5681	0.0969
540	0.5046	0.09
550	0.4262	0.0781
560	0.3433	0.0659
570	0.295	0.06
580	0.2784	0.0581
590	0.2595	0.054
600	0.2389	0.0495
610	0.2745	0.0578
620	0.3197	0.0674
630	0.3421	0.0718
640	0.3331	0.0685
650	0.350	0.0713
660	0.561	0.1128
670	0.8435	0.1595
680	0.7485	0.1388
690	0.389	0.0812
700	0.136	0.0317
710	0.0545	0.0128
720	0.025	0.005

Table 2-2 Values of a0 and a1

2.4 Backscatter:

Once photons reach an element they may be scattered in different directions. Backscatter refers to the re-scattering of these photons. The total backscatter coefficient is given by:

$$b_b = b_{bw} + b_{bp}$$

where b_{bw} pure water backscattering coefficient and b_{bp} is the backscattering of particles which is given by:

$$b_{bp} = X\left(\frac{550}{?}\right)^{Y}$$

Table displays the values of each parameter stated by Dr. Zhonping Lee[14].

Variables	Values
Solar zenith angle (q_w)	$0\,°, 30\,°, 60\,°$
Particle phase function	Petzold average particle
Chlorophyll absorption [chl-a] mg m $^{-3}$	0.4, 1.0, 2.0, 5.0
$a_g(440)\ m^{-1}$	0.0331
b	0.3, 1.0, 5.0
r	0, 0.1, 0.3, 1.0
$H\ (m)$	0.5, 1, 3, 8, 16, 32, infinite
l	390-710, every 10 nm
S	0.014
Y	1
X	$0.018\,b[chl\_a]^{0.62}$
G	0.03307

Table 2-3 Parameters' description

2.5 Concluding Remarks

This chapter introduced Zhongping Lee's bio-optical model for the estimation of inherent optical properties. The resulting model is non-linear and parameterized by 8 parameters and the bottom albedo.

$$R_{rs} = f(G, S, X, Y, P, H, r(l), q, q_W)$$

CHAPTER 3 IMPLEMENTATION

Chapter 3 discusses the implementation of Zhongping Lee's optical model. Modules are displayed in Figures for visualization. The model implementation was implemented using IDL 3.6.

3.1 General Description of the program.

IDL is an environment developed for scientific computations; specifically its ENVI toolbar is a very important tool in remote sensing. It is also used in medical imaging. IDL stands for ***I****nteractive* ***D****ata* ***L****anguage* and is used for data analysis, visualization, and cross-platform application development.

The reason we worked in windows environment is because there is a wide knowledge in this environment and it is fairly simple to use. IDL was chosen because of its well recognized use and validation. The implementations' also run faster than those developed using other application programs used for scientific computing like MATLAB.

In our implementation, we identified each variable, section, structure, function and set of instructions to make it clear and readable for future modifications. We also gave it a structure so that you can differentiate amongst each different set of instructions and functions including the main procedure using different levels of indentations. Each function is called from the general code. Each component of the model is calculated in its respective function separately.

The well-known values or coefficients (i.e. pure water absorption, pure water backscatter among others) are contained within a file called constants created at the moment of execution to avoid file handling or recognition problems in different PC's. Indentations identify the instructions belonging to each clause. Each set of instructions, the main procedure and functions are well identified along with their variables and parameters to simplify the future modifications to this code. Every reserved word for IDL is written in capital to distinguish reserved words from functions, procedures and variables.

This project followed two important criteria in computer programming:

- Reduce time and cost of the algorithm
- Write a readable code for future modifications

Statistical and mathematical algorithms tend to be long and tedious and take a long time to process the code. This is why it is so important to reduce the amount of code lines as much as possible without affecting efficiency. The software structured is shown in Figure 3.1. Next we will describe the different program components.

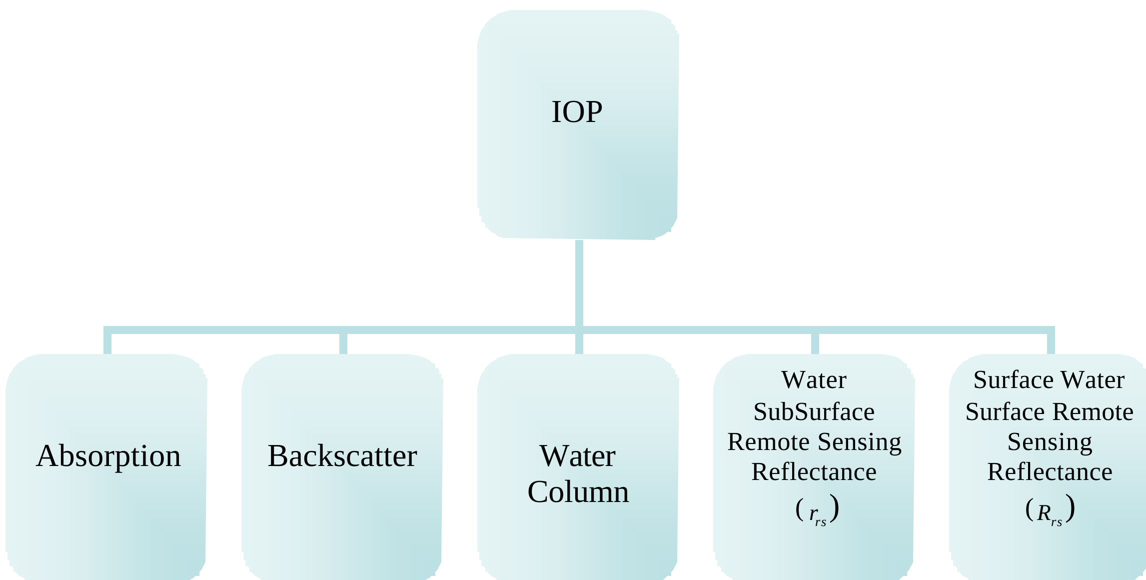

Figure 3-1 Organization chart of code

Figure 3-1 displays an organization chart of the structure of the code. All functions are called from the main procedure called IOP. Further on we will discuss how to run this code using IDL's command prompt.

3.2 Main Procedure *IOP*

The main program manipulates or controls the whole code. This is where al the functions are called from. The main program consists of a procedure called ***IOP*** shown in Figure 3.1.

Within this procedure all variables that are needed to be used in more than one function are declared to avoid repetition and confusion for future modification of the code. This also reduces processing time and cost. The main code is kept fairly short and it only consists of call to functions within the program. Every component of the model is calculated separately in its own function. The code consists of five functions. These functions calculate the absorption, $a(l)$, backscatter, $b_b(l)$, water column, D_u^C and D_u^B, below-surface remote sensing reflectance $r_{rs}(l)$, and above-water surface remote sensing reflectance, $R_{rs}(l)$. Each variable is given a significant name for easy recognition; when possible its original representation. U and other global parameters for the model are calculated here to avoid redundancy and reduce processing time.

```
PRO IOP
        restore,filename = 'C:\LeeAlgorithm\constants'

                    ;----------------Variables' Declaration-----------------------

Total_Backscttr=   DINDGEN(N_ELEMENTS(Band))    ;Holds value of total backscatter coefficient
Total_Abs =        DINDGEN(N_ELEMENTS(Band))    ;Holds value of total absorption coefficient
Absorp =           DINDGEN(N_ELEMENTS(Band))    ;Holds total absorption coefficient
Backscttr =        DINDGEN(N_ELEMENTS(Band))    ;Holds total backscatter coefficient
WaterCol =         DINDGEN(N_ELEMENTS(Band))    ;Holds total water column
rrs_below_srf =    DINDGEN(N_ELEMENTS(Band))    ;water sub-surface remote sensing reflectance
Rrs_above_surf =   DINDGEN(N_ELEMENTS(Band))    ;Holds value of water surface remote sensing reflectance
DuC =              DINDGEN(N_ELEMENTS(Band))    ;Optical path-elongation factors for  the water column
DuB =              DINDGEN(N_ELEMENTS(Band))    ;Optical path-elongation factors for the water bottom
u =                DINDGEN(N_ELEMENTS(Band))    ;Parameter
k =                DINDGEN(N_ELEMENTS(Band))    ;Attenuation coefficient (= absorption + backscatter)

                    ;----------------Default Values-----------------------

chla = 0.4                                      ;chlorophyll concentration
Beta = 0.3              ;Empirical value that varies to simulate a range from normal to highly turbid waters
X = 0.018*Beta*(chla)^0.62                      ;0.018*Beta*(chla)^0.62
P = 0.06*(chla)^0.65                            ;0.06*(chla)^0.65
Y = 1                                           ;Parameter
H = 20                                          ;Bottom depth
G = P                                           ;Absorption of gelbstoff at 440nm
rho = 0.1                                       ;Bottom albedo
theta = 0.0
thetaw = 0.0

                    ;--------------General code starts here------------------------

        OPENW, temp, 'X:\Michelles_Project\Project_Data\data.txt', /GET_LUN
        READ, Beta, PROMPT='Enter Beta: '
        READ, X, PROMPT='Enter X: '
        READ, Y, PROMPT='Enter Y: '
        READ, G, PROMPT='Enter G: '
        READ, P, PROMPT='Enter P: '
        READ, H, PROMPT='Enter H (depth): '
        READ, chla, PROMPT='Enter chl-a: '
        READ, rho, PROMPT='Enter rho (albedo): '
        READ, Theta, PROMPT='Enter Theta (angle): '
        Absorp = Absorption(P, G, X, Y)
        Backscttr = Backscatter(X, Y)
        FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
```

```
			u[i] = Backscttr[i]/(Absorp[i] + Backscttr[i])
		ENDFOR
		WaterCol = WaterColumn(hydrob, hydroa, u, DuC, DuB)
		FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
			k[i] = Backscttr[i] + Absorp[i]
		ENDFOR
		rrs_below_srf = rrs_below(DuC, DuB, H, u, k, rho, theta, thetaw)
		Rrs_above_srf = Rrs_surface(rrs_below_srf)
		WINDOW, 0
		PLOT, band, Absorp, TITLE = 'Absorption',BACKGROUND = 255, COLOR = 0, FONT=3
		WINDOW, 1
		PLOT, band, backscttr, TITLE = 'Backscatter',BACKGROUND = 255, COLOR = 0, FONT=3
		WINDOW, 2
		PLOT, band, rrs_below_srf, TITLE = 'rrs',BACKGROUND = 255, COLOR = 0, FONT=3
		WINDOW, 3
		PLOT, band, Rrs_above_srf, TITLE = 'Rrs',BACKGROUND = 255, COLOR = 0, FONT=3
		PRINTF, temp, Absorp, Backscttr, rrs_below_srf, Rrs_above_srf, DuC, DuB
		CLOSE, temp
END ;Main
```

Listing 3-1 Main Procedure *IOP*

3.3 Absorption

The absorption function is called *Absorption*. It receives parameters *P, G, X* and *Y*. Each component within the absorption coefficient is calculated separately but within the within the same cycle to reduce processing cost and time. However, each component is calculated in a separate instruction line to simplify modifications to each particular component. The *Absorption* code is shown in List 3.2. List 3.2 represents the following equation:

The values of a_w are well known.

```
FUNCTION Absorption, Ptemp, Gtemp, Xtemp, Ytemp
		restore,filename = 'C:\LeeAlgorithm\constants'
		Absorp_Phyto = DINDGEN(N_ELEMENTS(Band))		;Holds value of absorption of phyto in water
		Absorp_Gelbs = DINDGEN(N_ELEMENTS(Band))		;Holds value of absorption of gelbstoff in water
		TA = DINDGEN(N_ELEMENTS(Band))
		S = 0.014
		var440nm = 440 ;nm
		PRINT, ' '
		PRINT,'ABSORPTION:'
		PRINT, ' '
		PRINT, '	Band	Absorption Gelbstoff		Absorption Phytoplankton		Absorption:'
		PRINT, ' '
		FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
			Absorp_Phyto[i] = (a0[i] + a1[i] * ALOG(Ptemp)) * Ptemp
			Absorp_Gelbs[i] = Gtemp * EXP(S*(Var440nm-Band[i]))
			TA[i]				= AW[i] + Absorp_Phyto[i] + Absorp_Gelbs[i]
			PRINT, Band[i],'			',Absorp_Gelbs[i],'			', Absorp_Phyto[i],'			',TA[i]
		ENDFOR
		PRINT, ' '
		PRINT, ' '
		PRINT, ' '
		RETURN, TA
END
```

Listing 3-2 Module for *Absorption*

Table 3.2 describes each parameter.

Parameter	Representation
$a_f(440)$	*Ptemp*
G	*Gtemp*
X	*Xtemp*
Y	*Ytemp*

Table 3-1 Parameters representation for *Absorption*

S represents *S*, *Absorp_Phyto* represents absorption of phytoplankton coefficient, *Absorp_Gelbs* represents absorption of gelbstoff coefficient, *TA* represents the total absorption coefficient. *AW* represents pure water absorption and the values of *AW* are contained in a file named *constants*.

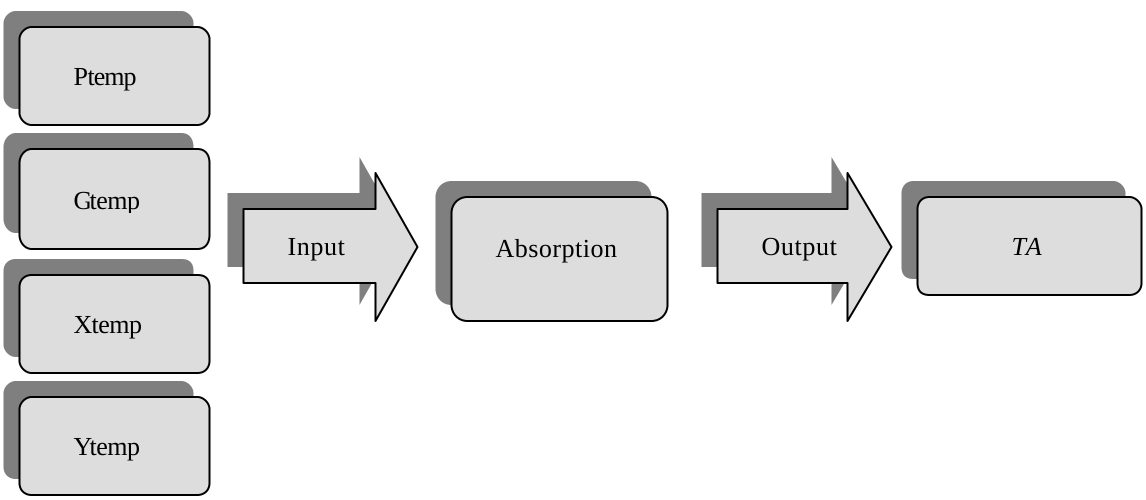

Figure 3-2 Input parameters and output parameter for *Absorption* module

3.4 Backscatter

The function for backscatter is called *Backscatter* and is shown in Figure 3.3. It contains parameters *X* and *Y*. Its components are also within a cycle but each component is calculated in a separate code line for easy modification. Every component and coefficient is well identified. The value of b_{bw} is also well known and stored in a file named *constants* within the folder of *MProject*.

```
FUNCTION Backscatter, Xtemp, Ytemp
	restore,filename = 'C:\LeeAlgorithm\constants'
	var550nm = 550
	Bp = DINDGEN(N_ELEMENTS(Band))
	BB = DINDGEN(N_ELEMENTS(Band))
	PRINT, ' '
	PRINT, 'BACKSCATTER:'
	PRINT, ' '
	PRINT, '   Band                    Pure Water Backscatter              Total Backscatter'
	PRINT, ' '
	FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
		Bp[i]=Xtemp * (550/Band[i])^Ytemp
		BB[i] =  Bp[i] + Bw[i]
		PRINT, band[i],'       ',Bw[i],'              ', BB[i]
	ENDFOR
	PRINT, ' '
	PRINT, ' '
	PRINT, ' '
	RETURN, BB
END
```

Listing 3-3 *Backscatter* module

The following table displays the representation of each parameter for each coefficient.

Parameter	Representation
X	*Xtemp*
Y	*Ytemp*

Table 3-2 Parameter description for Backscatter

Bp represents the particle backscatter and *BB* the total backscatter coefficient. *Bw* represents pure water backscatter. This value is contained in a file named *constants.*

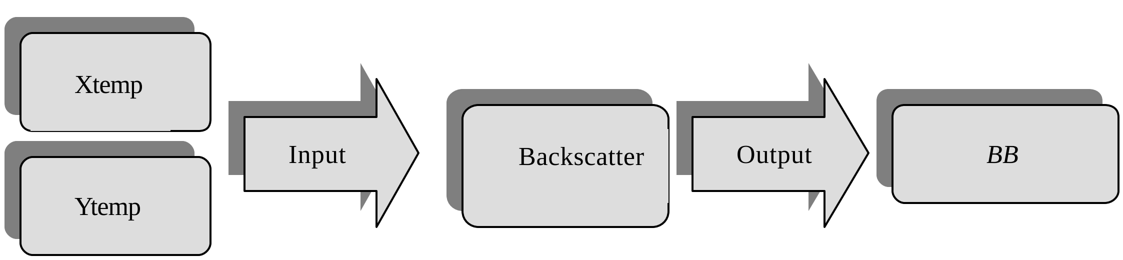

Figure 3-3 Input and output parameters for *Backscatter* module

3.5 Water Column

The water column procedure is named *WaterColumn* and receives parameters *BB, TA*, *utemp,*

D_u^C and D_u^B and implements equations. This is a procedure because we must modify values and keep those modified values when we return the two values: D_u^C and D_u^B. This module is shown in Listing 3.4. It is also structured with indentations and each component is well identified. Each component is separately calculated though it belongs to the same cycle again to reduce time and cost.

The function is as follows:

```
FUNCTION WaterColumn, BB, TA, utemp1, DuC, DuB
        restore,filename = 'C:\LeeAlgorithm\constants'
        WC = DINDGEN(N_ELEMENTS(Band))          ;Holds temp value of water column
        PRINT,' Band                    DuC                    DuB'
        PRINT, ' '
        FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
                DuC[i] = 1.03 * (1 + 2.4 * utemp1[i])^0.5
                DuB[i] = 1.05 * (1 + 5.5 * utemp1[i])^0.5
                PRINT,Band[i], '           ', DuC[i],'           ', DuB[i]
        ENDFOR
        PRINT, ' '
        PRINT, ' '
        PRINT, ' '
        RETURN, WC
END
```

Listing 3-4 *WaterColumn* Module

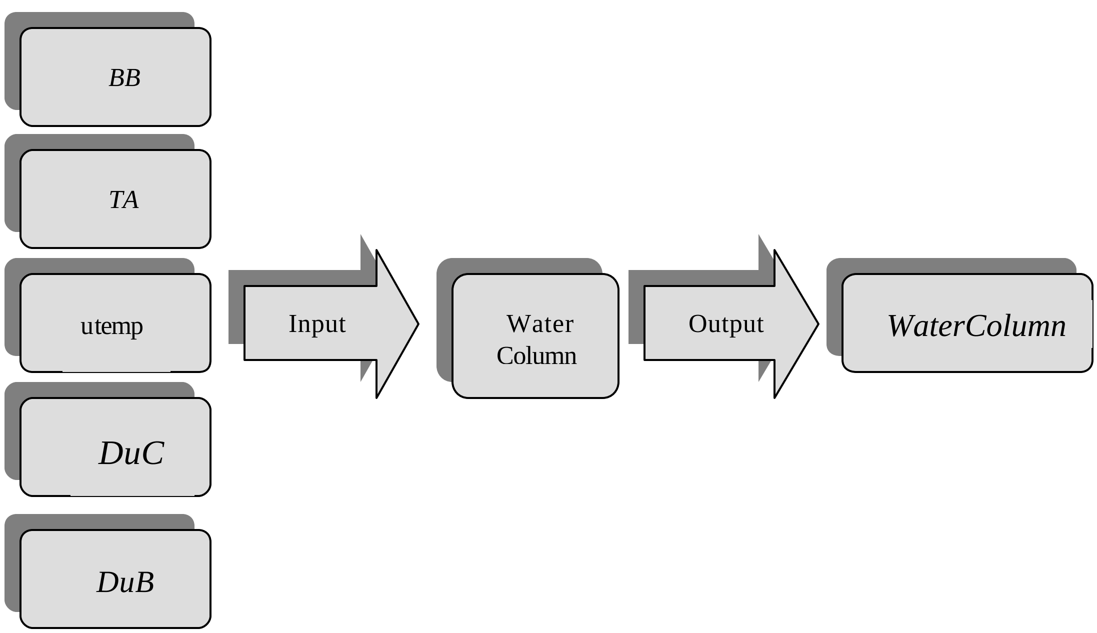

Figure 3-4 Input and output parameters for *WaterColumn* module

Parameter	Representation
b_b	*BB*
A	*TA*
u	*utemp*
D_u^C	*DuC*
D_u^B	*DuB*

Table 3-3 Parameter description for *WaterColumn*

3.6 Below-water surface remote sensing reflectance

The sub-surface water remote sensing reflectance function is named *rrs_below* and is shown in Listing 3.5. Its parameters consist of D_uC, D_uB, *H, u, k* and r. The whole equation is calculated in one line to avoid time and cost but each variable and model parameter is well described where declared to avoid confusion.

```
FUNCTION rrs_below, DuC, DuB, H, utemp2, k, rhotemp, thetatemp, thetawtemp
	g0 = 0.084
	g1 = 0.17
	restore,filename = 'C:\LeeAlgorithm\constants'
	rrs_bt = DINDGEN(N_ELEMENTS(Band))
	rrs0 = DINDGEN(N_ELEMENTS(Band))			;Holds temp value of below-water surface rrs
	rrsdp = DINDGEN(N_ELEMENTS(Band))			;Remote-sensing reflectance for optically deep
water
	FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
			rrsdp[i] = (g0 + g1 * utemp2[i]) * utemp2[i]
	ENDFOR
	PRINT, ' '
	PRINT,'BELOW WATER SURFACE rrs:'
	PRINT, ' '
	PRINT, '	Band					rrs'
	PRINT, ' '
	FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
		rrs_bt[i] = 0.3183 * rhotemp * exp(-((1 + DuB[i]/0.92) * k[i] * H))
	ENDFOR
	print, ' '
	FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
		rrs0[i] = rrsdp[i] * (1 -  exp(-(1+DuC[i]/0.92) * k[i] * H)) + rrs_bt[i]
		PRINT, Band[i],'				', rrs0[i]
	ENDFOR
	PRINT, ' '
	PRINT, ' '
	PRINT, ' '
	RETURN, rrs0
END
```

Listing 3-5 *rrs_below* module

rrs_below is the name of the function that calculates the sub-surface reflectance (r_{rs}). *rrsb* is the variable that receives the value of the sub-surface remote sensing reflectance. The value of each band or wavelength is contained in the file *constants.*

Parameter	Representation
r	*rhotemp*
k	*ktemp*
u	*utemp2*
D_u^C	*DuC*
D_u^B	*DuB*
H	*Htemp*

Table 3-4 Parameter description for *rrs_below*

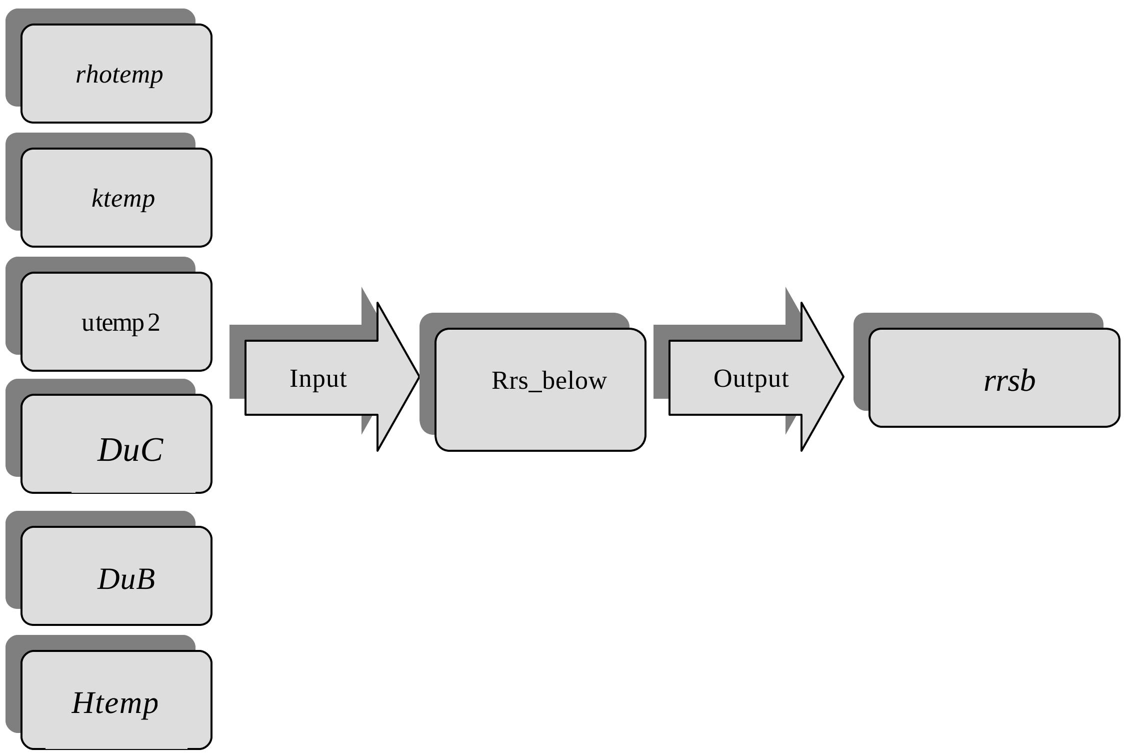

Figure 3-5 Input and output parameters for *rrs_below* module

3.7 Water-Leaving Reflectance

This is the most important function of the code because this is where we extract our information from. It is named *Rrs_surface* and receives parameter *rrsblw*. This parameter, *rrsblw,* contains the value of the sub-surface remote sensing reflectance for each wavelength. Again the whole equation is calculated in one instruction line to avoid long processing time.

```
FUNCTION Rrs_surface, rrs_blw
        restore,filename = 'C:\LeeAlgorithm\constants'
        Rrs_srf = DINDGEN(N_ELEMENTS(Band))            ;Holds temp value of water surface Rrs
        PRINT, ' '
        PRINT, 'WATER SURFACE Rrs:'
        PRINT, ' '
        PRINT, '    Band                                   Rrs'
        PRINT, ' '
        FOR i=0,N_ELEMENTS(Band)-1 DO BEGIN
                Rrs_srf[i] = 0.5 / (1 - 1.5 * rrs_blw[i])
                PRINT, band[i], '                      ',Rrs_srf[i]
        ENDFOR
        RETURN, Rrs_srf
END
```

Listing 3-6 *Rrs_surface* module

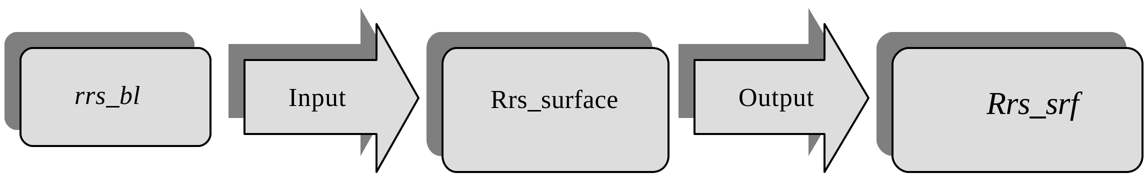

Figure 3-6 Input and output parameters for *Rrs_surface*

Each component is printed on screen from its respective function.

Parameter	Representation
r_{rs}	*rrs_blw*

Table 3-5 Parameter description for *Rrs_surface*

Rrs_srf represents water-surface remote sensing reflectance and is the value that is returned to the *MainPro* procedure. This program contains a simple interface. The interface is activated and performed through IDL's command prompt..

The following section demonstrates each step of the user interface.

3.8 Concluding Remarks:

This chapter discussed the implementation of the bio-optical model in IDL and how to use this program. In the next chapter, we will present the validation for this program.

CHAPTER 4 VALIDATION

Chapter 4 presents the results of the validation of our implementation of Zhongping Lee's bioptical model. For validation we used Dr. Zhongping Lee's own implementation of the model written in Excel. His model has been thoroughly validated with Hydrolight. Hydrolight is a widely used application for the simulation of estimation of Inherent Optical properties.

4.1 Methodology

In the following image we display our results against Zhongping Lee's implementation to demonstrate similarity. The method used to verify equality amongst both implementations is linear regression using r^2. Through linear regression we can calculate the statistics for a line by using the "least squares" method to calculate a straight line that best fits the data. The equation for the straight line would be:

$$y = mx + b$$

where the dependent x-value is a function of the independent y-values. The m-values are coefficients corresponding to each x-value, and b is a constant value. b is known as the slope and m as the intercept in y. The equations for m and b are as follows:

$$m = \frac{\sum(x_{Ours} - \overline{x}_{ours})(y_{Lee} - y_{Lee})}{\sum(x_{Ours} - \overline{x}_{Ours})^2}$$

$$b = \overline{y} - m\overline{x}$$

r^2 is the coefficient of determination. It compares estimated and actual y-values, and ranges in value from 0 to 1. If it is 1, there is a perfect correlation in the sample— there is no difference between the estimated y-value and the actual y-value. At the other extreme, if the coefficient of determination is 0, the regression equation is not helpful in predicting a y-value. r^2 is determined as follows:

$$r^2 = \left[\frac{1}{n-1} \Sigma \left(\frac{x - \bar{x}}{S_x} \right) \left(\frac{y - \bar{y}}{S_y} \right) \right]^2$$

where the limits of the summation are *i* to *n*. In this case the data would be our R_{rs} against Zhongping Lee's R_{rs} and our r_{rs} against Zhongping Lee's r_{rs}. The results are the following.

4.2 Results of Validation:

In our first example we verify the results of Zhongping Lee's implementation against ours. Table displays the conditions for this example.

Parameter	Value
Chla	0.4
Beta	0.3
H	20
Rho	0.1
X	0.00306
Y	1

Table 4-1 Parameter Description

The results are displayed in Figure 4-1 for R_{rs} and 4-2 for r_{rs} respectively.

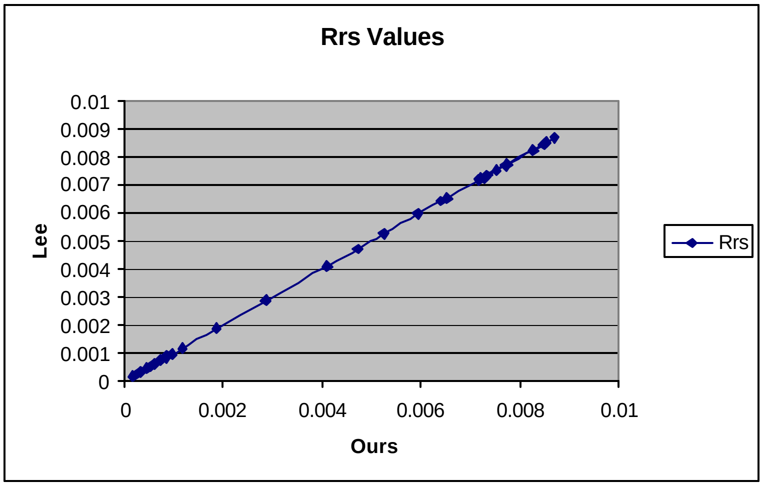

Figure 4-1 Lee's R_{rs} against our R_{rs}

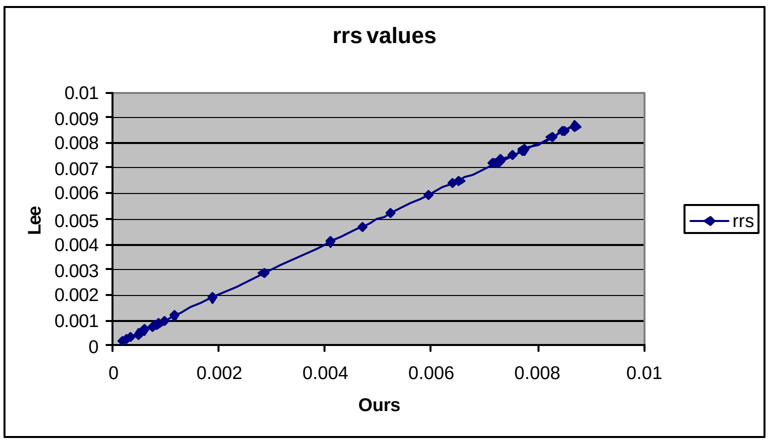

Figure 4-2 Lee's r_{rs} against our r_{rs}

These results show that our implementation produces results equal to those of model implemented by Dr. Zhongping Lee.

To further validate our code we applied linear regression using r to seven different cases which we used to verify that the values of our implementation are equal to those of Zhongping Lee's implementation. These cases consist of changing one of the parameters while the rest stay the same. Table 4-2 displays the values of the parameters for all 7 cases.

Original Values	
Chla	0.4
Beta	0.3
H	20
Rho	0.1
X	0.00306
Y	1

Table 4-2 Original values of parameters

Table 4-3 displays the values for each case. Values in red are those altered.

*Values in red represent the changed values

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Chla	2	0.4	0.4	0.4	0.4	0.4	0.4
Beta	0.3	0.05	0.3	0.3	0.3	0.3	0.3
H	20	20	1	20	20	20	20
Rho	0.1	0.1	0.1	0.1	1	0.1	0.1
X	0.00306	0.00306	0.00306	0.00306	0.00306	1	0.00306
Y	1	1	1	1	1	1	0.5

Table 4-3 Parameter values for the seven cases

Now we will display the results of each validated case. Table 4-4 lists the results of the r_{rs} for all seven cases.

r_{rs}							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
m	1	1	0.999999959	1	0.999999842	1	0.999999915
b	-4.2E-11	7.95E-11	-5.8146E-10	1.43E-10	1.97E-10	4.9E-11	1.1E-10
r^2	0.999999953	1	1	1	1	1	1

Table 4-4 Results of the seven cases for r_{rs}

Table 4-5 lists the results of the R_{rs} for all seven cases.

R_{rs}							
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
m	1	1	1	1	1	1	0.99999993
b	2.16E-08	8.48E-9	2.31E-09	-9.5E-09	1.13E-08	1.38E-08	3.76E-08
r^2	0.999999958	1	1	1	1	1	1

Table 4-5 Results of seven cases for R_{rs}

Since m=1 and r^2 =1 for all cases, our implementation complies with that of Dr. Zhongping Lee. Now we will illustrate the results of each of the cases in the represented by graphs.

Case 1:

In this case we change the value of chla=0.4 to chla=2

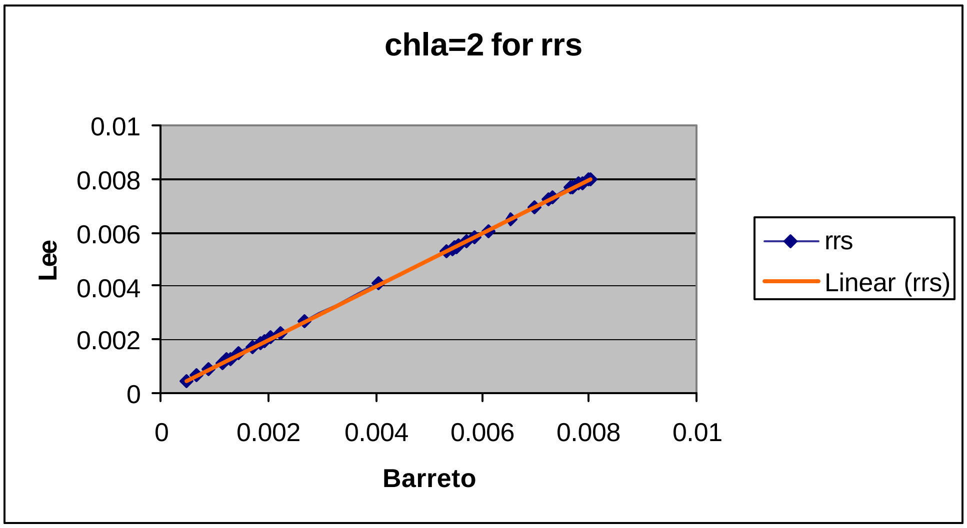

Figure 4-3 r_{rs} **for Case 1**

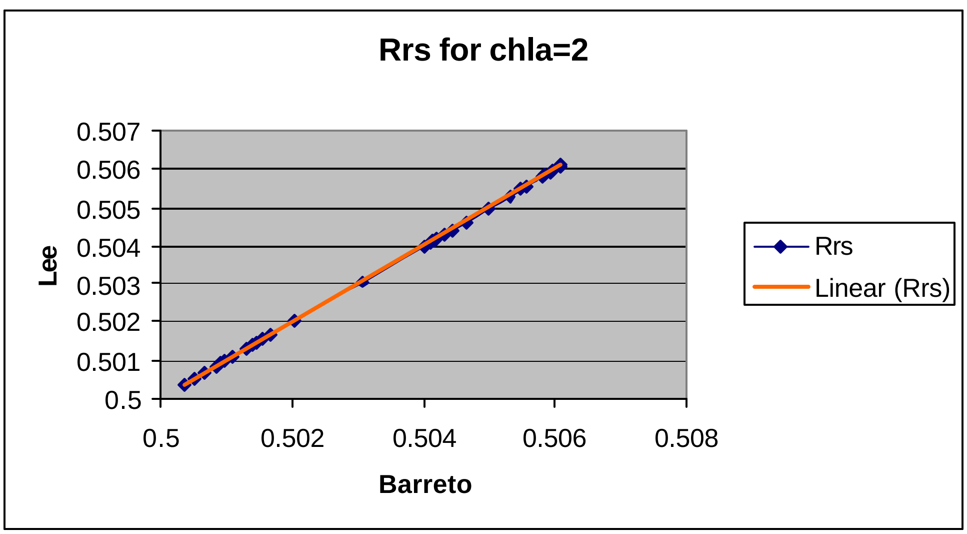

Figure 4-4 R_{rs} **for Case 1**

The red line is a trendline indicating that r^2 =1, this way indicating that our values are equal to those produced by Dr. Zhonping Lee's implementation.

Case 2:

In our next case we change the value of b which originally is 0.3 is now 0.05.

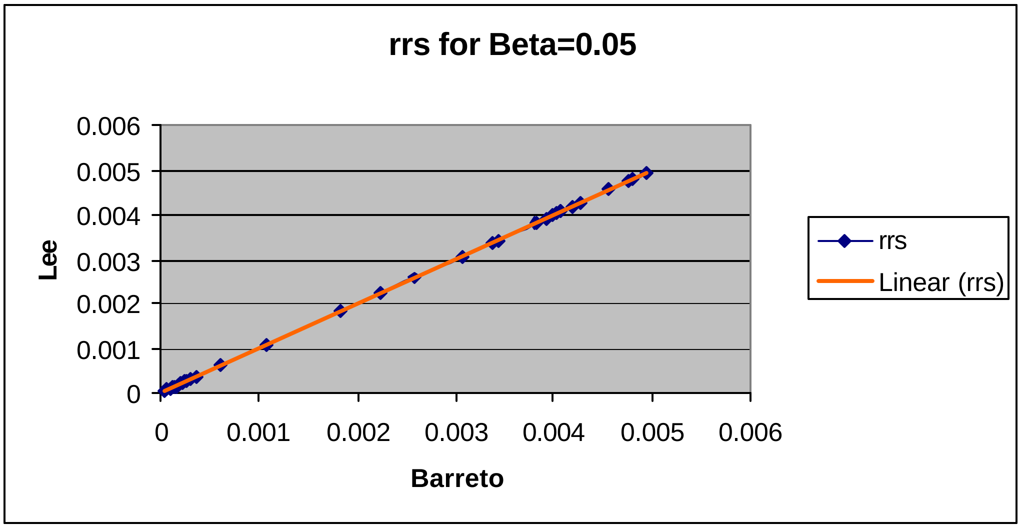

Figure 4-5 r_{rs} **for Case 2**

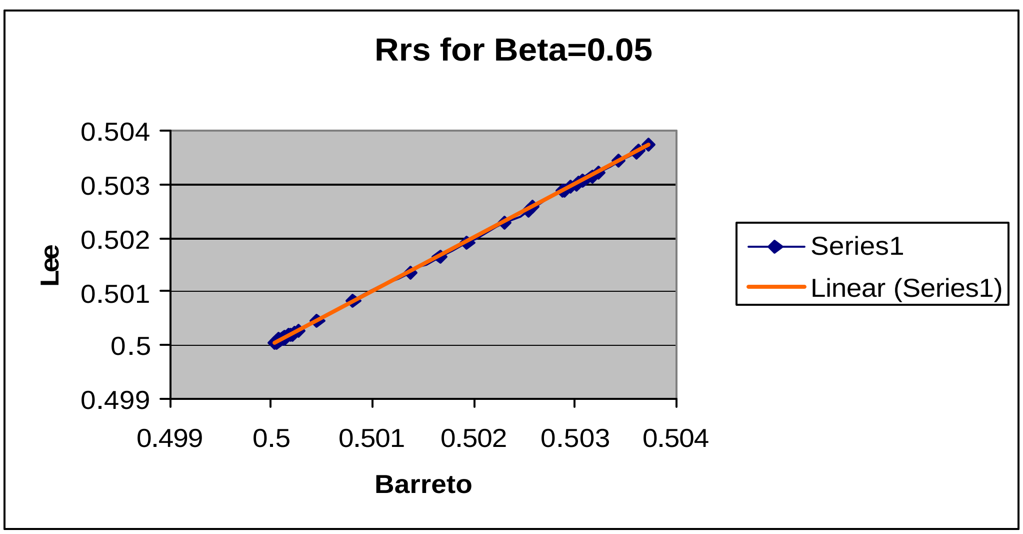

Figure 4-6 R_{rs} **for Case 2**

Case 3:

In this case we change the value of r which originally is 0.1 to 1 and still observe the same results, our trendline indicates $r^2 = 1$ meaning our results are equal to Lee's implementation.

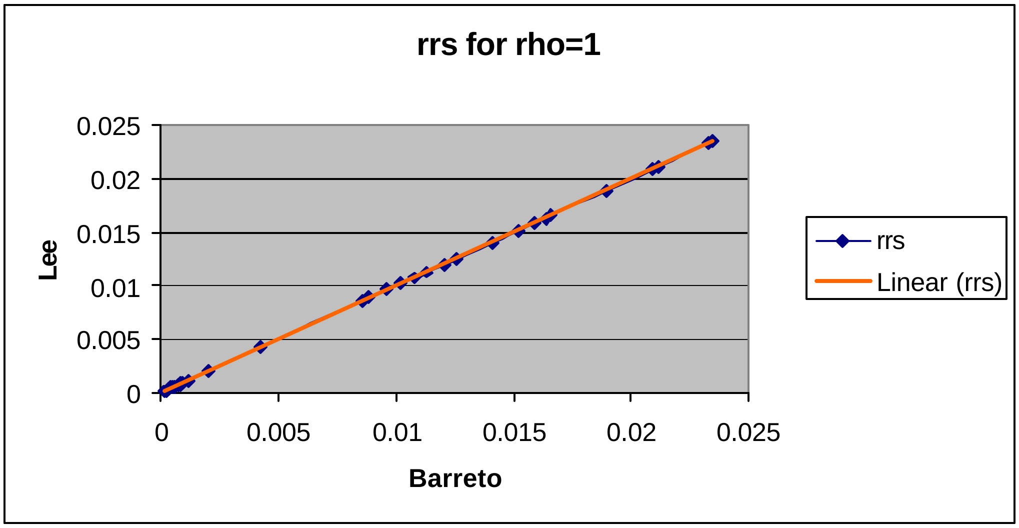

Figure 4-7 r_{rs} **for Case 3**

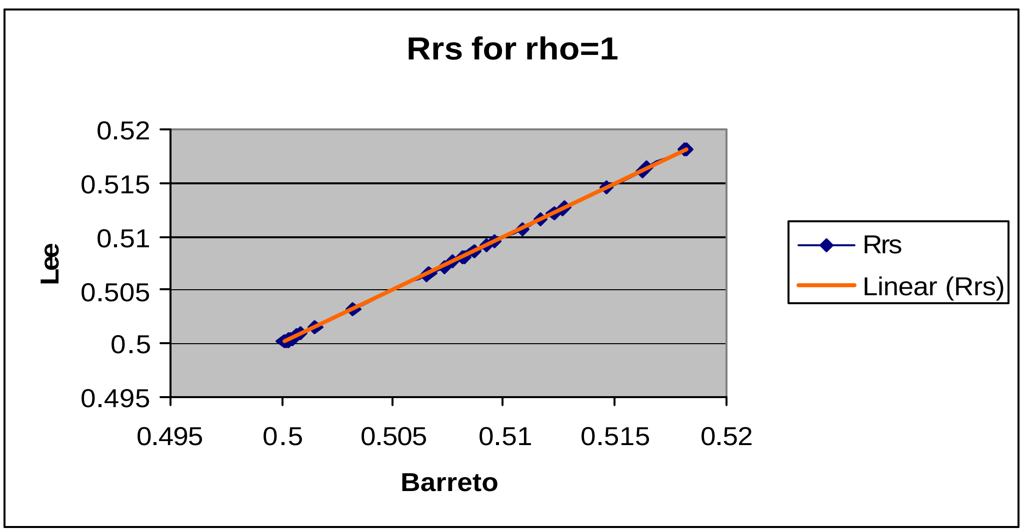

Figure 4-8 R_{rs} **for Case 3**

Case 4:

In this case we change the value of H which originally was 20 to 1.

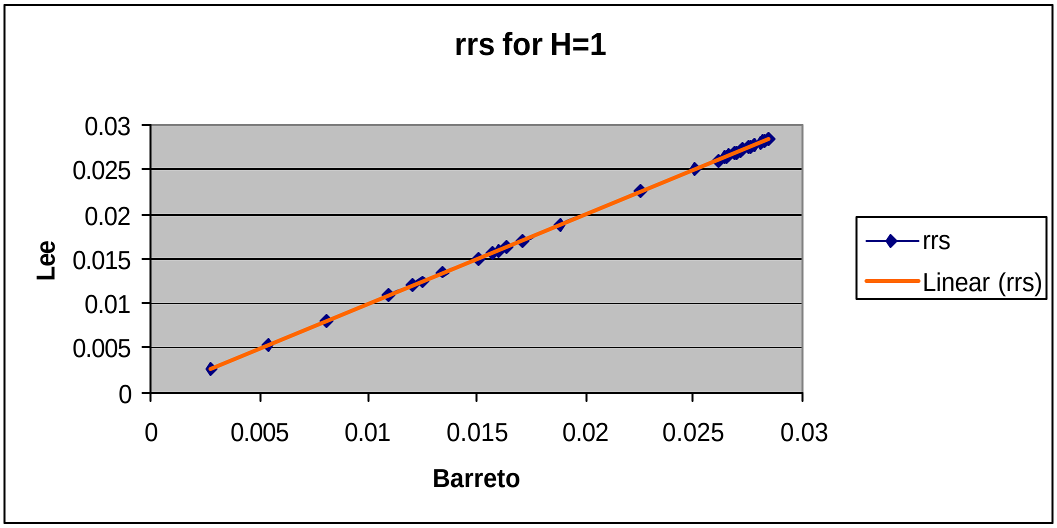

Figure 4-9 r_{rs} **for Case 4**

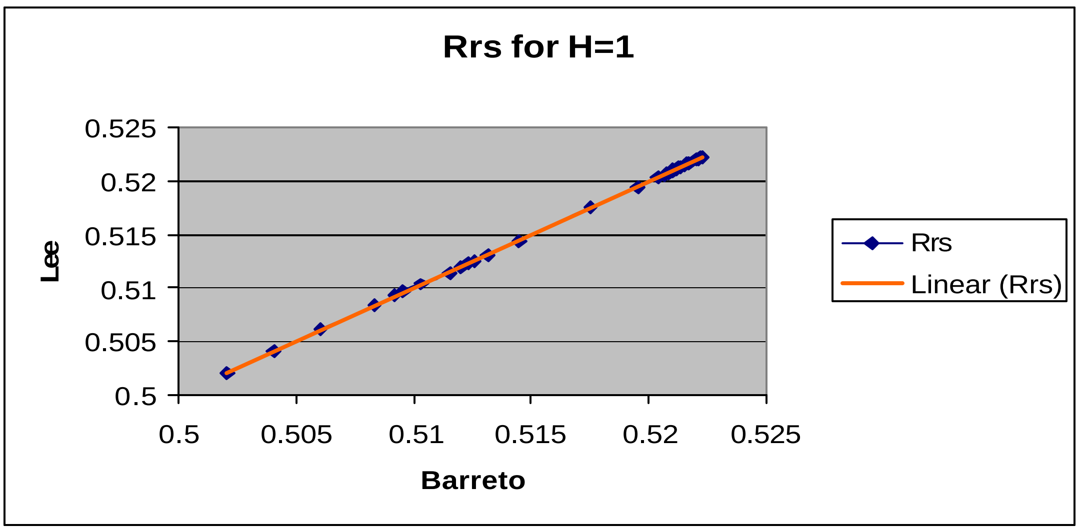

Figure 4-10 R_{rs} **for Case 4**

Case 5:

In this case we change the value of H to 20 to verify the two extremes of depth.

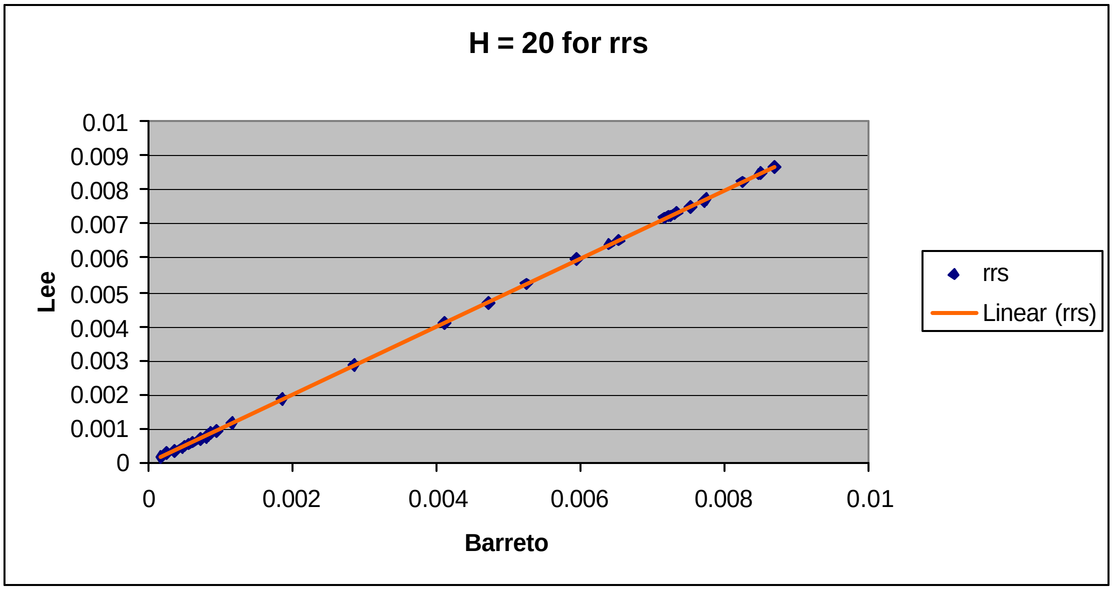

Figure 4-11 r_{rs} **for Case 5**

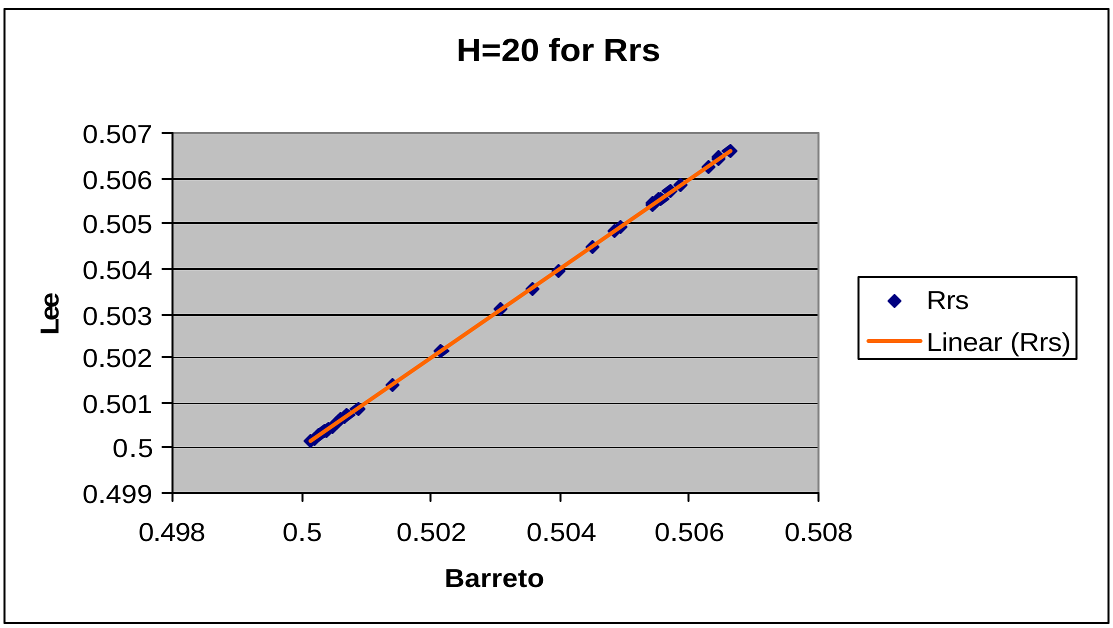

Figure 4-12 R_{rs} **for Case 5**

Case 6:

In this case we the original value of X is changed 0.003059644 to 1. Table 4.8 lists the values for this case.

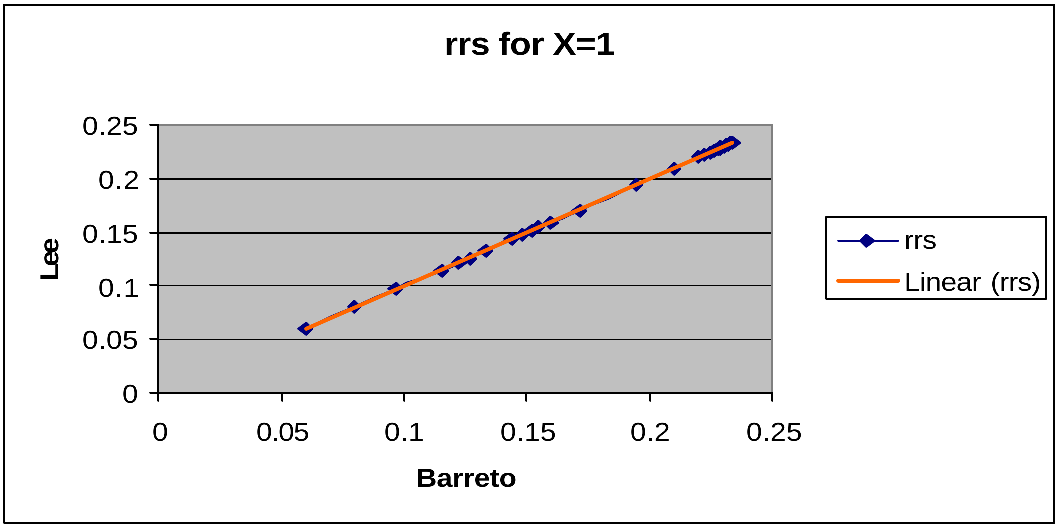

Figure 4-13 r_{rs} **for Case 6**

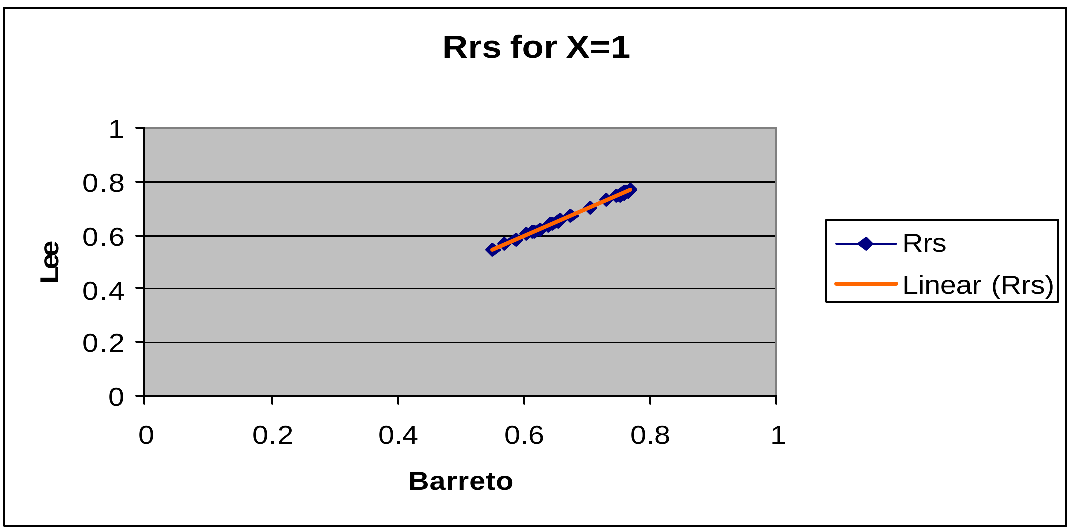

Figure 4-14 R_{rs} **for Case 6**

Case 7:

In this case we change Y from 1 to 0.5.

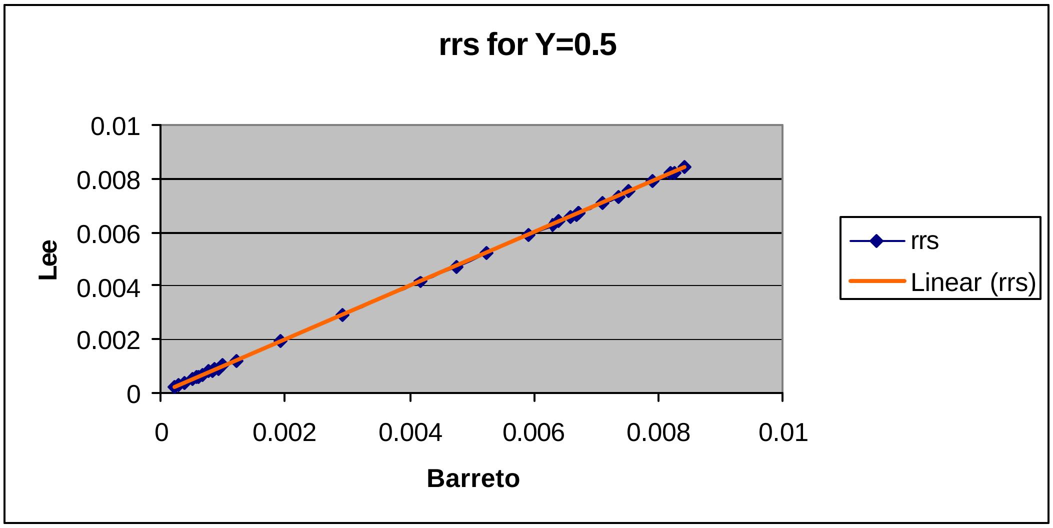

Figure 4-15 r_{rs} **for Case 7**

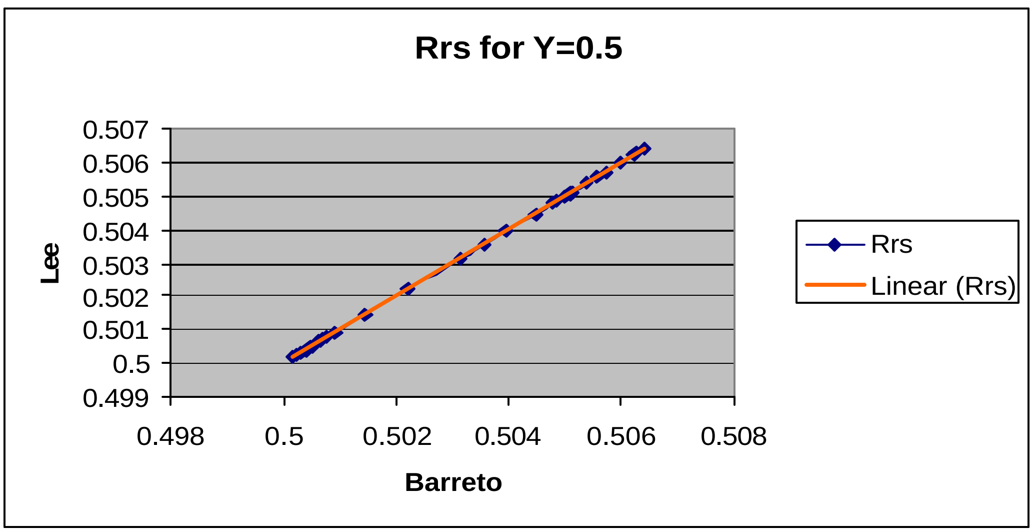

Figure 4-16 R_{rs} **for Case 7**

To finalize we will display the spectral response (R_{rs} and r_{rs}) for all the cases for our implementation. First we will show the R_{rs} for all 7 Cases.

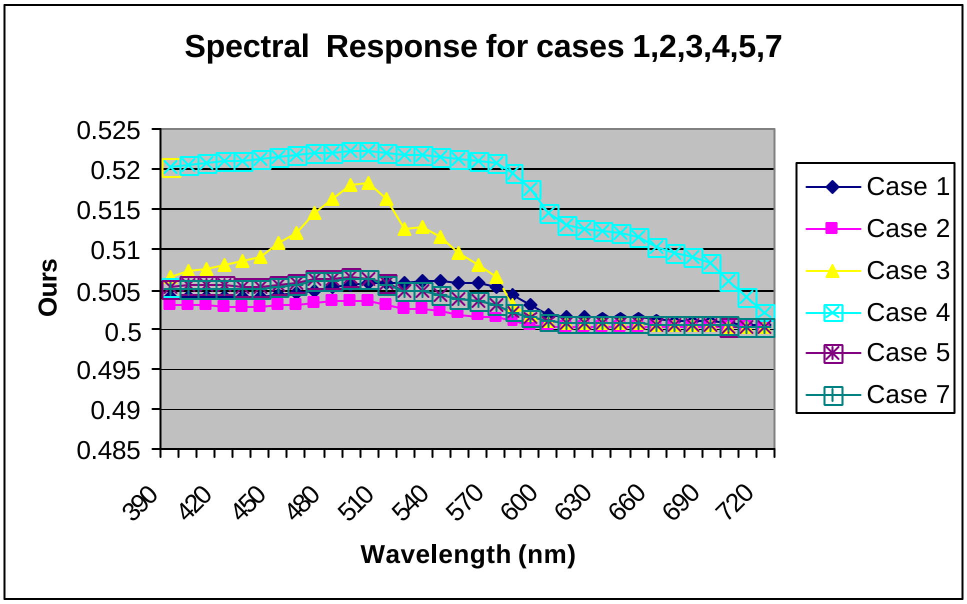

Figure 4-17 R_{rs} **spectral response of our implementation**

You can observe the change in spectral signature with the change in value of only one of the parameters. To finalize we will display the results for r_{rs} produced by our implementation. Case 6 for *Rrs* was shown separately because it's response affected that of the rest of the cases and the rest of the spectral signatures could not be well distinguished. This is due to the great effects the change in value for this parameter.

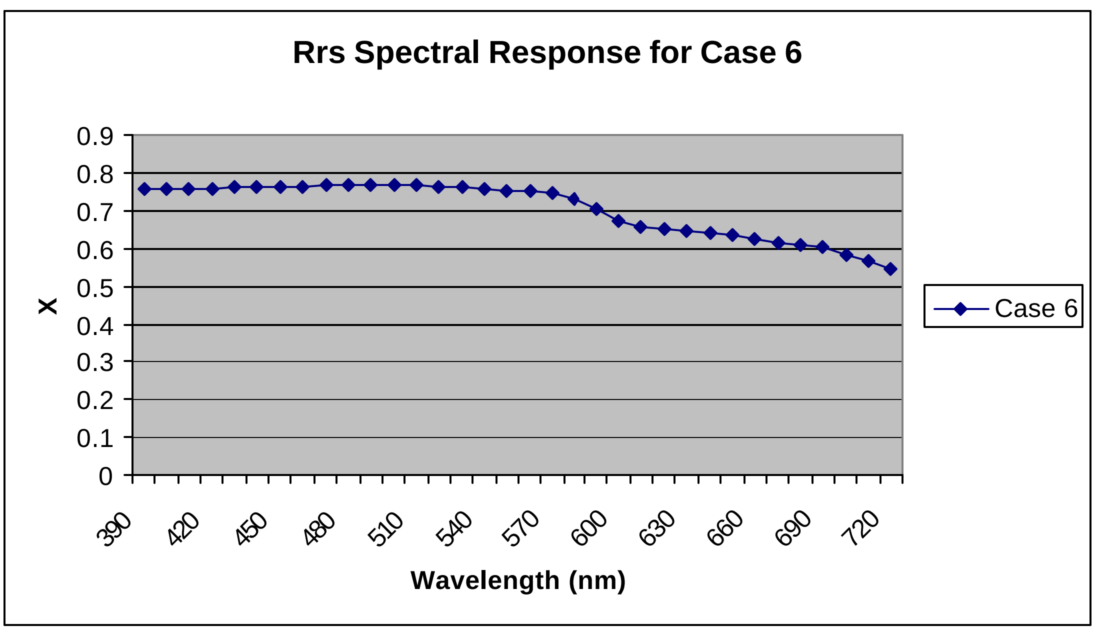

Figure 4-18 Spectral Response for Case 6

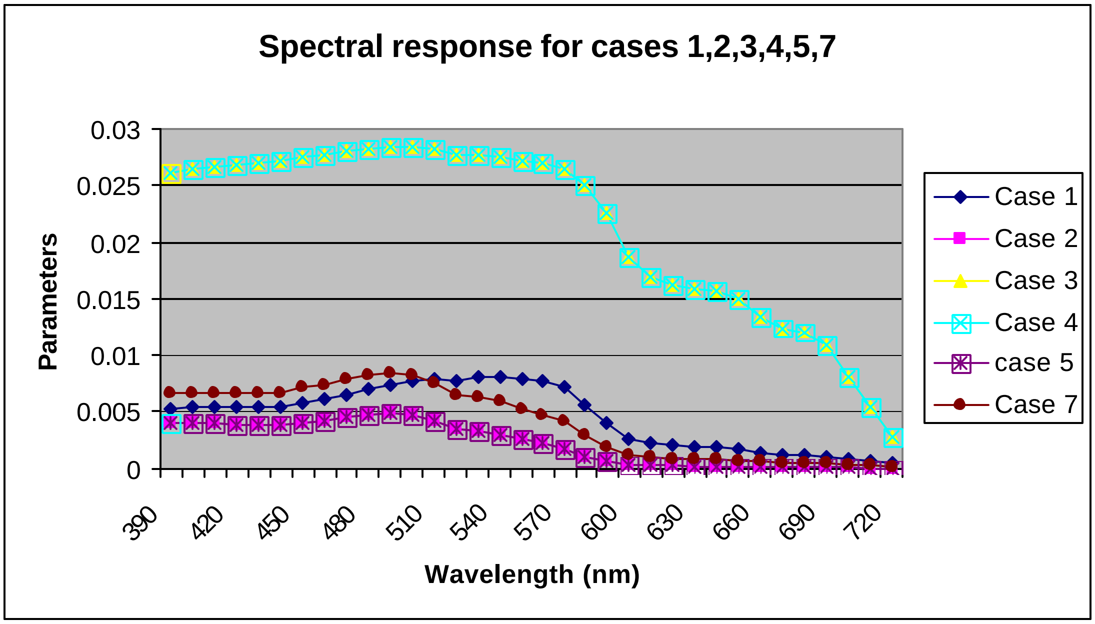

Figure 4-19 r_{rs} **spectral response of our implementation**

Again Case 6 was taken separately to better observe the other cases.

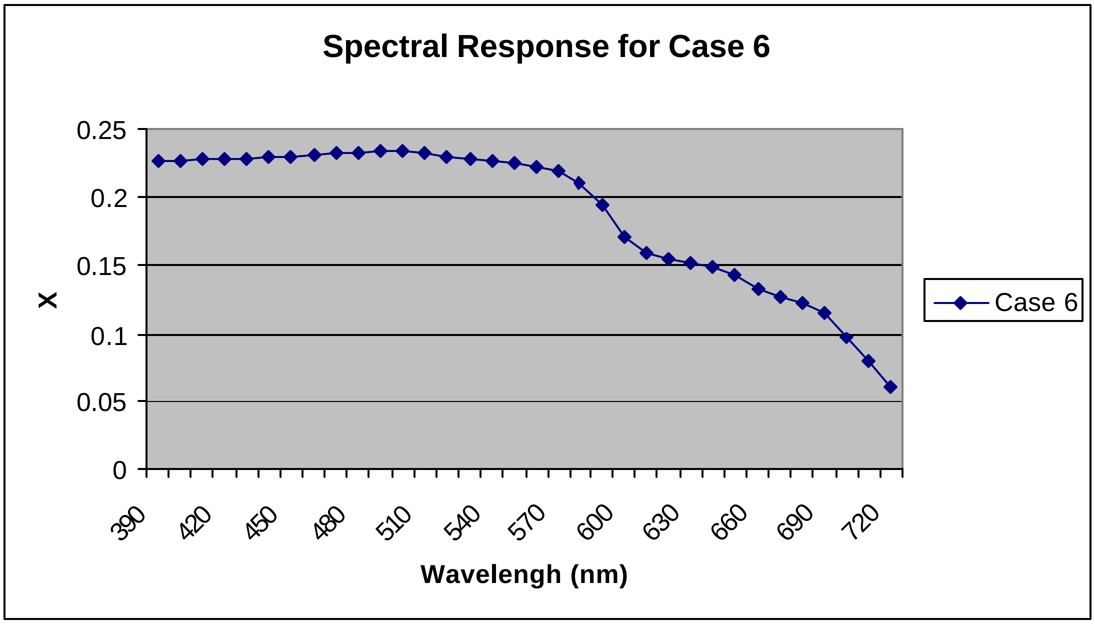

Figure 4-20 Spectral Response for Case 6

4.3 Running IOP

Now we will describe how to run the program. The program is named *IOP*. This section is divided into different steps outlined to display the execution of *IOP*.

Step 1: Access project stored in the C:\ directory by clicking on **Open Project** from IDL's **File** menu.

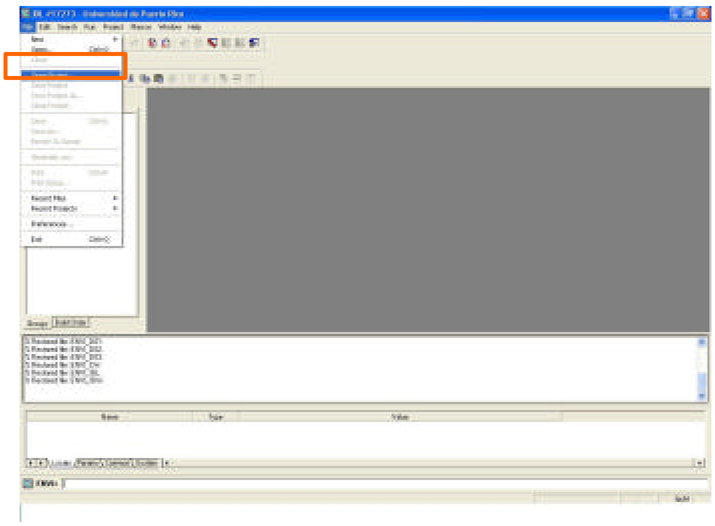

Figure 4-21 Opening Project

Select **Local Disk (C:\)** in the **Look in** window by clicking on the arrow and search for the pathname is **C:\Lee_Algorithm\MProject.prj**.

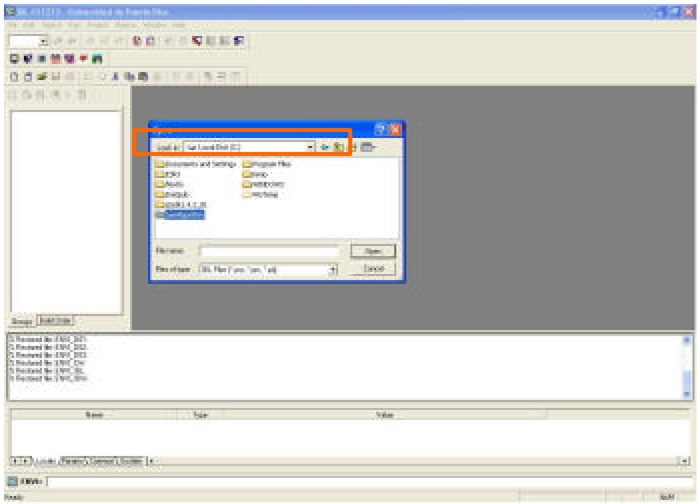

Figure 4-22 Accessing C:\ drive

Select **MProject**. Then click **Open**.

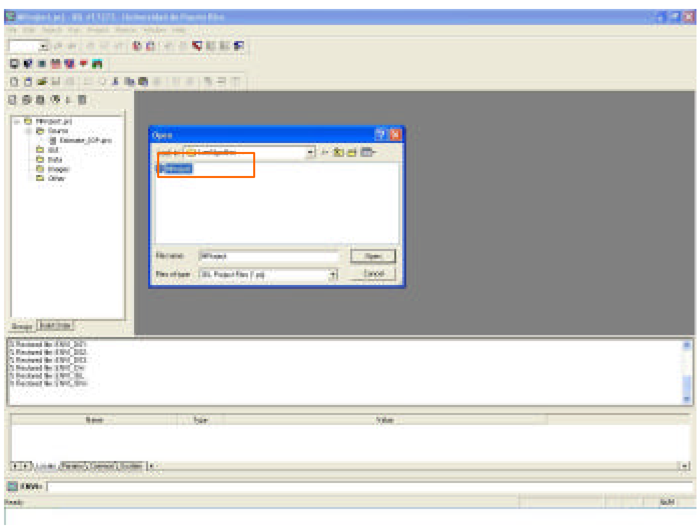

Figure 4-23 Accessing Project

Step 2: Compile program before execution. Figure 3.10 displays the icon provided to compile the whole project.

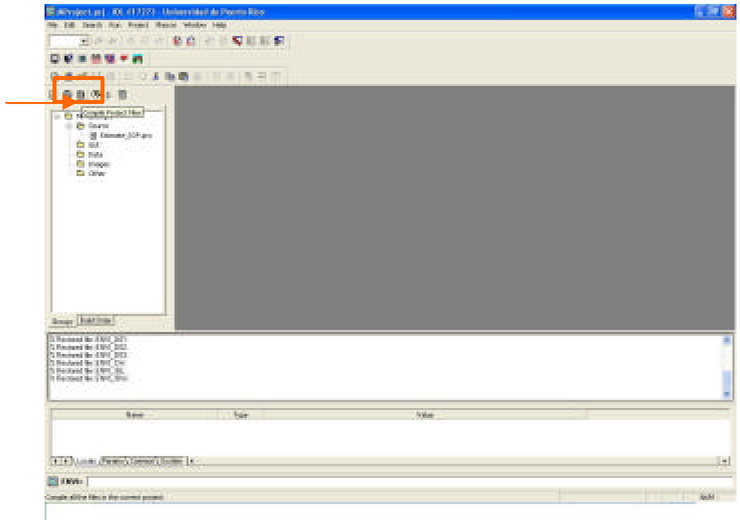

Figure 4-24 Compiling Project

Step 3: After Compiling the project, run project by typing ***IOP*** in IDL's command prompt.

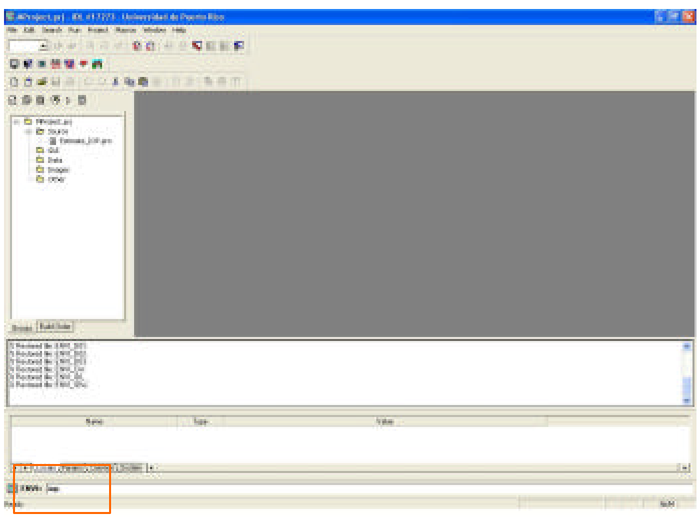

Figure 4-25 Executing Project

Step 4: Enter data indicated in IDL's command prompt and press enter after each data entered. Data may be integer, double or real.

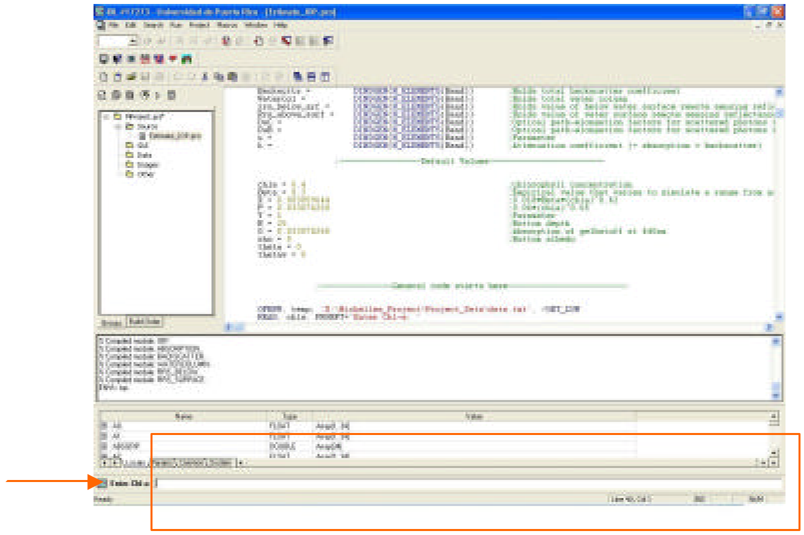

Figure 4-26 Entering parameters to algorithm

Results will be displayed above IDL's command window (*see Figure3.13*). Four plots will also be shown displaying results for total absorption coefficient, a, total backscatter coefficient, b_b, subsurface water reflectance, r_{rs} and surface water reflectance, R_{rs} (see Figure 3.13). Use scrollbar see all the results.

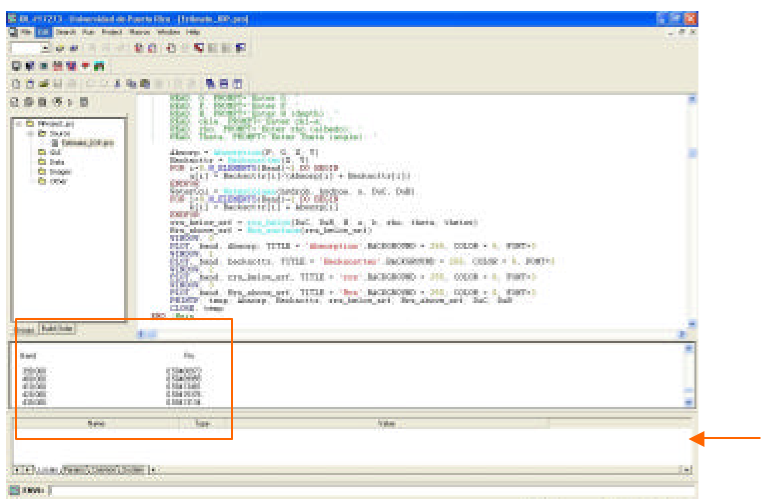

Figure 4-27 Results display

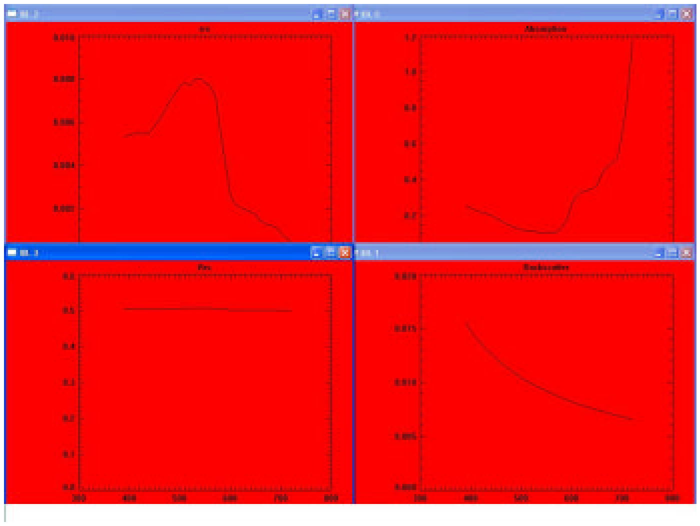

Figure 4-28 Plots Display

4.4 Concluding Remarks

This chapter described the results of our code validation. The code was validated against a model provided by Dr. Zhongping Lee. The validation was successful.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions:

This report presented the implementation of Zhongping Lee's bio-optical model for the determination of the water leaving radiance given the inherent optical properties and the bottom reflectance in the Interactive Data Language (IDL). The model was implemented using a modular structure where each component was implemented as a function used to computed the optical properties and parameters needed by the model to determine the water leaving radiance. The report describes how to run the program from the IDL command prompt and describes in detail each function that composes the program.

The implementation is validated against a model implementation in excel provided by Dr. Lee. Comparisons were based in 7 cases where different parameters were varied and comparisons between the output of the implemented model and Lee's model are done using linear regression. Validation results show that the developed implementation produce the same numerical results as Lee's implementation.

5.2 Future Work

The main purpose of implementing this model in IDL is to use it as part of an inversion scheme to retrieve IOP from hyperspectral imagery. This is part of CenSSIS work on subsurface sensing of benthic habitats. The model can be used as part of an output error approach where the output of the IDL implementation is compared with water leaving radiance measured with a hyperspectral sensor and the parameters of the model are tuned until reasonable fit is achieves.

The model can also be used in simulation studies to understand how the water column affect the distort the signature of the bottom reflectance. Hydrolight is the industry standard for this analysis but it is computationally intensive and the developed model is a computationally fast alternative. To facilitate its use as a simulation tool we suggest the development of a Graphical User Interface.

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