O. Kopelevich

Topic 6: Radiative Transfer in Oceans

True ocean color – its formation, characteristics and calculation

In-water optical processes

Seawater optical characteristics and
optically active water components

Case 1 and Case 2 waters

Ocean reflectance and water leaving radiance

Computation methods

Influence of sea bottom

Effect of transspectral processes

Basic radiometric quantities

Radiant flux: the time rate of flow of radiant energy

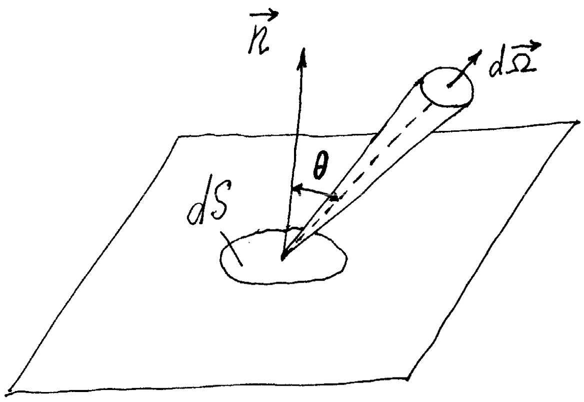
$$F = Q / t, \qquad [W]$$

Irradiance: the ratio of the radiant flux incident on an infinitesimal element of surface to the area of that element

$$E(S) = dF / dS, \quad \bar{E} = \int_{(S)} E(S)\, dS / \int_{(S)} dS = F / S, \quad [W \cdot m^{-2}]$$

Radiance: Radiant flux per unit solid angle per unit projected area of a surface

$$L = d^2F / d\Omega \cdot dS \cdot \cos\theta, \qquad [W \cdot m^{-2}\, sr^{-1}]$$



A considered surface can be real (for example, sea surface or bottom) or imaginary, constructed in mind inside of water medium, so the radiance or irradiance at an arbitrary point in water can be considered.

The radiance at a given point in the spherical co-ordinate system is a function of the polar angle θ and the azimuth angle φ

$$L(\theta, \varphi) = [dE(\theta, \varphi) / \cos\theta] / d\Omega;$$

$$dE(\theta,\varphi) = L(\theta, \varphi) \cdot \cos\theta \, d\Omega;$$

$$E = \int_{(2\pi)} L(\theta, \varphi) \cdot \cos\theta \cdot d\Omega$$

Irradiance, like radiance, is characterized by a value and a direction (which is defined by a normal to the considered surface). Along with the "vector irradiance", we can consider the "scalar irradiance".

Scalar irradiance is the integral of the radiance distribution over all directions about the considered point

$$E_o = \int_{(4\pi)} L(\theta, \varphi) \cdot d\Omega, \qquad [W \cdot m^{-2}]$$

Characteristics of underwater light field

Downwelling irradiance:

$$E_d = \int_0^{2\pi} d\varphi \int_0^{\pi/2} L(\theta, \varphi)\cdot\cos\theta\cdot\sin\theta\cdot d\theta;$$

Upwelling irradiance:

$$E_u = - \int_0^{2\pi} d\varphi \int_{\pi/2}^{\pi} L(\theta, \varphi)\cdot\cos\theta\cdot\sin\theta\cdot d\theta;$$

Downwelling scalar irradiance:

$$E_{od} = \int_0^{2\pi} d\varphi \int_0^{\pi/2} L(\theta, \varphi)\cdot\sin\theta\cdot d\theta;$$

Upwelling scalar irradiance:

$$E_{ou} = \int_0^{2\pi} d\varphi \int_{\pi/2}^{\pi} L(\theta, \varphi)\cdot\sin\theta\cdot d\theta;$$

Diffuse attenuation coefficient:

$$dE_{d,\,u,\,od,\,ou} = - K_{d,\,u,\,od,\,ou} \cdot dE_{d,\,u,\,od,\,ou} \cdot dz;$$

$$K = - dE / E\cdot dz = - d\ \ln E / dz;$$

$$K_d \neq K_u \neq K_{od} \neq K_{ou}.;$$

Optical depth:

$$\zeta = K_d \cdot z$$

The average cosine of angular distribution of light field:

$$\mu = \int_{(4\pi)} \cos\theta \cdot L(\theta, \varphi) \cdot d\Omega \,/ \int_{(4\pi)} L(\theta, \varphi) \cdot d\Omega;$$

The downwelling average cosine:

$$\mu_d = \int_0^{2\pi} d\varphi \int_0^{\pi/2} \cos\theta \cdot L(\theta, \varphi) \cdot d\theta \,/ \int_0^{2\pi} d\varphi \int_0^{\pi/2} L(\theta, \varphi) \cdot d\theta;$$

The upwelling average cosine:

$$\mu_u = - \int_0^{2\pi} d\varphi \int_{\pi/2}^{\pi} \cos\theta \cdot L(\theta, \varphi) \cdot d\theta \,/ \int_0^{2\pi} d\varphi \int_{\pi/2}^{\pi} L(\theta, \varphi) \cdot d\theta;$$

$$\mu_d = E_d / E_{0d} ; \qquad \mu_u = E_u / E_{0u} , \qquad \mu = (E_d - E_u)/ E_0 ;$$

Spectral density of an radiometric quantity:

$$F_\lambda = dF/d\lambda, \qquad [\text{ W nm}^{-1}];$$

$$E_\lambda = dE/d\lambda; \qquad [\text{W}\cdot\text{m}^{-2}\text{ nm}^{-1}];$$

$$L_\lambda = dL/d\lambda, \qquad [\text{W}\cdot\text{m}^{-2}\text{ nm}^{-1}\text{ sr}^{-1}];$$

Total downwelling irradiance:

$$E_\Sigma = \int_{300}^{2500} E(\lambda)\, d\lambda;$$

Photosynthetically available radiation:

$$PAR = \int_{400}^{700} E(\lambda)\, d\lambda;$$

Spectral characteristics of upwelling radiant flux

Irradiance reflectance: the ratio of the upwelling irradiance to the downwelling irradiance

$$R(\lambda, z) = E_u (\lambda, z) / E_d (\lambda, z).$$

The irradiance reflectance just beneath the sea surface ("subsurface irradiance reflectance") is a characteristic of "true" ocean color

$$R(\lambda, 0^-) = E_u (\lambda, 0^-) / E_d (\lambda, 0^-).$$

Because the light collectors with a narrow field–of-view are used for remote sensing (for example, SeaWiFS field-of-view is less than three angular minutes), it is common to deal with "remote sensing reflectance".

Subsurface remote-sensing reflectance:

$r_{RS} (\lambda, \theta, \varphi, 0^-) = L_u (\lambda, \theta, \varphi, 0^-) / E_d (\lambda, 0^-),$ $[sr^{-1}]$;

$r_{RS} (\lambda, \theta, \varphi, 0^-) = R (\lambda, 0^-) / Q (\lambda, \theta, \varphi, 0^-),$

$Q (\lambda, \theta, \varphi, 0^-) = E_u (\lambda, 0^-) / L_u (\lambda, \theta, \varphi, 0^-),$ $[sr]$;

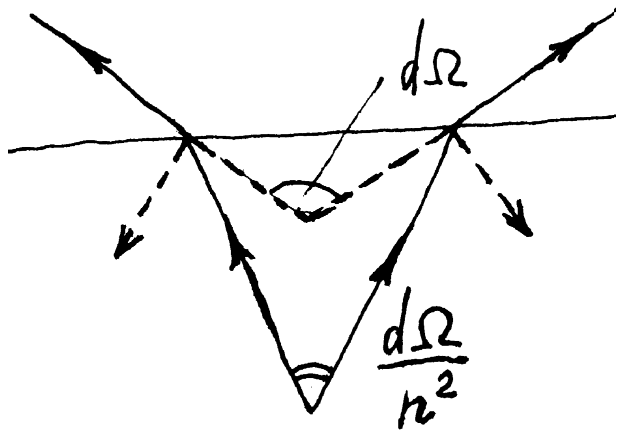
In the case of the isotropic angular distribution of $L_u (\theta,\varphi)$:

$Q(\theta,\varphi) = \pi$; in the real cases $Q(\theta,\varphi) = 3.5\text{-}4.2$.

For comparison with the satellite-sensed signal, it is needed to consider the above-surface remote-sensing reflectance which is the ratio of the upwelling radiance to the downwelling irradiance just above the sea surface

$$R_{RS}(\lambda, \theta, \varphi, 0^-) = L_u(\lambda, \theta, \varphi, 0^+) / E_d(\lambda, 0^+).$$

The subsurface upwelling radiance $L_u(0^-)$ passing through the sea surface decreases due to reflection and refraction; the above-surface downwelling irradiance passing through the sea surface decreases due to reflection but it is augmented due to internal reflection of the subsurface upward flux from the sea surface



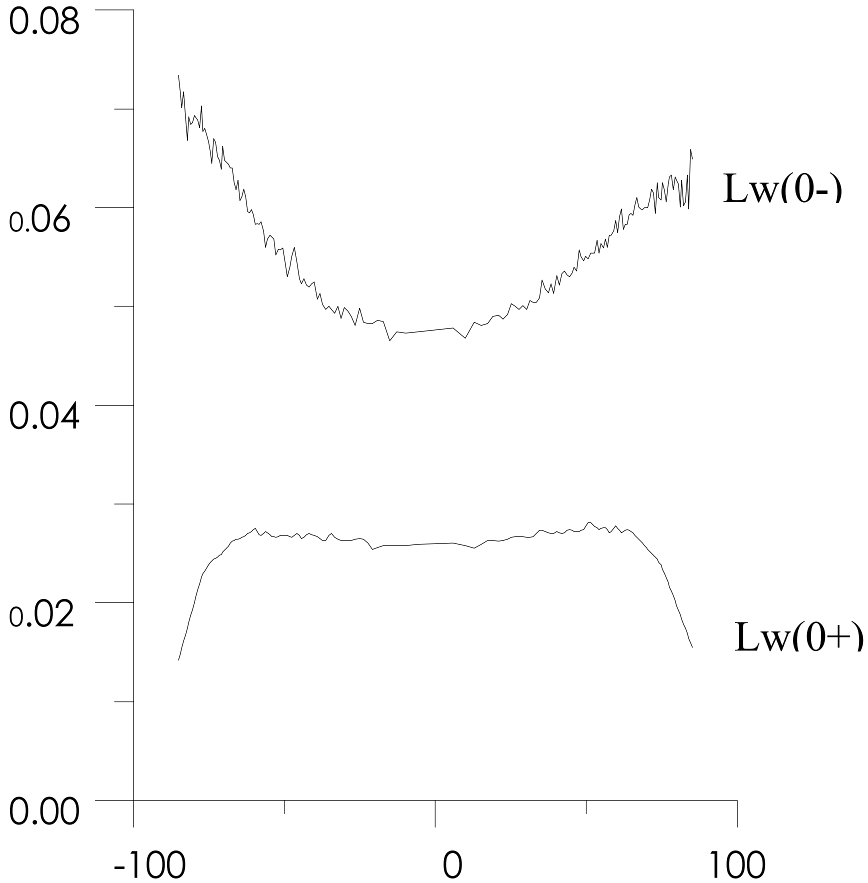
$L_u(0^+) = (t_- / n^2) \cdot L_u(0^-)$; $E_d(0^-) = t_+ \cdot E_d(0^+)/(1 - \gamma R) \cdot$

$R_{RS} = (t_- t_+ / n^2) \cdot r_{RS} / (1 - \gamma R)$; $R_{RS} = \zeta\, r_{RS} / (1 - \Gamma \cdot r_{RS})$;

$\zeta = t_- t_+ / n^2 \cdot$; $\Gamma = \gamma Q$.

For nadir viewing: $\zeta \approx 0.518$, $\Gamma \approx 1.562$, (Lee et al. 1998).

This is an example of the relationship between the subsurface and above-surface angular distributions of upwelling radiance (Monte Carlo calculation for the Philippine Sea; solar zenith angle θ_o = 20°; λ = 412 nm).



The above-surface upwelling radiance can be assumed as isotropic within the angle range of practical importance (up to 60°).

Normalized water-leaving radiance (Gordon et al. 1988):

$$L_{WN}(\lambda) = R_{RS}(\lambda) \cdot F_o(\lambda).$$

$$L_W = T(\theta_o) \cdot L_{WN} \cdot \cos\theta_o$$

Inherent optical characteristics

Refractive index: $m = n - i\,n'$;

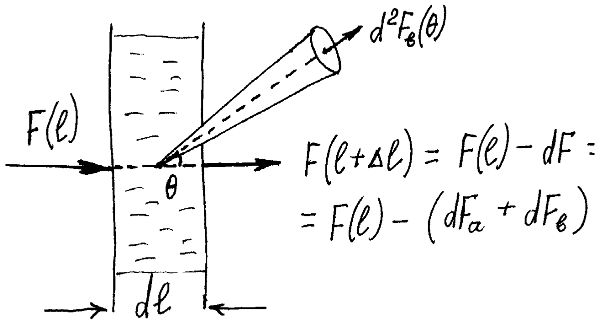
$n = c / v$; $n' = a \cdot \lambda / 4\pi$;

Absorption coefficient:

$dF_a = - a\, F\, dl$; $a = - dF_a / F\, dl$, $[m^{-1}]$;

Scattering coefficient:

$dF_b = - b\, F\, dl$; $b = - dF_b / F\, dl$, $[m^{-1}]$;



Volume scattering function: $d^2F_b(\theta) = -\beta(\theta)\, F\, dl \cdot d\Omega$;

$\beta(\theta) = -d^2 F_b(\theta) / F\, dl \cdot d\Omega$, $[m^{-1} \cdot sr^{-1}]$;

$$b = \int_{(4\pi)} \beta(\theta)\, d\Omega = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta\, d\theta;$$

Scattering phase function:

$P(\theta) = \beta(\theta)/b$; $\int_{(4\pi)} P(\theta)\, d\Omega = 1$;

a, b, $P(q)$ is a full set to describe seawater optical properties without considering the polarization.

Forward scattering coefficient:

$$b_f = 2\pi \int_0^{\pi/2} \beta(\theta) \sin\theta \, d\theta, \qquad [m^{-1}];$$

Backscattering coefficient:

$$b_b = 2\pi \int_{\pi/2}^{\pi} \beta(\theta) \sin\theta \, d\theta; \quad [m^{-1}];$$

The average cosine:

$$g = \langle\cos\theta\rangle = 2\pi \int_0^{\pi} \cos\theta \, P(\theta) \sin\theta \, d\theta.$$

Beam attenuation coefficient:

$$dF_c = -(dF_a + dF_b) = -c \, F \, dl; \qquad c = -dF_c/F \, dl = a + b;$$

$$F(l) = F(0) \exp [- \int_0^{l} c(l') \, dl'] = F(0) \exp [- \tau(l)];$$

The Bouguer law: $F(l) = F(0) \, e^{-cl}$;

Transmittance of the water layer:

$T = F(l) / F(0) = e^{-\tau}$;

Single-scattering albedo: $\omega_o = b / c$;

c, w_o, $P(q)$ is the other full set for describing seawater optical properties without considering the polarization.

All of the above characteristics depend on the wavelength:

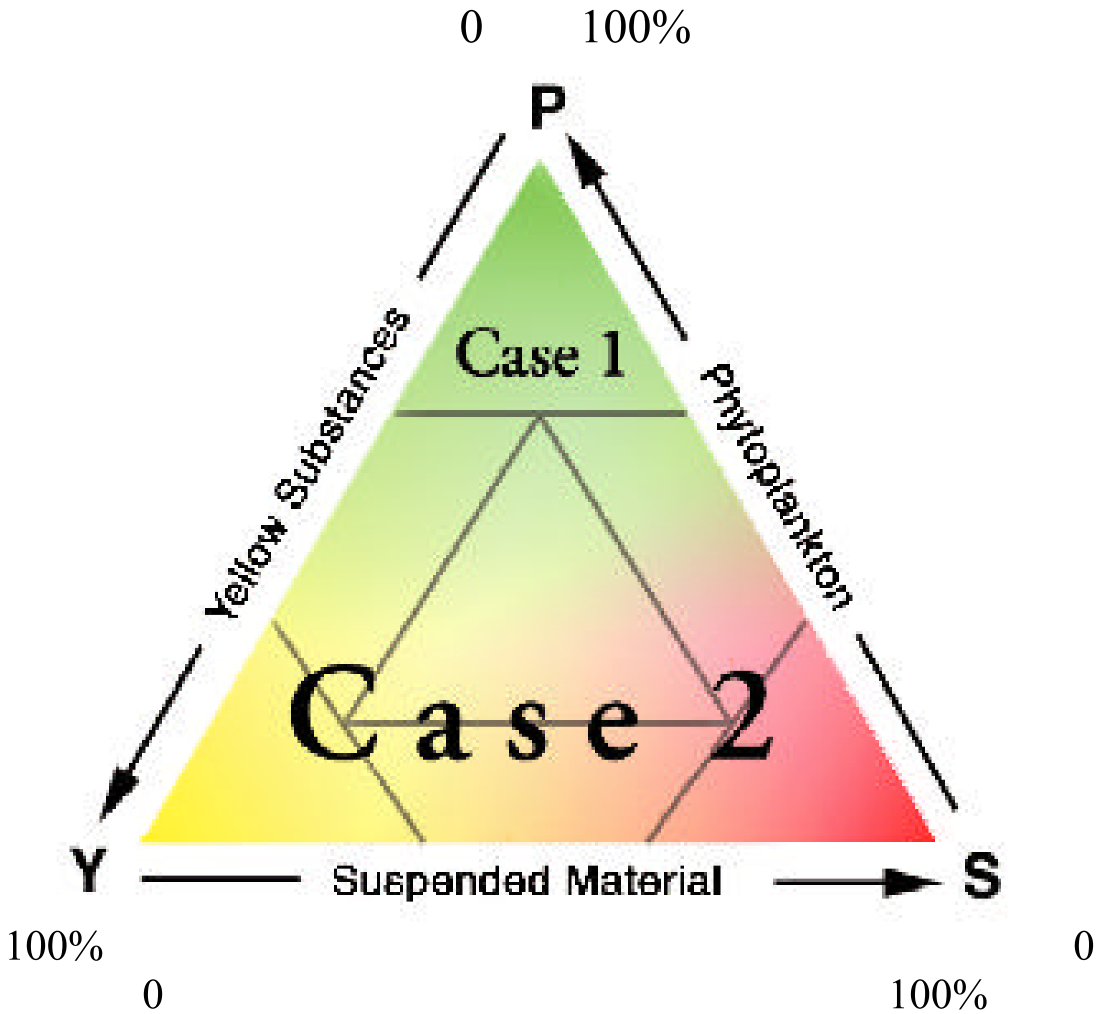
$m(\lambda)$, $n(\lambda)$, $n'(\lambda)$, $a(\lambda)$, $b(\lambda)$, $\beta(\theta, \lambda)$, $b_f(\lambda)$, $b_b(\lambda)$, $g(\lambda)$, $c(\lambda)$, $\omega_o(\lambda)$.

Three main optically active water constituents:

Phytoplankton

Suspended material (inorganic)

Yellow substances



Diagrammatic representation of Case 1 and Case 2 waters, Adapted from Prieur and Sathyendranath (1981) (see also IOCCG Report Number 3, 2000)

Quasi-single-scattering approximation

(Gordon 1973; Golubitsky, Levin, and Tantashev 1974)

The idea is based on the fact that the seawater scattering function is highly peaked in the forward direction, so the most part of the scattered light remains in the beam, and the loss is only due to absorption and backscattering.
The subsurface remote-sensing reflectance for the case of illumination by direct sun light and the isotropic backscattering can be represented (Golubitsky and Levin 1980)

$r^{dir}(\mu, \mu_0) = X / 2\pi(|\mu| + \mu_0);$ $\mu = \cos\theta,$ $\mu_0 = \cos\theta_{ow};$

$$X = b_b / (a + b_b).$$

For the nadir viewing: $r^{dir}(-1, \mu_0) = X / 2\pi(1 + \mu_0);$

Irradiance reflectance $R^{dir} = 0.31$ X with accuracy of 10%.

In the case of illumination by diffuse light:

$r^{dif}(-1) = 0.086$ X; $R^{dif} = 0.34$ X with accuracy of 20%.

In the case of combined illumination

$R = (1 - \alpha) R^{dir} + \alpha R^{dif}$, $\alpha = E_{diff} / E_{tot}$.

Generally: $r(\theta,\varphi) = f_r[\theta,\varphi, \theta_o, P(\theta')]\cdot X;$

$$R = f_R[\theta_o, P(\theta')]\cdot X.$$

Other formulae for the irradiance and remote-sensing subsurface reflectance

$R = \sum_{n=0} k_n X^n$; (Gordon et al. 1975)

(approximation of Monte Carlo computations)

θ_o	k_0	k_1	k_2	k_3
$\geq 20^o$	0.0001	0.3244	0.1425	0.1308
$\leq 30^o$ (and diffuse)	0.0003	0.3687	0.1802	0.0740

According to Kirk (1984):

$R = (0.975 - 0.629 \cos \theta_o) \cdot X/(1-X)$ for the cloudless case;

$R = 0.437X/(1-X)$ for the cloud case.

Nadir-viewing:

$r_{RS} \approx (0.0949 + 0.0794\ X)\ X$ Gordon et al. 1988;

$R = 0.33\ b_b / a$ Morel and Prieur 1977;

$r_{RS} \approx 0.0922\ b_b / a$ Morel and Gentili 1993;

$r_{RS} \approx (0.070 + 0.155\ X^{0.752})\ X$ Lee et al. 1998

(approximation of Hydrolight computations)

The numerical computation methods

A Monte Carlo technique is like as a roulette at Monte Carlo casino. The multitude of photons are put into consideration, and the generator of random numbers, instead of the wheel, is used to decide the fate of each of them. The decision is made in according to the probabilities of different events such as reflection, refraction, absorption, and scattering (these probabilities are given by corresponding coefficients (the attenuation coefficient, the single-scattering albedo, and the scattering phase function). Monte Carlo technique is applicable to any geometry, incident illumination, distribution of inherent optical properties and so on.

Hydrolight is a commercially software used for last years. It is much faster than Monte Carlo simulation for computation of upwelling radiance and computes all radiances with same accuracy whereas Monte Carlo simulation contains much more statistical noise in upwelling radiances than in downwelling.

DISORT computer code was developed by Stamnes, Tsay, Wiscombe, and Jayaweera. The modified DISORT version for computations of light propagation in the atmosphere-ocean system will be demonstrated you in operation at the afternoon session.

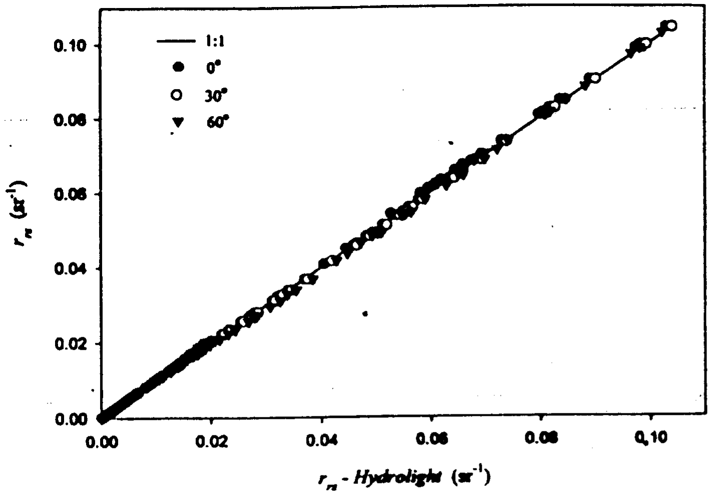


Fig. 5. Comparison of deep water r_{rs} values as computed by Hydrolight and by the SA model. Values for the different solar zenith angles are identified.

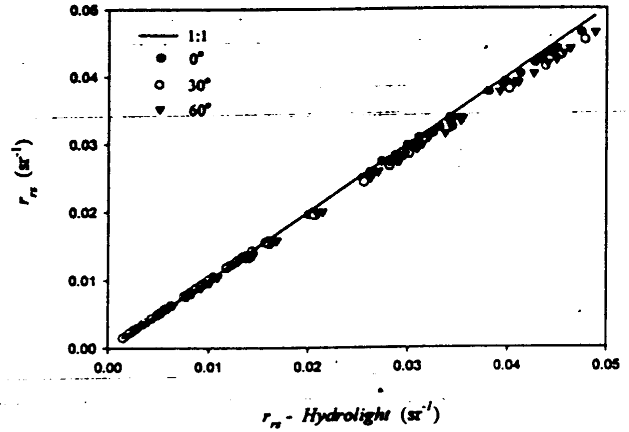


Fig. 11. Comparison of deep water r_{rs} values computed by Hydrolight with the Kopelevich phase function of Fig. 2 with r_{rs} values given by the SA model, which is based on the coastal particle phase function of Fig. 2.

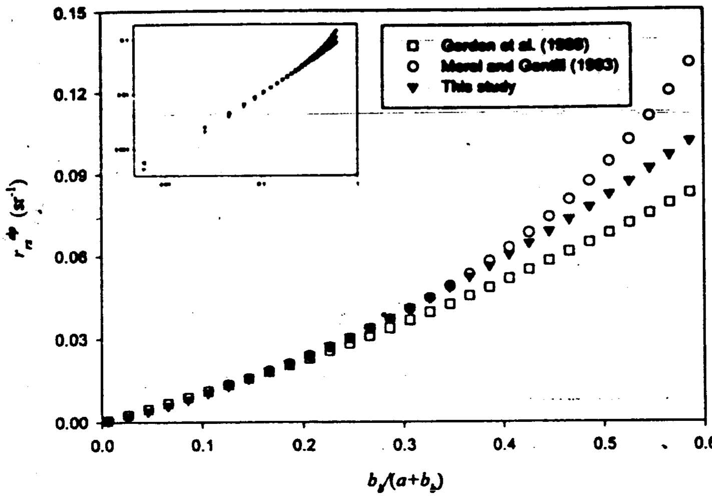
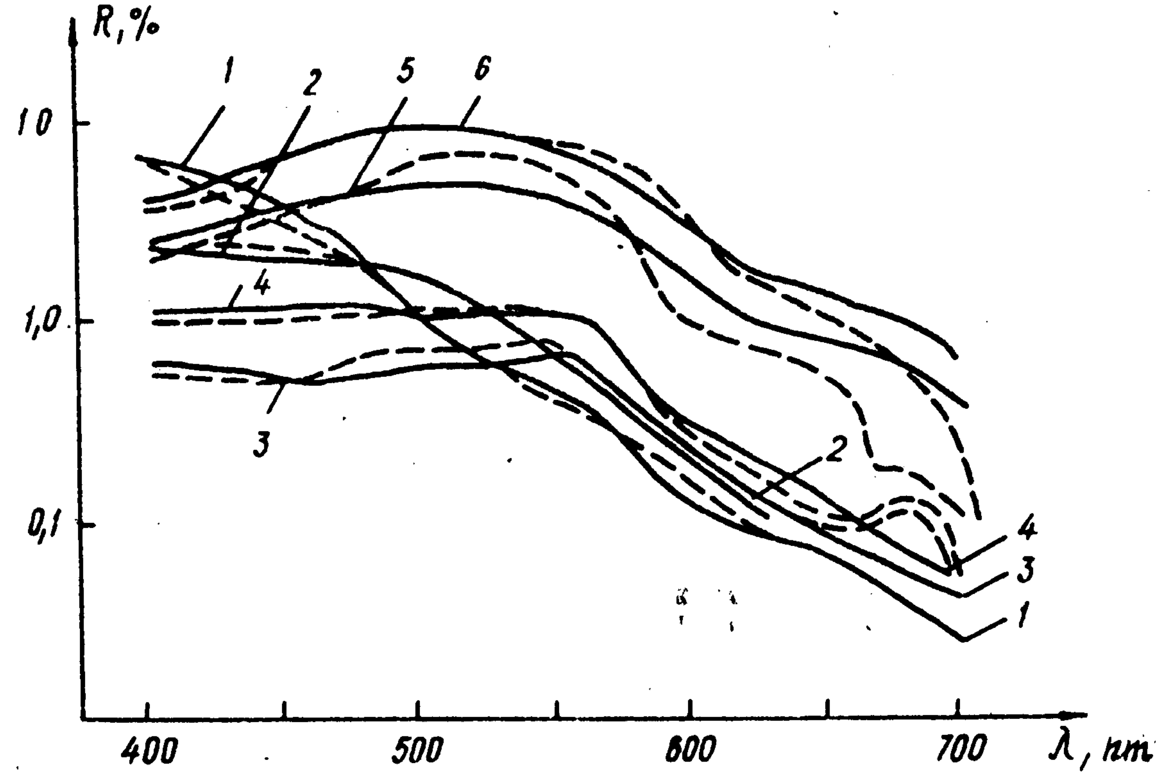


Fig. 7. Comparison of r_{rs}^{dp} values as determined by three different expressions.

Lee et al. (1998)

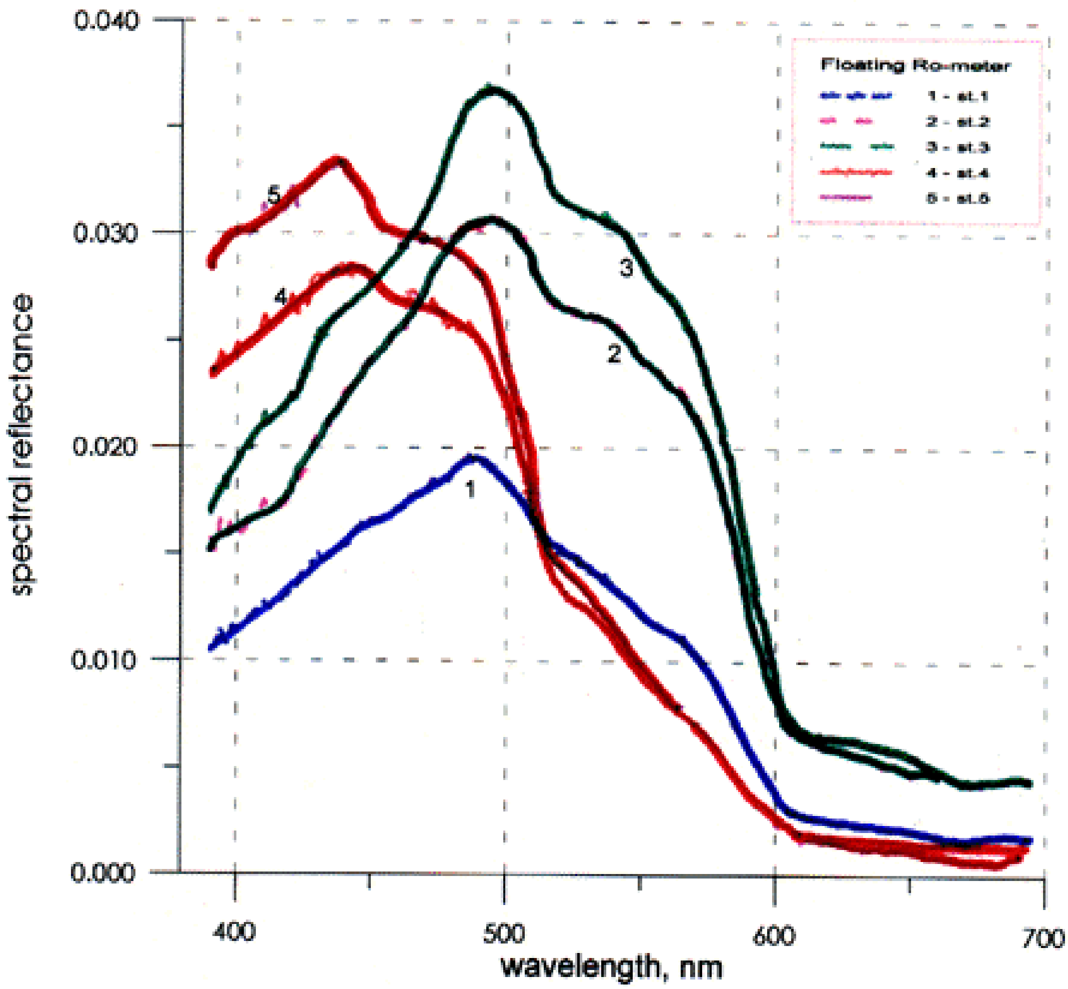
Use of semianalytic formula

$R(\lambda) = 0.33\, b_b(\lambda) / a(\lambda)$. Morel and Prieur 1977;

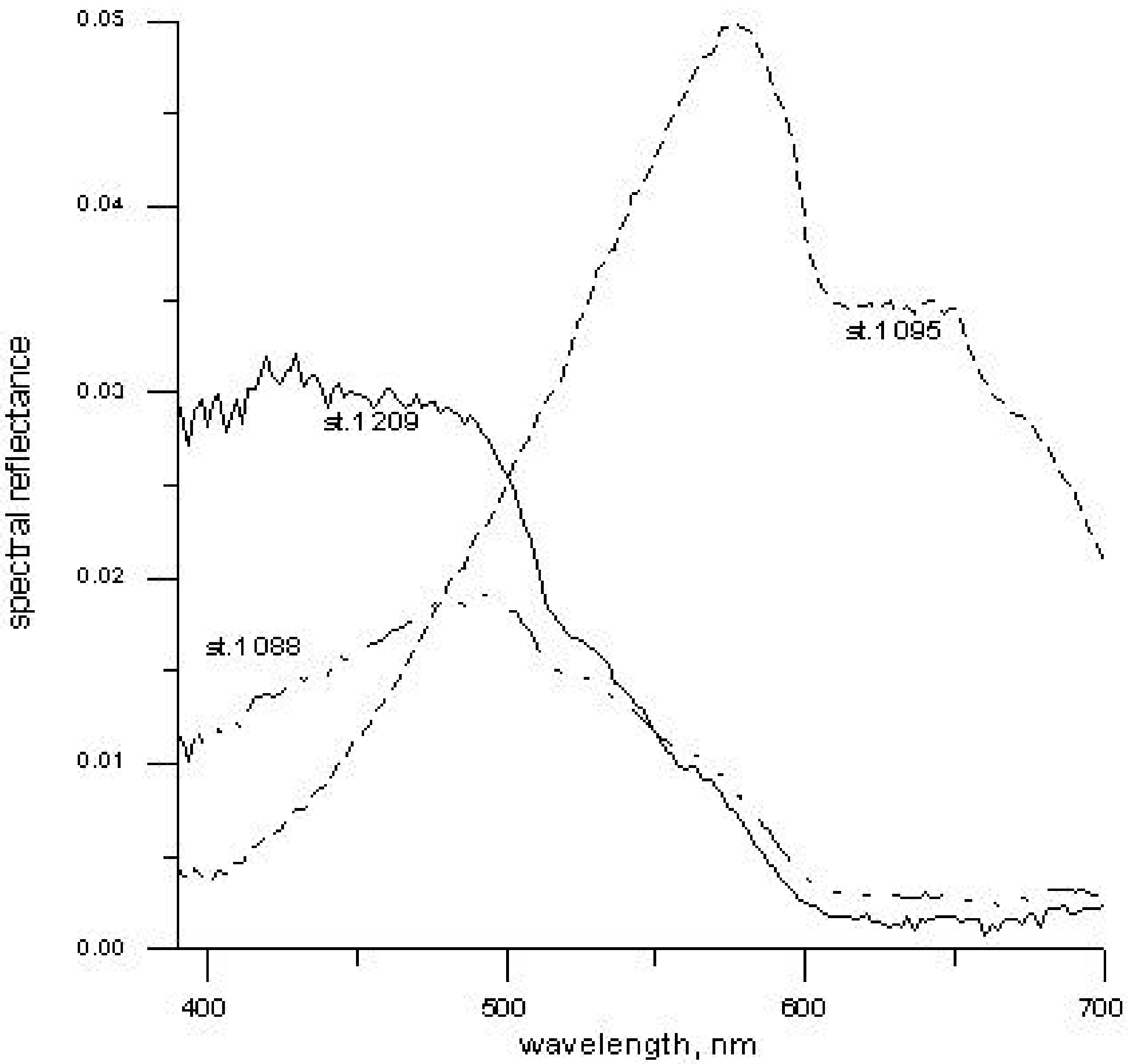


Comparison between calculated and measured spectral dependencies of $R(\lambda)$:

1.	Chl = 0.02 $mg\cdot m^{-3}$,	b_b = 0.0009 m^{-1};
2.	0.33	0.003
3.	7.7	0.006
4.	4.9	0.01
5.	6.4	0.045
6.	1.8	0.067.

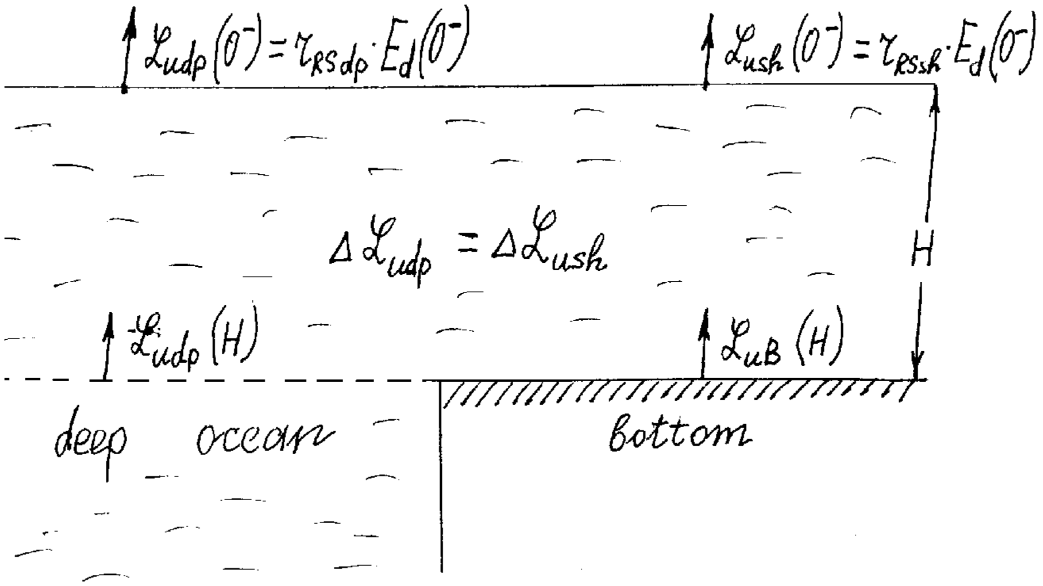


In situ measured spectra of water radiance reflectance: Black Sea – green and blue; Aegean Sea – red.



Examples of the spectral subsurface remote-sensing reflectance measured in different parts of the Barents Sea.
St.1209 - the north-eastern part of the Barents Sea;
St.1088 and St.1095 - the northern and southern parts of the Pechora Basin.

Influence of the bottom



It is assumed that in the case of shallow waters:

- The upwelling radiance $L_{ush}(0^-)$ is a sum of two components: the contribution arising from the upper layer of thickness H (L_{ush}) and the bottom reflectance

$$L_{ush}(0^-) = \Delta L_{ush} + L_{uB} \cdot \exp[- K_{uB} \cdot H];$$

$$L_{uB}(H) = R_B/\pi \cdot E_d(H) = = R_B/\pi \cdot E_d(0^-) \cdot \exp[- K_d \cdot H],$$

where R_B is the bottom albedo, $K_{uB} \cdot$ is a new diffuse attenuation coefficient which describes reduction of the upwelling irradiance from the depth to the surface.

- The contributions arising from the upper layer of thickness H in the cases of deep ocean and the shallow waters are equal:

$$\Delta L_{ush} = \Delta L_{udp} = r_{RSdp} \cdot E_d(0^-) \cdot \{1 - \exp[-(K_d + K_{uc}) \cdot H]\},$$

where K_{uc} $\cdot$is analogous to $K_{uB} \cdot$ in the case of infinite ocean.

$$L_{ush}(0^-) = R_B/\pi \cdot E_d(0^-)\cdot \exp[-(K_d\cdot + K_{uB})\cdot H] +$$

$$+ r_{RSdp}\cdot E_d(0^-)\cdot\{1 - \exp[-(K_d+K_{uc})\cdot H];$$

$$r_{RSsh} = r_{RSdp}\cdot\{1 - \exp[-(K_d+K_{uc})\cdot H] +$$

$$+ R_B/\pi\cdot \exp[-(K_d+K_{uB})\cdot H];$$

Lee et al. 1998:

$$r_{RSsh} = r_{RSdp}\cdot\{1 - A_o \exp[-(K_d+K_{uc})\cdot H] +$$

$$+ A_1 R_B\cdot \exp[-(K_d+K_{uB})\cdot H];$$

$K_d = \alpha\cdot D_d$; $K_{uc} = \alpha\cdot D_{uc}$; $K_{uB} = \alpha\cdot D_{uB}$; $\alpha\cdot = a + b_b$;

$D_d = 1/\cos\theta_w$;

$D_u = D_0 (1 + D_1 X)^{0.5}$ Kirk 1991.

From Hydrolight simulations:

$A_o = 1.03$; $A_1 = 0.31$;

$D_{uc} = 1.2 (1 + 2.0 X)^{0.5}$;

$D_{uB} = 1.1 (1 + 4.9 X)^{0.5}$.

Shallow water
(Lee et al. 1998)

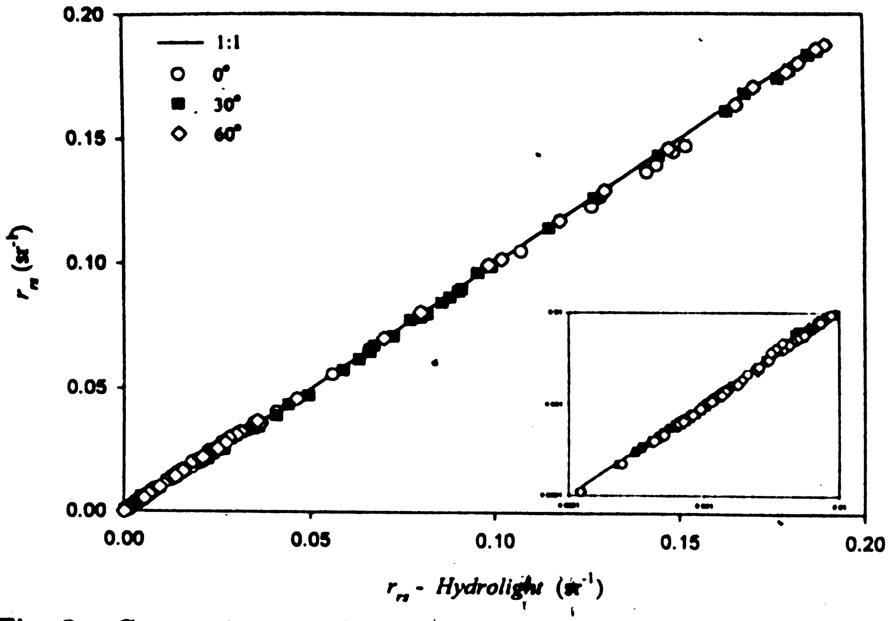


Fig. 8. Comparison of shallow water r_{rs} values as computed by Hydrolight and by the SA model for different solar zenith angles.

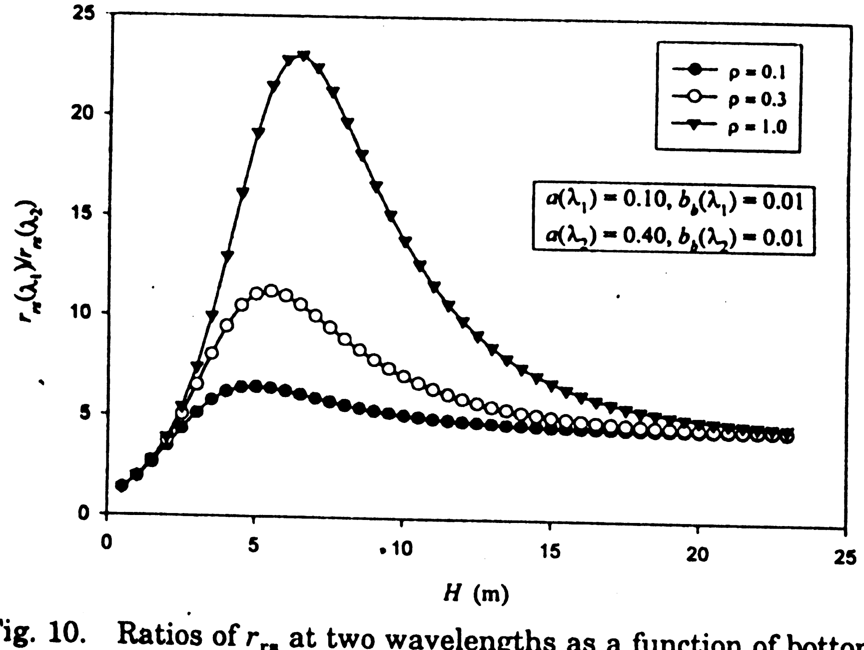


Fig. 10. Ratios of r_{rs} at two wavelengths as a function of bottom depth and reflectance.

Effect of transspectal processes.

(Haltrin et al. 1997).

$R_{el}/(R_{el}+R_{inel})$, %

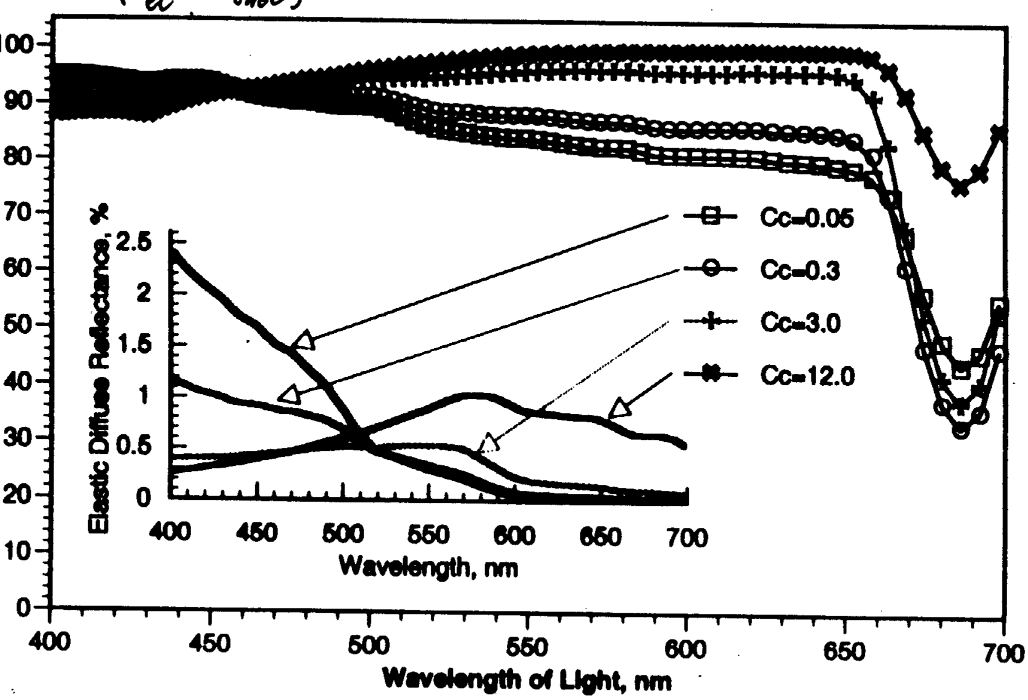


Fig.1. Elastic part of total diffuse reflectance

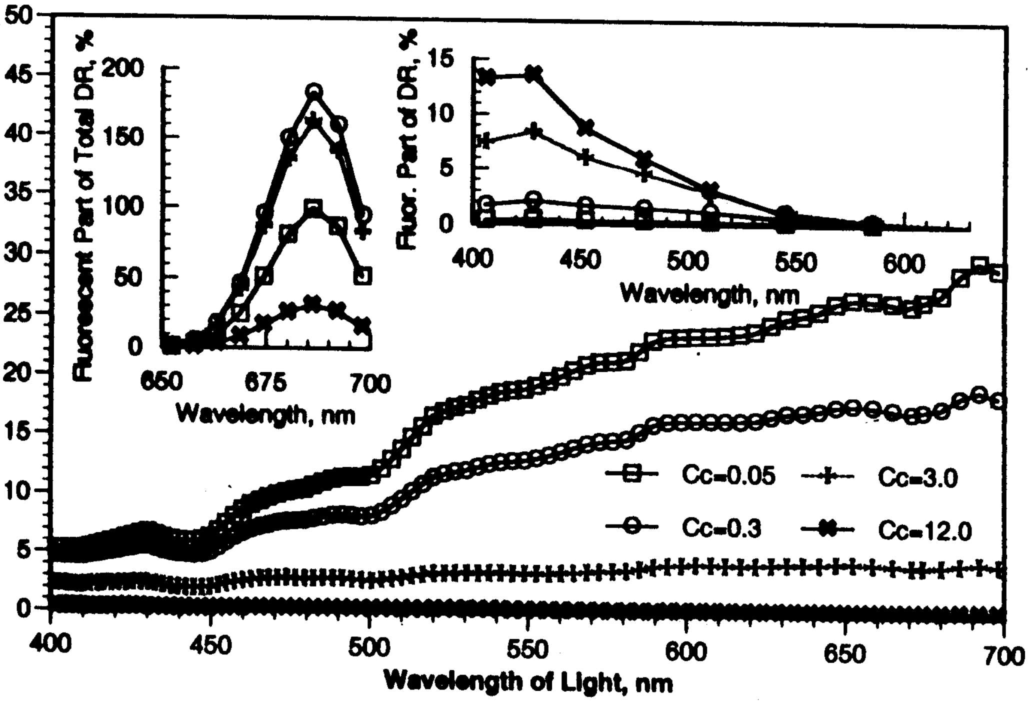


Fig.2. Ratio of inelastic to elastic diffuse reflectances