DESCRIPTION OF THE SUBROUTINES USED FOR BRDF GROUND

SUBROUTINE HAPKALBE

Function: To compute the spherical albedo following the the BRDF computed from *Hapke* (1981) Model.

Description: The target spherical albedo s is equal to the flux reflected by the target divided by the incoming flux for an isotropic source. It is defined by the relation:

$$s=\frac{\int_0^{\Pi/2} a(\theta_S)\cos(\theta_S)\sin(\theta_S)d\theta_S}{\int_0^{\Pi/2} \cos(\theta_S)\sin(\theta_S)d\theta_S}$$

where $a(\theta_S)$ is the directional albedo for a parallel solar beam, and is given by

$$a(\theta_s) = \frac{\int_0^{2\pi}\int_0^{\pi/2} \rho\left(\theta_s,\theta_v,\Delta\varphi = \varphi_s - \varphi_v\right)\cos(\theta_v)\sin(\theta_v)d\theta_v d\Delta\varphi}{\int_0^{2\pi}\int_0^{\pi/2} \cos(\theta_v)\sin(\theta_v)d\theta_v d\Delta\varphi}$$

with $\rho(\theta_S,\theta_V,\Delta\varphi)$, the bidirectionnal reflectances generated by the users's inputs (see *HAPKBRDF)*.

SUBROUTINE IAPIALBE

Function: Same as *HAPKALBE* but for a BRDF from the subroutine *IAPIBRDF*.

SUBROUTINE MINNALBE

Function: Same as *HAPKALBE* but for a BRDF from the subroutine *MINNBRDF*.

SUBROUTINE OCEALBE (and GLITALBE)

Function: Same as *HAPKALBE* but for a BRDF from the subroutine *OCEABRDF*.

SUBROUTINE RAHMALBE

Function: Same as *HAPKALBE* but for a BRDF from the subroutine *RAHMBRDF*.

SUBROUTINE ROUJALBE

Function: Same as *HAPKALBE* but for a BRDF from the subroutine *ROUJBRDF*.

SUBROUTINE VERSALBE

Function: Same as *HAPKALBE* but for a BRDF from the subroutine *VERSBRDF*.

SUBROUTINE WALTALBE

Function: Same as *HAPKALBE* but for a BRDF from the subroutine *WALTBRDF*.

SUBROUTINE BRDFGRID

Function: To generate a BRDF following user's inputs.

Description: The user enters the value of ρ for a sun at a given zenith sun angle θ_S by steps of 10° for zenith view angles θ_V (from 0° to 80° and the value at 85°) and by steps of 30° for azimuth view angles φ_V from 0° to 360°. The user does the same for a sun which would be at θ_V. In addition, the spherical albedo of the surface has to be specified.

The parameters are:

1. for θ_S you have to enter $\rho(\theta_V,\varphi_V)$

   ρ(0°,00°), ρ(10°,00°)...ρ(80°,00°), ρ(85°,00°)
   ρ(0°,30°), ρ(10°,30°)...ρ(80°,30°), ρ(85°,30°)
   ...
   ρ(0°,360°), ρ(10°,360°)...ρ(80°,360°), ρ(85°,360°)

2. for θ_S=θ_V you have to enter $\rho(\theta_V,\varphi_V)$

   ρ(0°,00°), ρ(10°,00°)...ρ(80°,00°), ρ(85°,00°)
   ρ(0°,30°), ρ(10°,30°)...ρ(80°,30°), ρ(85°,30°)
   ...
   ρ(0°,360°), ρ(10°,360°)...ρ(80°,360°), ρ(85°,360°)

3. the spherical albedo of the surface

SUBROUTINE HAPKBRDF

Function: To generate a BRDF following the *Hapke*'s (1981) model.

Description (from Pinty and Verstraete, 1991): From the fundamental principles of radiative transfer theory, *Hapke* (1981) derived an analytical equation for the bidirectional reflectance function of a medium composed of dimensionless particles. The singly scattered radiance is derived exactly, whereas the multiply scattered radiance is evaluated from a two-stream approximation, assuming that the scatterers making up the surface are isotropic. The bidirectional reflectance ρ of a surface illuminated by the sun from a direction (θ_S,φ_S), observed from a direction (θ_V,φ_V), and normalized with respect to the reflectance of a perfectly reflecting Lambertian surface under the same condition is given by

$$\rho(\theta_S,\varphi_S,\theta_V,\varphi_V)=\frac{\omega}{4}\frac{1}{\mu_S+\mu_V}\{[1+B(g)]P(g)+H(\mu_S)H(\mu_V)-1\}$$

where $\mu_S=\cos(\theta_S)$ and $\mu_V=\cos(\theta_V)$

g, the phase angle between the incoming and the outgoing rays is defined as:

$$\cos(g)=\cos(\theta_S)\cos(\theta_V)+\sin(\theta_S)\sin(\theta_V)\cos(\varphi_S-\varphi_V)$$

B(g) is a backscattering function that accounts for the hot spot effect

$$B(g)=\frac{S_H(0)}{\omega P(0)}\frac{1}{[1+(1/h)\tan(g/2)]}$$

H(x) is a function to account for multiple scattering

$$H(x)=\frac{1+2x}{1+2(1-w)^{1/2}x}$$

In these equations:

- ω is the average single scattering albedo of the particles,
- P(g) is the average of the phase function of the particles, it is computed here by the *Heyney and Greenstein*'s function:

$$P(g)=\frac{1-\Theta^2}{1+\Theta^2+2\Theta\cos(g)}$$

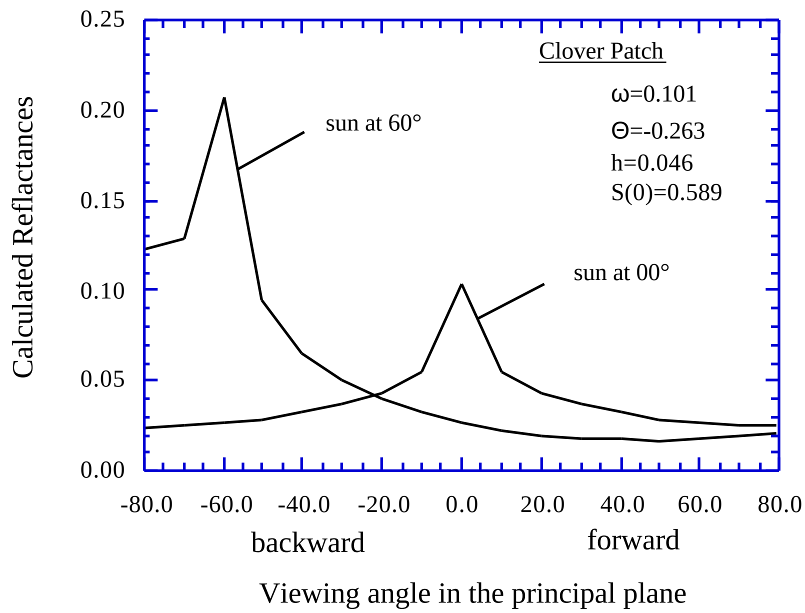
with Θ is the asymmetry factor ranging from -1 (backward scattering) to +1.

- S(0) is the amplitude of the hot spot,
- h is the width of the hot spot.

The parameters are:

$1-\omega$, Θ, S(0), h,

where ω is the average single-scattering albedo of the scatterers, Θ the asymmetry factor for the phase function, S(0) amplitude of the hot spot, and h width of the hot spot



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B.W. HAPKE, Bidirectional reflectance spectroscopy - 4. The extinction coefficient and the opposition effect, *Icarus*, 67, 264-280, 1986.

B. PINTY, and M. VERSTRAETE, Extracting Information on Surface Properties From Bidirectional Reflectance Measurements, *J. Geophys. Res.*, 96, 2865-2874, 1991.

SUBROUTINE IAPIBRDF

Function: To generate a BRDF following the *Iaquinta and Pinty's* (1994) model.

Description (from Iaquinta and Pinty, 1994): The model presents an improvement of the original model by *Verstraete et al.*, 1990, in order to account for the effects due to an underlying soil below the vegetation canopy. The singly scattered component is solved exactly using an analytical hot-spot description. The multiply scattered component is approximated on the basis of Discrete Ordinates Method reduced to a one-angle problem.

The reflectance field is split into three main components which are unscattered (0), singly scattered (1) and multiply scattered (M) by the leaves:

$$\rho^{tot}(\Omega_o,\Omega)=\rho^0(\Omega_o,\Omega)+\rho^1(\Omega_o,\Omega)+\rho^M(\Omega_o)$$

where the canopy is illuminated from the direction Ω_o ($\mu_o=\cos(\theta_o),\varphi_o$) by the direct solar radiation, and observed from the direction Ω ($\mu=\cos(\theta),\varphi$).

• The single scattering by canopy elements $\rho^1(\Omega_o,\Omega)$ is given by

$$\rho^1(\Omega_o,\Omega)=\frac{\Gamma(\Omega_o\rightarrow\Omega)}{|\mu_o|\mu}\int_0^{L_T} T_o(L)T(L)dL$$

where • $\Gamma(\Omega_o\rightarrow\Omega)$ is the area scattering phase function (bi-Lambertian)

• L is the leaf area index ($0<L<L_T$)

• $T_o(L)$ is the transmission of direct solar radiation through the canopy layers above the level L, it can be written as follow

$$T_o(L)=\exp\left(-\frac{G(\Omega_o)}{|\mu_o|}\right)$$

• T(L) is the transmission of scattered radiation, it can be written as follow

$$T(L)=\exp\left(-\frac{G(\Omega_o)}{\mu}\frac{V_2(\Omega_o,\Omega,L)}{V(\Omega,L)}L\right)$$

where $$\frac{V_2(\Omega_o,\Omega,L)}{V(\Omega,L)} \quad \left(1-\frac{4}{3\Pi}\right)\frac{L}{L_i} \qquad \text{if} L<L_i$$
$$=1-\frac{4}{3\Pi}\frac{L_i}{L} \qquad \text{if} L\geq L_i$$

with

$$L_i=\frac{2r\Lambda}{\sqrt{\tan^2(\theta_o)+\tan^2(\theta)-2\tan(\theta_o)\tan(\theta)\cos(\varphi_o-\varphi)}}$$

Λ denotes the leaf area density [m^2 m^{-3}] and r [m] is the radius of the sun-flecks on the illuminated leaf

• The second component of the reflectance is the uncollided radiation $\rho^0(\Omega_o,\Omega)$ (first order reflectance from the soil), which is written

$$\rho^0(\Omega_o,\Omega)=R_s T_o(L_T)T(L_T)=R_s\exp\left\{-\left(\frac{G(\Omega_o)}{|\mu_o|}+\frac{G(\Omega)}{\mu}\frac{V_2(\Omega_o,\Omega,L_T)}{V(\Omega,L_T)}\right)L_T\right\}$$

where R_s is the soil albedo

• Using a canopy transport equation reduced to a one-angle problem and assuming isotropic scattering, the multiply scattered radiation exiting at the top of the canopy is given by

$$\rho^M(\Omega_o)=\frac{1}{|\mu_o|}\int_0^1 I^M(0,\mu')\mu'd\mu'$$

where I^M is the multiply scattered intensity which means photons which have been scattered two or more times in the finite canopy.

In the above equations, the extinction coefficient of the radiation transport equation uses the G-function. Physically $G(\Omega_p)$ is the leaf area projected to the direction Ω_p by a unit leaf area in the canopy

$$G(\Omega_p)=\frac{1}{2\Pi}\int_{2\Pi+} g_L(\Omega_L)|\Omega_L.\Omega_p|\, d\Omega_L$$

where $g_L(\Omega_L)$ is the probability density of the distribution of leaf normals with respect to the upward hemisphere (its computation is depending of the input parameter ild)

The area scattering phase function $\Gamma(\Omega_o \rightarrow \Omega)$ is given by

$$\frac{1}{\Pi}\Gamma(\Omega' \rightarrow \Omega)=\frac{1}{2\Pi}\int_{2\Pi+} g_L(\Omega_L)|\Omega'.\Omega_L|\ f(\Omega' \rightarrow \Omega,\Omega_L)d\Omega_L$$

where $f(\Omega' \rightarrow \Omega,\Omega_L)$ is the leaf scattering distribution function. Here, it is assuming that the leaves follow a bi-Lambertian scattering model and then $f(\Omega' \rightarrow \Omega,\Omega_L)$ can be written

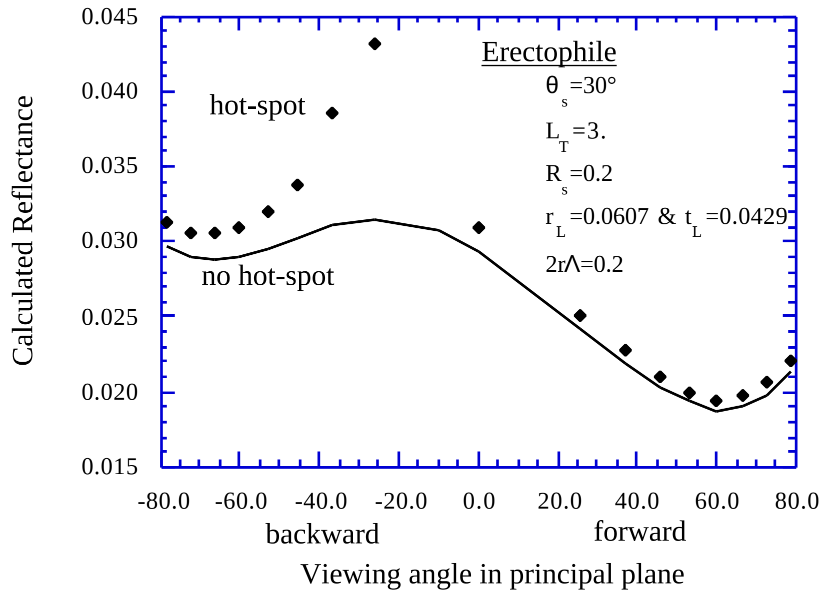
$$f(\Omega' \rightarrow \Omega,\Omega_L)=\begin{cases} \dfrac{r_L|\Omega.\Omega_L|}{\Pi} \text{ if}(\Omega.\Omega_L)(\Omega'.\Omega_L)<0 \\ \dfrac{t_L|\Omega.\Omega_L|}{\Pi} \text{ if}(\Omega.\Omega_L)(\Omega'.\Omega_L)>0 \end{cases}$$

with r_L the leaf reflection coefficient and t_L the leaf transmission coefficient

The parameters are :

1- ild, ihs
2- L_t, $2r\Lambda$
3- r_L, t_L, R_s

where ild is the leaf angle distribution (1=planophile, 2=erectophile, 3=plagiophile, 4=extremophile, 5=uniform), ihs a hot spot describter (0=no hot-spot, 1=hot spot), L_t the leaf area index in [1. - 15.], $2r\Lambda$ a hot-spot parameter in [0. (no hot-spot) - 2.0], r_L the leaf reflection coefficient in [0., 0.99], t_L the leaf transmission coefficient in [0., 0.99], R_s the soil albedo in [0., 0.99]



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M. VERSTRAETE, B. PINTY, and R.E. DICKINSON, A Physical Model of the Bidirectional Reflectance of Vegetation Canopies- 1. Theory, *J. Geophys. Res.*, 95, 11755-11765, 1990.

SUBROUTINE MINNBRDF

Function: To generate a BRDF following the *Minnaert*'s (1941) model.

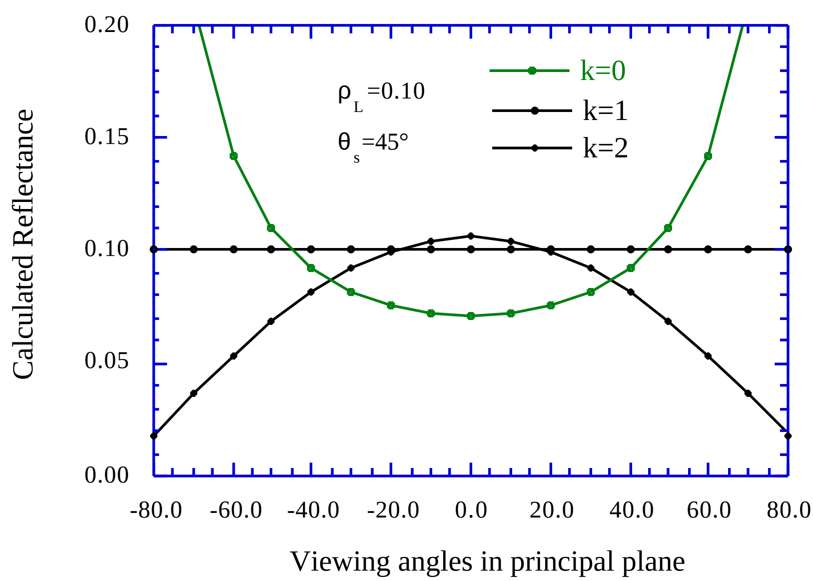
Description: Using the optical reciprocity principle, *Minnaert* (1941) defined a simple model to compute the BRDF. The reflectance is written

$$\rho(\theta_s,\theta_v,\varphi)=\rho_L\frac{k+1}{2}(\cos(\theta_v)\cos(\theta_s))^{k-1}$$

where ρ_L is the albedo of the surface and k the surface parameter. For k=1, the BRDF corresponds to an ideal Lambertian surface; k=0 corresponds to a minimum reflectance at nadir and k=2 at a maximum reflectance at nadir.

The parameters are:

1- k, ρ_L



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M. MINNAERT, The reciprocity principle in lunar photometry, *Astrophy. J.*, 93 , 403-410, 1941

SUBROUTINE OCEABRDF (and OCEATOOLS)

Function: To compute the directional reflectance of the ocean surface according to the whitecaps, sun glint and pigment concentration influences.

Description: In the solar spectral range, the reflectance of the ocean surface $\rho_{os}(\lambda)$ can be assumed for a given set of geometrical condition θ_s, θ_v and φ as the sum of three components dependent of the wavelength λ (*Koepke*, 1984):

$$\rho_{os}(\theta_s,\theta_v,\varphi,\lambda) = \rho_{wc}(\lambda) + \{1-W\}.\rho_{gl}(\theta_s,\theta_v,\varphi,\lambda) + \{1-\rho_{wc}(\lambda)\}.\rho_{sw}(\theta_s,\theta_v,\varphi,\lambda)$$

where

- $\rho_{wc}(\lambda)$ is the reflectance due to the whitecaps
- $\rho_{gl}(\lambda)$ is the specular reflectance at the ocean surface
- $\rho_{sw}(\lambda)$ is the scattered reflectance emerging from the sea water
- W is the relative area covered with whitecaps, for water temperature greater than 14°C it can be expressed from the wind speed ws (*Monahan and O'Muircheartaigh*, 1980) by $W=2.9510^{-6}.ws^{3.52}$

1-Reflectance of whitecaps $\rho_{wc}(\lambda)$

According to *Koepke*, 1984, "the optical influence of the whitecaps is given by the product of the area of each individual whitecaps W with its corresponding reflectance $\rho_f(\lambda)$. However, the area of an individual whitecap increases with its age while its reflectance decreases. Since whitecaps of different ages are taken into consideration in the W values, the combination of W with $\rho_f(\lambda)$ gives $\rho_{wc}(\lambda)$ values that are too high". Thus *Koepke* defines, in place of $\rho_f(\lambda)$, an effective reflectance of ocean foam, patches $\rho_{ef}(\lambda)$ nearly independent of wind speed by the relation

$$\rho_{wc}(\lambda) = W.\rho_{ef}(\lambda) = W.f_{ef}.\rho_f(\lambda)$$

where f_{ef} is the efficiency factor slightly dependent of the wind speed but independent of the wavelength (f_{ef}=0.4.± 0.2).

The figure 1 shows the reflectance of the whitecaps as a function of the wind speed in the visible spectral range; in this range the effective reflectance $\rho_{ef}(\lambda)$ is a constant value (22 ± 11)%.

2-Reflectance of the sun glint $\rho_{gl}(\lambda)$ *(SUBROUTINE SUNGLINT)*

Cox and Munk (1954,1955) made measurements of the sun glitter from aerial photographs. They defined a many-faceted model surface whose wave-slopes vary according to isotropic and anisotropic Gaussian distribution with respect of the surface wind.

Let us consider the system of coordinates (P,X,Y,Z) where P is the observed point, Z the altitude, PY is pointed to the sun direction and PX to the direction perpendicular to the sun plane. In this system the surface slope is defined by its two components Z_x and Z_y by

$$Z_x = \frac{\partial Z}{\partial X} = \sin(\alpha)\tan(\beta) \qquad\qquad Z_y = \frac{\partial Z}{\partial Y} = \cos(\alpha)\tan(\beta)$$

where α is the azimuth of the ascent (clockwise from the sun) and β the tilt. Using spherical trigonometry Z_x and Z_y can be related to the incident and reflected directions ($\Pi/2 \geq \theta_s$ and $\theta_v \geq 0$) through

$$Z_x = \frac{-\sin(\theta_v)\sin(\phi_s - \phi_v)}{\cos(\theta_s) + \cos(\theta_v)} \qquad\qquad Z_y = \frac{\sin(\theta_s) + \sin(\theta_v)\cos(\phi_s - \phi_v)}{\cos(\theta_s) + \cos(\theta_v)}$$

In the case of an anisotropic distribution of slope components (dependent of the wind direction), let us consider new principal axes (P;X',Y',Z'=Z) defined by a rotation of χ from the sun (P;X,Y,Z) system with PY' parallel to the wind direction (related clockwise from the North by ϕ_w, then $\chi = \phi_s - \phi_w$). The slope components are now expressed as

$$Z_x' = \cos(\chi).Z_x + \sin(\chi).Z_y \qquad\qquad Z_y' = -\sin(\chi).Z_x + \cos(\chi).Z_y$$

and the slope distribution is expressed by a Gram-Charlier series as

$$P(Z'_x, Z'_y) = \frac{1}{2\Pi\sigma'_x\sigma'_y}\exp\left(-\frac{\xi^2+\eta^2}{2}\right)\Big\{1 - \tfrac{1}{2}C_{21}(\xi^2 - 1) - \tfrac{1}{6}C_{03}(\eta^3 - \eta) +$$
$$+ \tfrac{1}{24}C_{40}(\xi^4 - 6\xi^2 + 3) + \tfrac{1}{4}C_{22}(\xi^2 - 1)(\eta^2 - 1) + \tfrac{1}{24}C_{04}(\eta^4 - 6\eta^2 + 3)\Big\}$$

where • $\xi = Z_x'/\sigma_x'$ and $\eta = Z_y'/\sigma_y'$

• σ_x' and σ_y' are the rms values of Z_x' and Z_y', the skewness coefficients C21 and C03, and the peakedness coefficients C40, C22 and C04 has been defined by Cox and Munck for a clean (uncontaminated) surface as follows

$$\sigma_x'^2 = 0.003 + 0.00192ws \pm 0.002 \qquad \sigma_y'^2 = 0.00316ws \pm 0.004$$
$$C_{21} = 0.01 - 0.0086ws \pm 0.03 \qquad C_{03} = 0.04 - 0.033ws \pm 0.12$$
$$C_{40} = 0.40 \pm 0.23 \qquad C_{22} = 0.12 \pm 0.06 \qquad C_{04} = 0.23 \pm 0.41$$

And the directional reflectance is written

$$\rho_{gl}(\theta_s, \theta_v, \phi_s, \phi_v) = \frac{\Pi \, P(Z'_x, Z'_y) \, R(n, \theta_s, \theta_v, \phi_s, \phi_v)}{4 \cos(\theta_s) \cos(\theta_v) \cos^4(\beta)}$$

where $R(n, \theta_s, \theta_v, \phi_s, \phi_v)$, defined below, is the *Fresnel*'s reflection coefficient (n is the complex refractive index of the sea water, see below).

Figure 2 shows computations of ρ_{gl} for a wind speed of 05 and 15m/s, χ equal to 00, 90, 180, and 270°, a solar zenith angle of 30° and a wavelength of 0.550µm.

3-Fresnel's reflection coefficient (SUBROUTINE FRESNEL and INDWAT)

The coefficient $R(n, \theta_s, \theta_v, \varphi_s, \varphi_v)$ is computed (*Born and Wolf*, 1975) involving the absorption of the water ($n = n_r - i n_i$) as

$$R(n, \theta_s, \theta_v, \phi_s, \phi_v) = \frac{1}{2} \frac{\left[(n_r^2 - n_i^2)\cos(\theta_i) - u\right]^2 + \left[2 n_r n_i \cos(\theta_i) + v\right]^2}{\left[(n_r^2 - n_i^2)\cos(\theta_i) + u\right]^2 + \left[2 n_r n_i \cos(\theta_i) - v\right]^2}$$

with

$$u^2 = \frac{1}{2}\left\{\left|n_r^2 - n_i^2 - \sin^2(\theta_i)\right| + \sqrt{\left[n_r^2 - n_i^2 - \sin^2(\theta_i)\right]^2 + 4 n_r^2 n_i^2}\right\}$$

$$v^2 = \frac{1}{2}\left\{-\left|n_r^2 - n_i^2 - \sin^2(\theta_i)\right| + \sqrt{\left[n_r^2 - n_i^2 - \sin^2(\theta_i)\right]^2 + 4 n_r^2 n_i^2}\right\}$$

$$\cos(\theta_i) = \sqrt{\tfrac{1}{2}[1 + \cos(\theta_s)\cos(\theta_v) + \sin(\theta_s)\sin(\theta_v)\sin(\phi_s - \phi_v)]}$$

$$\sin(\theta_i) = \sqrt{\tfrac{1}{2}[1 - \cos(\theta_s)\cos(\theta_v) + \sin(\theta_s)\sin(\theta_v)\sin(\phi_s - \phi_v)]}$$

In 6S, the complex index of refraction of the sea water (we assume that the outside medium is vacuum) is deduced from the complex index of refraction of the pure water given by *Hale and Querry*, 1973. By default, we assume a typical sea water (Salinity=34.3ppt, Chlorinity=19ppt) as reported by *Sverdrup* (1942, p. 173). *McLellan* (1965, p. 129) reported on measurements of the index of refraction an increase as a function of the chlorinity. For a chlorinity of 19.0 ppt, the increase was found to have a value of +0.006 and to be linear with the salt concentration C_{sal} (see also *Friedman*, 1969). For the extinction coefficient, *Friedman*, 1969, reported that no correction is required between 1.5 and 9 μm.

Then in 6S we apply a correction δn_r of +0.006 on the index of refraction of pure water and no correction δn_i for the extinction coefficient. Therefore the user is able to enter his own salt concentration. In that case, a linear interpolation is assumed to correct the index of refraction of the pure water, so that $\delta n_r=0$ for C_{sal}=0ppt and $\delta n_r=+0.006$ for C_{sal}=34.3ppt.

4-Reflectance emerging from the sea water $\rho_{sw}(\lambda)$ (SUBROUTINE MORCASIWAT for R_w)

The reflectance emerging from sea water (also called remote sensing reflectance of the sea water) $\rho_{sw}(\theta_s,\theta_v,\varphi,\lambda)$ is the reflectance as observed just above the sea surface (level 0^+). This reflectance can be related to the reflectance R_w which is the ratio of the upwelling to downwelling radiance just below the sea surface (level 0^-). If we assume the ocean as a Lambertian reflector $\rho_{sw}(\theta_s,\theta_v,\varphi,\lambda)$ can be expressed by the relation:

$$\rho_{sw}(\theta_s,\theta_v,\varphi,\lambda)=\frac{1}{n^2}\,\frac{R_w(\lambda).t_d(\theta_s).t_u(\theta_v)}{1-a.R_w(\lambda)}$$

where:

•t_d is the transmittance for the downwelling radiance, and is expressed to the Fresnel reflectance coefficient $R_{a\text{-}w}(\theta_s,\theta_d,\varphi)$ for the air-water interface by the relation:

$$t_d(\theta_s)=1-\int_0^{2\Pi}\int_0^{\Pi/2}R_{a-w}(\theta_s,\theta_d^a,\varphi).\cos(\theta_d^a).\sin(\theta_d^a).d\theta_d^a.d\varphi$$

The angle θ_d^a represents (see Figure 3) the zenithal angle of the reflected solar beam according to the wave-slopes distribution (*Cox and Munk*'s model, see below).

•t_u is the transmittance for the upwelling radiance, and is expressed to the Fresnel reflectance coefficient $R_{w\text{-}a}(\theta_v,\theta_u,\varphi)$ for the water-air interface by

$$t_u(\theta_v)=1-\int_0^{2\Pi}\int_0^{\Pi/2}R_{w-a}(\theta_v,\theta_u^w,\varphi).\cos(\theta_u^w).\sin(\theta_u^w).d\theta_u^w.d\varphi$$

The angle θ_u^w represents (see Figure 3) the zenith angle in the water of the upwelling beam according to the *Fresnel and Snell*'s law: $n_{air}\sin(\theta_{air})=n_{sea}\sin(\theta_{sea})$ and to the wave-slopes distribution.

•a is defined by

$$a=1-\int_0^{\Pi/2}t_u(\theta_v).\cos(\theta_v).\sin(\theta_v).d\theta_v$$

In order to minimize computations we adopted a constant value of a=0.485. In theory, the value of a depends on wind speed and water index of refraction. In practice, this value varies very little with wind speed (see table 2 of *Austin*, 1974) and the index of refraction of water in that range of wavelength (0.4μm-0.7μm) is almost constant and taken equal to 1.341.

As described above the irradiance reflectance $R_w(\lambda)$ is the ratio of the upwelling spectral irradiance $E_u(\lambda)$ to the downwelling irradiance $E_d(\lambda)$ just below the surface. This ratio is particularly dependent on the inherent optical properties of the sea water: the total absorption coefficients $a(\lambda)$ [m^{-1}] and the total backscattering coefficient $b_b(\lambda)$ [m^{-1}]. For example, *Morel and Prieur*, 1977, have shown within a good approximation (when $a(\lambda) << 1$) that it can be expressed as:

$$R_w(\lambda) = 0.33 \frac{b_b(\lambda)}{a(\lambda)}$$

According to *Morel*, 1988, "in many situations phytoplankton and their derivative, and detrital products (mainly particulate, but also dissolved) play a predominant role in determining the optical properties of oceanic waters. These waters are classified (by *Morel*) as "case I" waters and are opposed to "case II" waters for which sediments, or dissolved yellow substance, make an important or dominant contribution to the optical properties". Here we use the so called "case I waters" (defined in a range from 0.4 to 0.7 μm) which roughly corresponds to the case I, case IA, case IB, case II, and case III of the *Jerlov*'s chart of optical water type (*Jerlov*, 1951, 1976). For the so called "Case I waters", *Morel* splits the total backscattering coefficient into

$$b_b(\lambda) = \frac{1}{2} b_w(\lambda) + \tilde{b}_b(\lambda).b$$

where:

•$b_w(\lambda)$ is the molecular scattering coefficient of water and is given Figure 4

•$\tilde{b}_b(\lambda)$ is the ratio backscattering/scattering coefficient of the pigments and is related to the pigment concentration C (Chl a + Pheo a, in $mg.m^{-3}$) and the wavelength (in μm) by

$$\tilde{b}_b(\lambda) = 0.002 + 0.02(0.5 - 0.25 \log_{10} C) \frac{0.550}{\lambda}$$

•b is the scattering coefficient of pigment expressed by

$$b=0.3C^{0.62}$$

Also according to *Morel*'s "Case I waters", the total absorption coefficient is written as

$$a(\lambda)=u(\lambda).K_d(\lambda)$$

where:

•$u(\lambda)$ is computed as follow

$$u(\lambda) = 0.90 \frac{1 - R_w(\lambda)}{1 + 2.25 R_w(\lambda)}$$

•$K_d(\lambda)$ is the total diffuse attenuation coefficient for downwelling irradiance and is given by

$$K_d(\lambda)=K_w(\lambda)+\chi_c(\lambda)C^{e(\lambda)}$$

with $K_w(\lambda)$ (the diffuse attenuation coefficient for pure oceanic water), $\chi_c(\lambda)$ and $e(\lambda)$ are tabular values. We report Figure 5 the computations of $K_d(\lambda)$ for several pigment concentrations.

Always according to the *Morel*'s model (Case I waters) the computation of the reflectance $R_w(\lambda)$ is only dependent of the pigment concentration C. The Figure 6 shows the computed reflectance R_w in the range from 0.4 to 0.7 μm for different concentrations C.

If the only information you have is the water type following the *Jerlov*'s chart, you can use the approximate C values given by *Morel*, 1988:

0-0.01	0.05	0.1	0.5	1.5-2	$mg.m^{-3}$
I	IA	IB	II	III	

The Parameters are:

1- ws, ϕ_w, C_{sal}, C

with: ws is the wind speed (in m/s)

ϕ_w is the direction of the wind (clockwise from the North)

C_{sal} is the salt concentration (in ppt). If $C_{sal} < 0$ then C_{sal}=34.3ppt by default

C is the pigment concentration (Chl a + Pheo a in $mg.m^{-3}$)

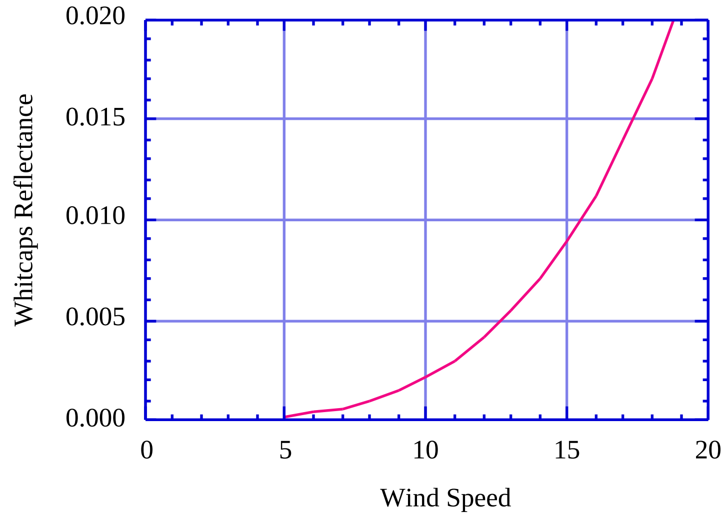

Figure 1: Whitecaps Reflectance as defined by *Koepke*, 1984, in the visible spectral range.

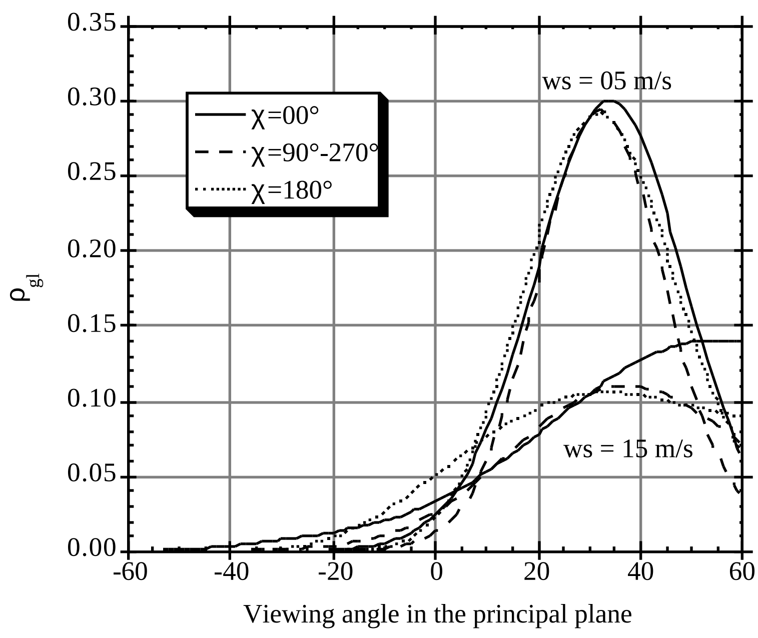

Figure 2: Reflectance of the sunglint in the principal plane for a wind speed of 5 and 15 m/s and for several $\chi=\phi_s-\phi_w$. The solar zenith angle has been up to 30° and the wavelength to 0.550µm.

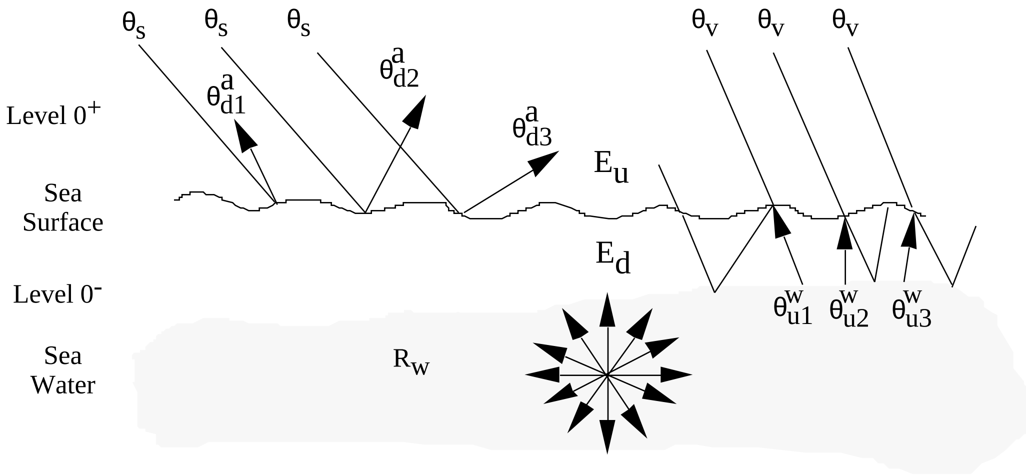

Figure 3

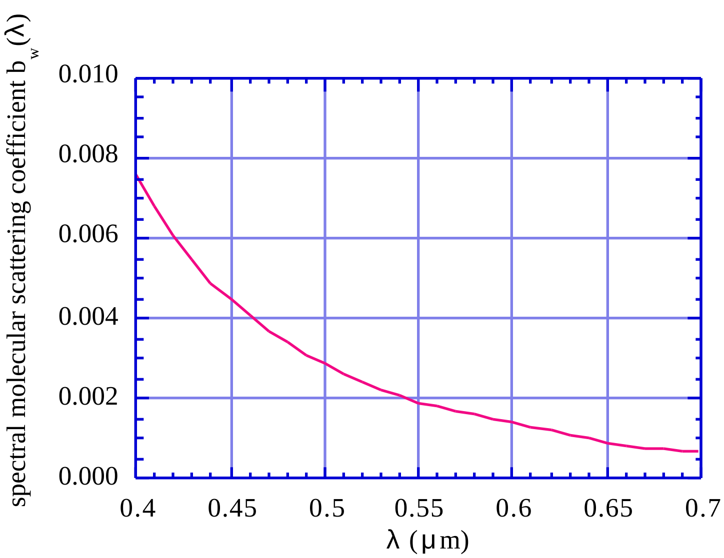

Figure 4: spectral molecular scattering coefficients (m^{-1})

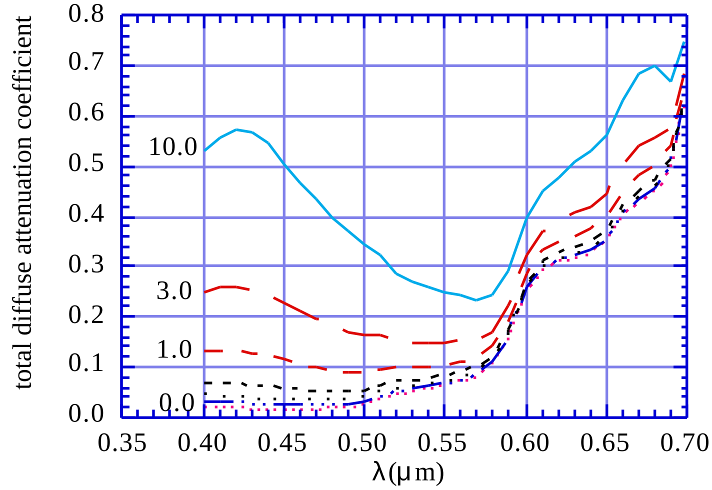

Figure 5: Diffuse attenuation coefficients (m^{-1}) as modeled in *Morel*'s case I waters for several pigment concentration (0.0-0.03-0.1-0.3-1-3-10 $mg.m^{-3}$)

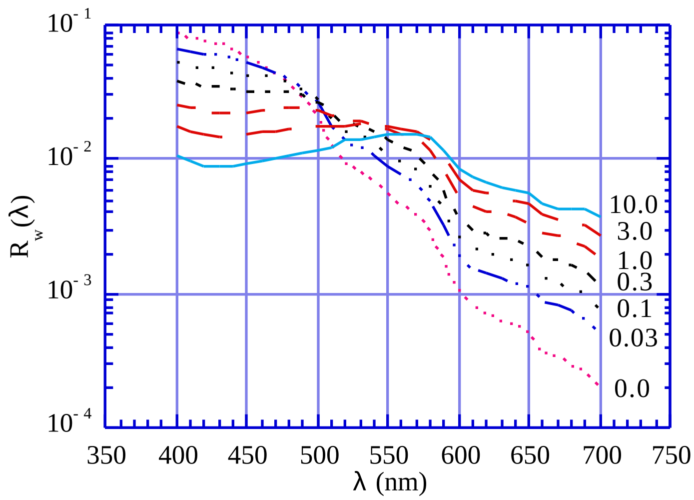

Figure 6: Spectral irradiance reflectances as defined by the *Morel*'s model related to the "Case I waters" for several pigment concentration (0.0-0.03-0.1-0.3-1-3-10 $mg.m^{-3}$)

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SUBROUTINE RAHMBRDF

Function: To generate a BRDF following the *Rahman et al.'s* model.

Description (from Raman et al., 1993): The model follows a semi-empirical approach and is designed to be applicable to arbitrary natural-surfaces both in visible and near-infrared using 3 parameters.

The bidirectional reflectance $\rho(\theta_s,\theta_v,\varphi_s\text{-}\varphi_v)$ is assumed to be:

$$\rho(\theta_s,\theta_v,\varphi_s,\varphi_v) = \rho_0 \frac{(\cos\theta_s)^{k-1}(\cos\theta_v)^{k-1}}{(\cos\theta_s + \cos\theta_v)^{1-k}} F(g)\,[1 + R(G)]$$

where: -ρ_0 is, according to the authors, an arbitrary parameter characterizing the intensity of the reflectance of the surface cover, but it should not be taken as a single scattering albedo or as a normalized reflectance: the only constraint on it is $\rho_0 \geq 0$,

-k indicates the level of anisotropy of this surface,

-F(g) is a function to moderate the overall contributions in the forward and backward scattering (modified *Heyney and Greenstein*'s function):

$$F(g) = \frac{1-\Theta^2}{[1+\Theta^2 - 2\Theta\cos(\Pi - g)]^{1.5}}$$

with g the phase angle defined by:

$$\cos(g) = \cos(\theta_s)\cos(\theta_v) + \sin(\theta_s)\sin(\theta_v)\cos(\varphi_s - \varphi_v)$$

and Θ an asymmetry factor controling the relative amount of forward ($0\leq\Theta\leq+1$) and backward scattering ($-1\leq\Theta\leq 0$)

-R(G) is a function to account for the hot spot

$$R(G) = \frac{1-\rho_0}{1+G}$$

with G a geometrical factor expressed by:

$$G = \sqrt{(\tan\theta_s)^2 + (\tan\theta_v)^2 - 2\tan\theta_s\tan\theta_v\cos(\varphi_s - \varphi_v)}$$

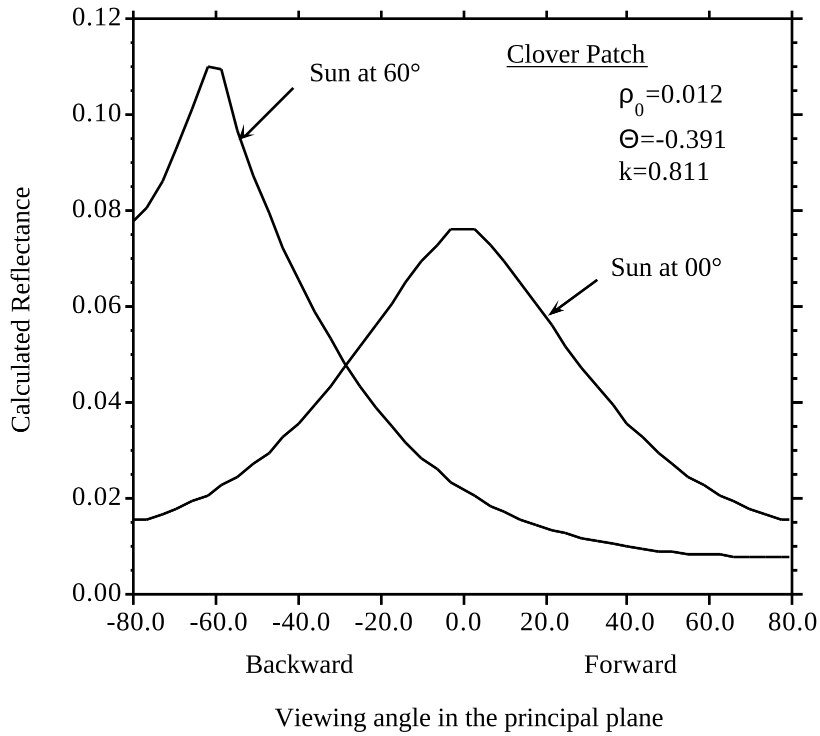
Parameters are:

1- ρ_0, Θ, k

with ρ_0=intnsity of the reflectance of the surface cover

Θ=asymmetry factor used in the modified *Heyney and Greenstrein*'s function

k=structural parameter



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SUBROUTINE ROUJBRDF

Function: To generate a BRDF following the *Roujean et al.*'s (1992) model.

Description (from Roujean et al., 1992): The model follows a semi-empirical approach and is designed to be applicable to heterogeneous surfaces. It considers that the observed surface bidirectional reflectance is the sum of two main processes operating at a local scale:

- A diffuse reflection component taking into account the geometrical structure of opaque reflectors on the surface, and shadowing effects

- A volume scattering contribution by a collection of dispersed facets which simulates the volume scattering properties of canopies and bare soils.

This combinaison is made by assuming that the bidirectional reflectance $\rho(\theta_s,\theta_v,\varphi)$ can be expressed as:

$$\rho(\theta_s,\theta_v,\varphi)=\alpha\rho_{geom}+(1-\alpha)\rho_{vol}$$

where α is an empirical coefficient which characterizes the relative weight of the geometric and volume component in the final bidirectional signature.

Then the bidirectional reflectance model may be written

$$\rho(\theta_s,\theta_v,\varphi)=k_0+k_1f_1(\theta_s,\theta_v,\varphi_r)+k_2f_2(\theta_s,\theta_v,\varphi_r)$$

where: • $\varphi = |\varphi_s-\varphi_v|$

• k_0, k_1 and k_2 are related to basic macroscopic properties of the surface

$$k_0=\rho_0[\alpha+(1-\alpha)e^{-bF}]+\frac{r}{3}(1-e^{-bF})(1-\alpha)$$

$$k_1=\frac{hl}{S}\rho_0\alpha$$

$$k_2=r(1-e^{-bF})(1-\alpha)$$

with ρ_0, the background and protrusion reflectance,
h, the average height of the surface protrusions,
l, the average length of the surface protrusions,
S, the horizontal surface associated with each protrusion,
r, the facet reflectance,
F, the facet area index.

• f_1 and f_2 are simple analytic functions of the solar and viewing angles

$$f_1(\theta_s,\theta_v,\varphi)=\frac{1}{2\Pi}\left\{(\Pi-\varphi)\cos(\varphi)+\sin(\varphi)\right\}tg(\theta_s)tg(\theta_v) -\frac{1}{\Pi}\left\{tg(\theta_s)+tg(\theta_v)+\sqrt{tg^2(\theta_s)+tg^2(\theta_v)-2tg(\theta_s)tg(\theta_v)\cos(\varphi)}\right\}$$

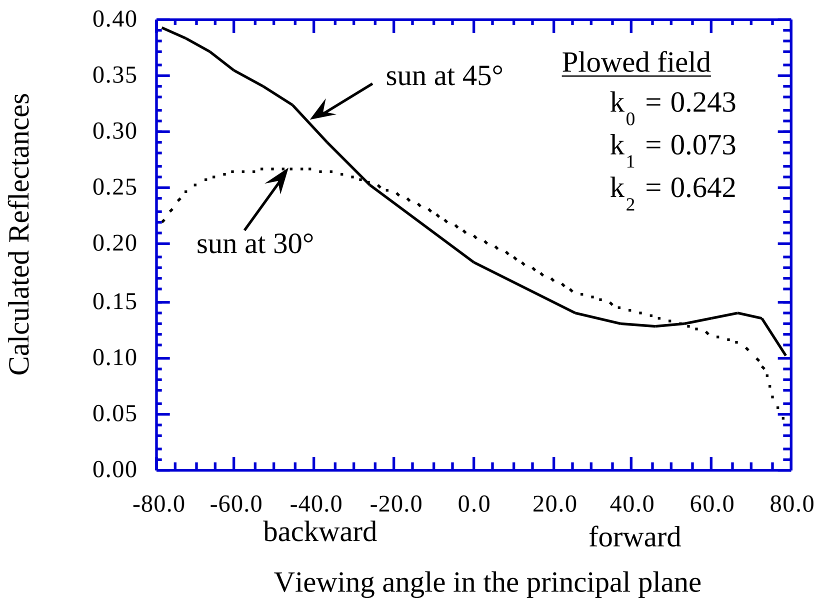
$$f_2(\theta_s,\theta_v,\varphi)=\frac{4}{3\Pi}\frac{1}{\cos(\theta_s)+\cos(\theta_v)}\left\{\left(\frac{\Pi}{2}-\xi\right)\cos(\xi)+\sin(\xi)\right\}-\frac{1}{3}$$

with ξ, the phase angle defined by

$$\cos(\xi) = \cos(\theta_s)\cos(\theta_v) + \sin(\theta_s)\sin(\theta_v)\cos(\varphi)$$

The parameters are:

1- k_0, k_1, k_2



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SUBROUTINE VERSBRDF

Function: To generate a BRDF following the *Verstraete et al.*'s (1990) model.

Description (from Pinty and Verstraete, 1991): Using the basic framework previously suggested by *Hapke* (1981) (see HAPKBRDF), *Verstraete et al.* (1990) developed a model for predicting the bidirectional reflectance exiting from a simple vegetation canopy. They concentrate on the case of a fully covered, homogeneous and semi-infinite canopy made of leaves only. With the same notations as for *Hapke*'s model, the parametric version of the derived model (see *Pinty et al.*, 1990) is as follow:

$$\rho(\theta_s,\varphi_s,\theta_v,\varphi_v)=\frac{\omega \quad \kappa_s}{4\kappa_v\mu_s+\kappa_s\mu_v}\{[1+P_v(G)]P(g)+H(\kappa_s/\mu_s)H(\kappa_v/\mu_v)-1\}$$

where

- ω is average single-scattering albedo of the particle making up the surface
- $\mu_s=\cos(\theta_s)$ and $\mu_v=\cos(\theta_v)$
- κ_s and κ_v describe the leaf orientation distribution for the illumination and viewing angles, respectively. There are 3 possible options (see below, line1-opt3)

  -κ_s and κ_v are entered by the user

  -κ is obtained from *Goudriaan*'s (1977) parameterization

  $$\kappa_x = \Psi_1 + \Psi_2\,\mu_x$$

  with $\Psi_1 = 0.5 - 0.6333\,\chi_l - 0.33\,\chi_l^2$ and $\Psi_2 = 0.877\,(1 - 2\,\Psi_1)$

  -κ is obtained from the *Dickinson et al.*'s (1990) correction to *Goudriaan*'s (1977) parameterization

  $$\kappa_x = \Psi_1 + \Psi_2\,\mu_x$$

  with $\Psi_1 = 0.5 - 0.489\,\chi_l - 0.11\,\chi_l^2$ and $\Psi_2 = 1 - 2\,\Psi_1$

  where χ_l is a function of the leaf angle distribution in the canopy, and varies from -0.4 for an erectophile canopy to +0.6 for a planophile canopy. The equal probability for all leaf orientations is given by $\chi_l=0$.

- Pv(G) is the function that accounts for the joint transmission of the incoming and outgoing radiation and thereby also for the hot spot phenomenon.

$$P_v(\theta_s,\varphi_s,\theta_v,\varphi_v)=\frac{1}{1+V_p(\theta_s,\varphi_s,\theta_v,\varphi_v)}$$

with $V_p(\theta_s,\varphi_s,\theta_v,\varphi_v)$ is a function defined by

$$4\left(1-\frac{4}{3\Pi}\right)\frac{1}{2r\Lambda}\frac{\mu_v}{\kappa_v}\sqrt{\tan^2(\theta_s)+\tan^2(\theta_v)-2\tan(\theta_s)\tan(\theta_v)\cos(\varphi_s-\varphi_v)}$$

r is the radius of the Sun flecks on the inclined scatterers (in m)

Λ is the scatterer area density of the canopy (in $m^2.m^{-3}$)

• P(g) is the average of the phase function of the particles. There are 3 options to compute P(g) (see below, line1-opt4):

-the case of an isotropic phase function

$$P(g) = 1$$

-the empirical function introduced by *Henyey and Greenstein* (1941)

$$P(g)=\frac{1-\Theta^2}{1+\Theta^2+2\Theta\cos(g)}$$

-the phase function is approximated by a *Legendre* polynomial function

$$P(g)=1+\Theta\cos(g)+L_2\frac{3\cos^2(g)-1}{2}$$

where Θ is the asymmetry factor ranging from -1 (backward scattering) to +1, g the phase angle between the incoming and the outgoing rays defined as

$$\cos(g) = \cos(\theta_s)\cos(\theta_v) + \sin(\theta_s)\sin(\theta_v)\cos(\varphi_s-\varphi_v),$$

and L_2 the second coefficients of the *Legendre* polynomial.

• H(x) is a function to account for multiple scattering (see below, line1-opt5)

- for single scattering

$$H(x)=0$$

- for multiple scattering

$$H(x)=\frac{1+2x}{1+2(1-\omega)^{1/2}x}$$

There are three lines of input parameters:

line 1- choice of options	: opt3, opt4, opt5
line 2- structural parameters	: str1, str2, str3, str4
line 3- optical parameters	: optics1, optics2, optics3

line 1:

opt 3- 0 for given values of κ
1 for *Goudriaan*'s parameterization of κ
2 for *Dickinson et al.*'s correction to *Goudriaan*'s parameterization of κ

opt 4- 0 for isotropic phase function
1 for *Heyney and Greenstein*'s phase function
2 for *Legendre* polynomial phase function

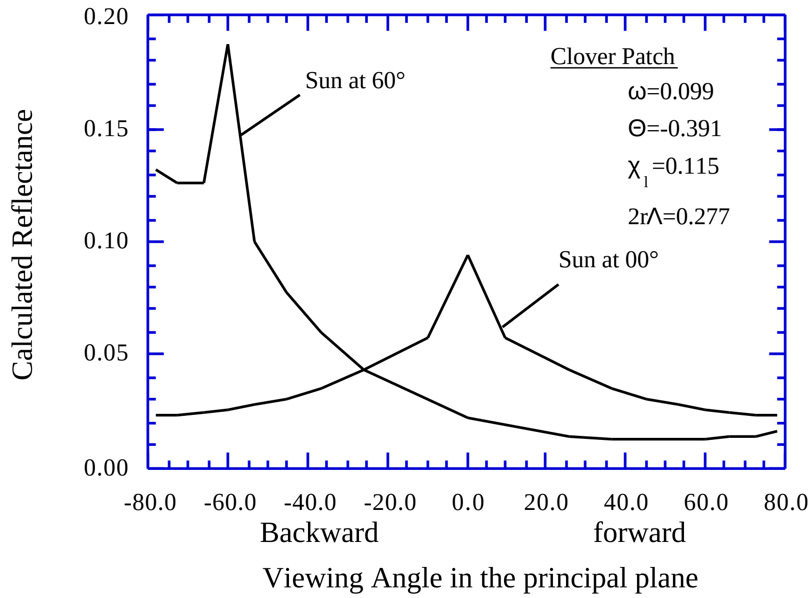
opt 5- 0 for single scattering only
1 for *Dickinson et al.*'s parameterization of multiple scattering

line 2:

str1- leaf area density (in $m^2\ m^{-3}$)
str2- radius of the sun flecks on the scatterer (in m)
str3- leaf orientation parameter
if opt3=0 then str3=κ_s
if opt3=1 or 2 then str3=χ_l
str4- leaf orientation parameter (continued)
if opt3=0 then str4=κ_v
if opt3=1 or 2 then str4 is not used

line 3:

optics 1- single scattering albedo, value between 0.0 and 1.0
optics 2- phase function parameter
if opt4=0 then this input is not used
if opt4=1 then asymmetry factor, value between -1.0 and 1.0
if opt4=2 then first coefficient of *Legendre* polynomial
optics 3- second coefficient of *Legendre* polynomial (if opt4=2)



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SUBROUTINE WALTBRDF

Function: To generate a BRDF following the *Walthall et al.*'s (1985) model.

Description (from Walthall et al., 1985): Using a deterministic model, *Walthall et al.* (1985) have simulated different canopy reflectance distributions. The 2-D contours of this distribution appears to be similar to the shape of the limacon of *Pascal*. Using the simple limacon equation other equation forms were used in an attempt to fit the 3-D reflectance surface directly. They found satisfactory results with the following equation:

$$\rho(\theta_s,\theta_v,\varphi_s,\varphi_v) = a\,\theta_v^2 + b\,\theta_v \cos(\varphi_v-\varphi_s) + c$$

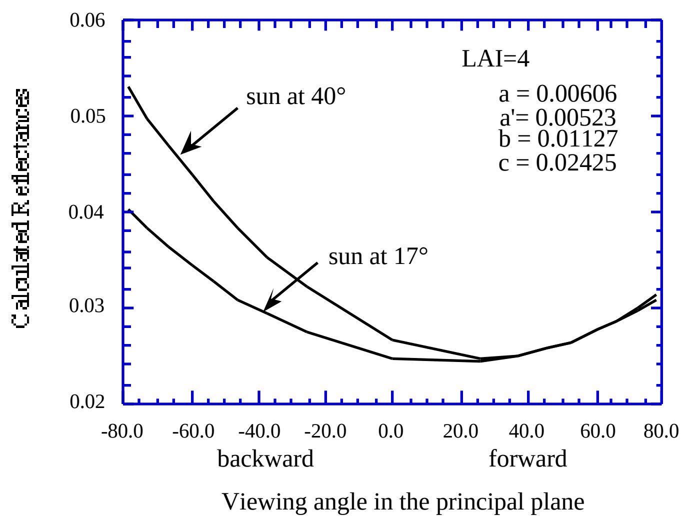
where ρ is the reflectance at a given view zenith θ_v and view azimuth φ_v look angles; a, b, and c are coefficients derived using a linear least-squares fitting procedure.

The model has to be slightly modified to match the reciprocity principle. The reflectance is written:

$$\rho(\theta_s,\theta_v,\varphi_s,\varphi_v) = a\,\theta_s^2\,\theta_v^2 + a'\,(\theta_s^2+\theta_v^2) + b\,\theta_s\,\theta_v \cos(\varphi_v-\varphi_s) + c$$

The parameters are:

1- a, a', b, c



References

C.L. WALTHALL, J.M. NORMAN, J.M. WELLES, G. CAMPBELL, and B.L. BLAD, Simple equation to approximate the bidirectional reflectance from vegetative canopies and bare soil surfaces, *Applied Optics*, Vol 24, n°3, 383-387, 1985.

SUBROUTINE AKBRDF

Function: To generate a BRDF following the *Kuusk's (1994)* model.

Description (Kuusk, 1994, 1995): The single scattering radiance of a canopy layer H is

$$I_c^1 = \frac{F_0\mu_0}{\pi\mu\mu_0}\int_0^H u_L(z)\,\Gamma(r_0,r)\,p(z,r_0,r)\,dz \qquad (1)$$

where $\mathbf{F}_0\mu_0/\pi$ is the intensity of the incident direct flux on a horizontal surface, u_L is leaf area density, $\Gamma(r_0,r)$ is the phase function of single scattering, $p(z,r_0,r)$ is the bidirectional gap probability inside a canopy at the level z in directions $r_0(\theta_0,\Phi_0)$ and $r(\theta,\Phi)$, μ_0 and μ stay for the respective cosines.

The phase function $\Gamma=\Gamma_D+\Gamma_{SP}$ and bidirectional gap probability $p(z,r_0,r)=p(r_0)p(r)C_{HS}(r_0,r)$ are functions of the leaf angle distribution $g_L(\theta_L)$. Here Γ_D is the phase function of diffuse scattering of lambertian leaves, see Eq. (8) of Subroutine IAPIBRDF, Γ_{SP} is the phase function of Fresnel reflection on the leaf surface. The phase function of specular reflection is corrected for the leaf hair and surface roughness (Nilson and Kuusk, 1989). Hot spot factor

$$C_{HS}(H,\alpha) = \exp\left\{\sqrt{\frac{G_L^{(1)}\,G_L^{(2)}}{\mu_1\mu_2}}\;\frac{L_H s_L}{\Delta(r_1,r_2)}\left[1-\exp\left(-\frac{\Delta(r_1,r_2)}{s_L}\right)\right]\right\} \qquad (2)$$

considers for the finite leaf size s_L, $\Delta(r_1,r_2) = \sqrt{1/\mu_1^2 + 1/\mu_2^2 - 2\cos\alpha/(\mu_1\mu_2)}$ is a geometry factor, π-α is the scattering angle.

G-function $G_L(r)$ is given by Eq. (7) of Subroutine IAPIBRDF. In the case of spherical orientation of leaves, and of fixed angle of leaves, exact analytical expressions for the phase function Γ and G-function are obtained by T. Nilson (see Ross, 1981). In the case of an elliptical leaf angle distribution :

$$g_L(\theta_L) = B_g\Big/\sqrt{1-\varepsilon^2\cos^2(\theta_L-\theta_m)} \qquad (3)$$

the analytical approximations for the G-function and phase function Γ are obtained by Kuusk (1995). Here the eccentricity ε and the modal inclination θ_m are the LAD parameters, B_g is a normalizing factor.

Single scattering from the soil is given by

$$I^1_{soil} = \rho_{soil}(r_0,r)\, p(H,r_0,r) \qquad (4)$$

where $\rho_{soil}(r_0,r)$ is the bidirectional reflectance of soil. The parabolic approximation of Walthall et al. (1985) is applied for the BRDF of soil $\rho_{soil}(r_0,r)$.

Multiple scattering of radiation on foliage and soil is considered in the Schwarzschild's approximation (Nilson and Kuusk, 1989).

The wavelength-dependent optical parameters of the CR model are calculated with the PROSPECT model of Jacquemoud and Baret (1990) – leaves, and with Price's (1990) base functions – soil.

Figure 1 shows a comparison of the measured and calculated BRDF for a barley canopy, and in Fig. 2 the nadir reflectance spectrum of a corn canopy is compared to that measured by Ranson et al. (1984).

As all the double integrals for directional functions are calculated analytically, the model works very fast.

The parameters are:

line 1 : structural parameters (u_L, ε, θ_m, s_L)
line 2 : optical parameters (c_{AB}, c_W, N, c_n, s_1)

u_L	– LAI
ε, θ_m	– LAD parameters
s_L	– relative leaf size
c_{AB}	– chlorophyll content, $\mu g/cm^2$
c_W	– leaf water equivalent thickness, cm
N	– the effective number of elementary layers inside a leaf
c_n	– the ratio of refractive indices of the leaf surface wax and internal material
s_1	– the weight of the 1st Price function for the soil reflectance

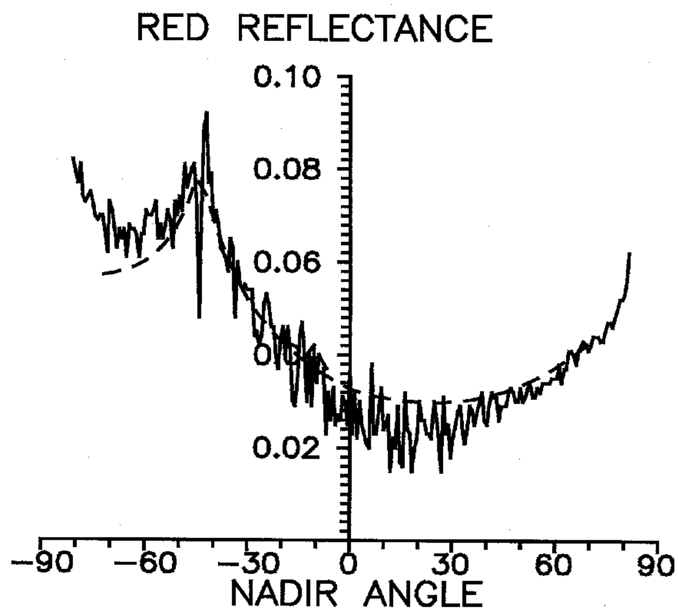


Figure 1

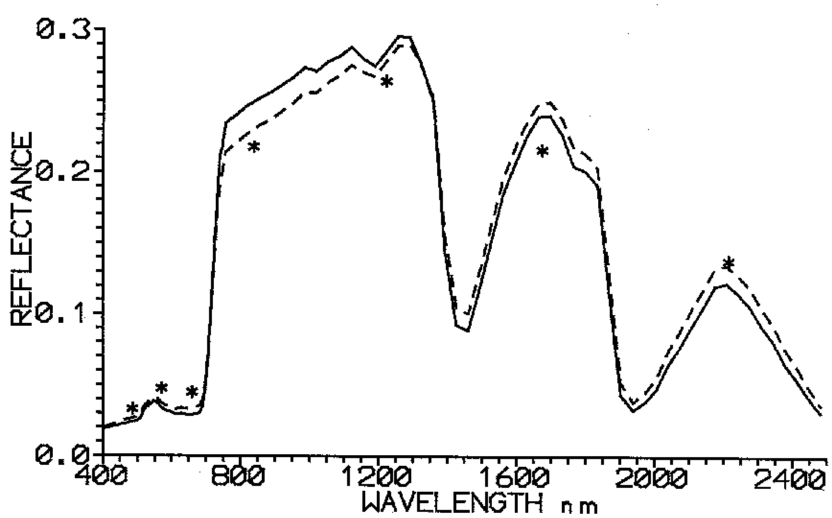


Figure 2

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DESCRIPTION OF THE SUBROUTINES USED TO UPDATE ATMOSPHERIC PROFILE (PLANE OR ELEVATED TARGET SIMULATION)

SUBROUTINE PRESPLANE

Function: Update the atmospheric profile (P(z),T(z),H_2O(z),O_3(z)) in case the observer is on board an aircraft.

Description: Given the altitude or pressure at aircraft level as input, the first task is to compute the altitude (in case the pressure has been entered) or the pressure (in case the altitude has been entered) at plane level. Then, a new atmospheric profile is created (P_p,T_p,H_2O_p,O_{3p}) for which the last level is located at the plane altitude. This profile is used in the gaseous absorption computation (ABSTRA.f) for the path from target to sensor (upward transmission). The ozone and water vapor integrated content of the "plane" atmospheric profile are also an output of this subroutine. The last output is the proportion of molecules below plane level which is useful in scattering computations (OS.f,ISO.f).

SUBROUTINE PRESSURE

Function: Update the atmospheric profile (P(z),T(z),H_2O(z),O_3(z)) in case the target is not at sea level.

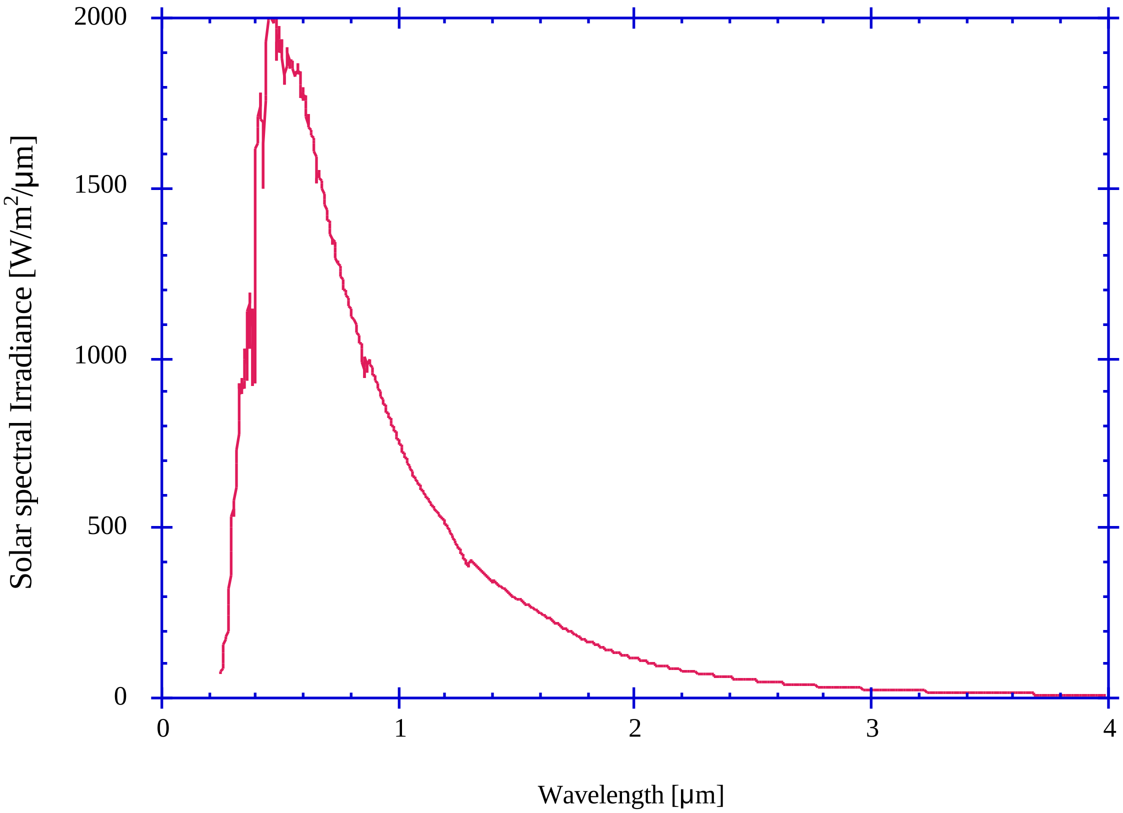
Description: Given the altitude of the target in kilometers as input, we transform the original atmospheric profile (Pressure, Temperature, Water Vapor, Ozone) so that first level of the new profile is the one at the target altitude. We also compute the new integrated content in water vapor and ozone, that are used as outputs or in computations when the user chooses to enter a specific amount of Ozone and Water Vapor.

DESCRIPTION OF THE SUBROUTINES

USED TO READ THE DATA

SUBROUTINE SOLIRR

Function: To read the solar irradiance (in $Wm^{-2}\mu m^{-1}$) from 250 *nm* to 4000 *nm* by steps of 2.5 *nm*, The total solar irradiance is put equal to 1372 Wm^{-2}. Between 250 and 4000 *nm* we have 1358 Wm^{-2}.



Reference:

H. NECKEL, D. LABS, The solar radiation between 3300 and 12500 *Solar Physics* 90, p. 205-258, 1984.

SUBROUTINE VARSOL

Function: To take into account the variation of the solar constant as a function of the Julian day.

Description: We apply a simple multiplicative factor D_S to the solar constant C_S . D_S is written as,

$$D_S=\frac{1}{(1-e\cos M)^2}$$

with

$$M = 0.9856\ (J-4)\ \frac{\pi}{180}$$

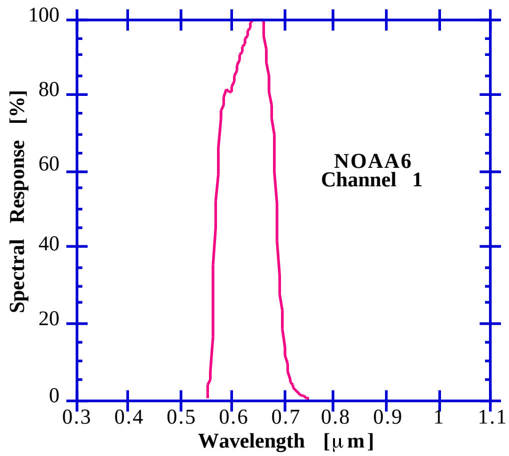
where e = 0.01673 and J is the julian day.

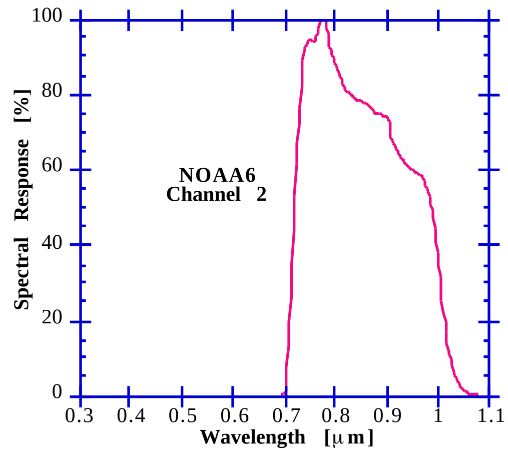
Reference:

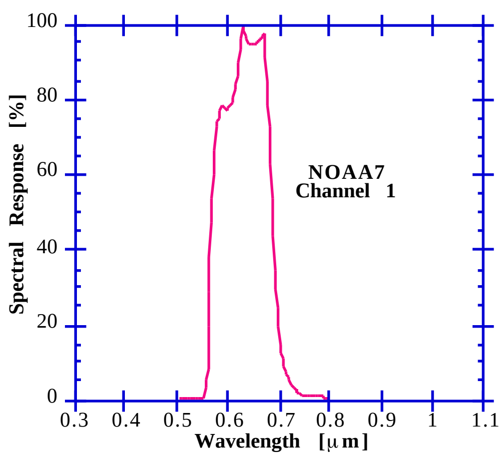
G.W. PALTRIDGE, C.M.R. PLATT, Radiative Processes in Meteorology and Climatology, *Development in Atmospheric Science*, *5*, Elsevier Scientific Publishing Company, New-York, N.Y. 10017, 1977.

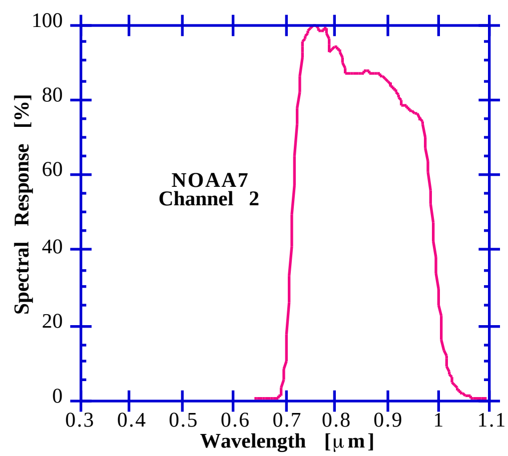
SUBROUTINE AVHRR

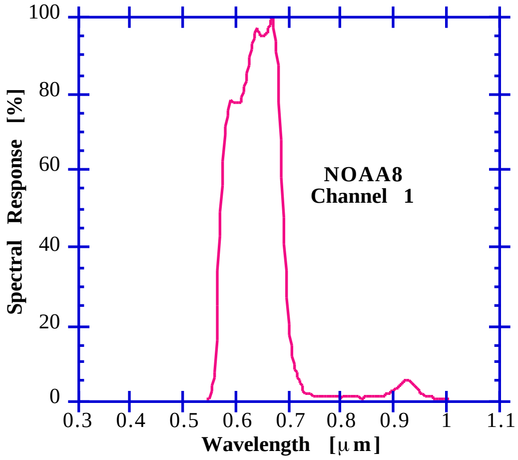
Function: To read the two spectral bands (red and near infrared) of Advanced Very High Resolution Radiometer (AVHRR) on NOAA 6, 7, 8, 9, 10, 11, 12 and 14 (extreme wavelengths and spectral response of the filter function).

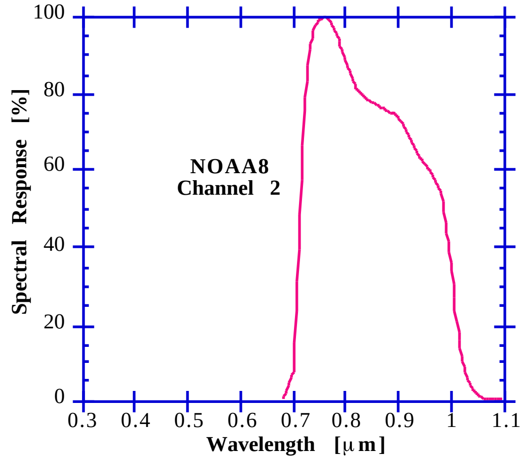


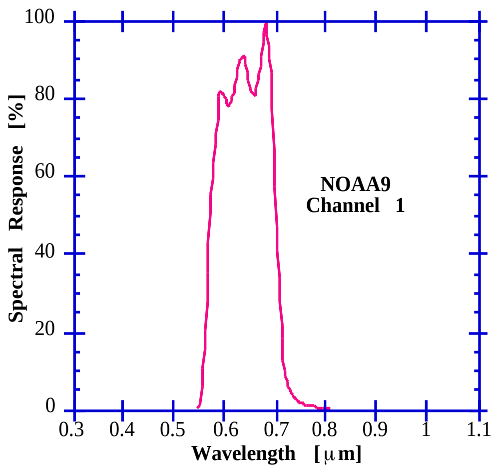


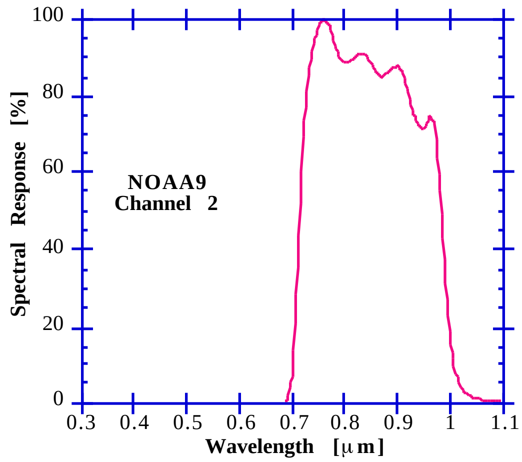


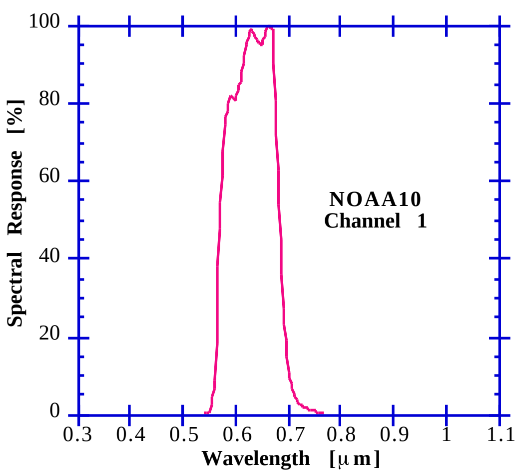


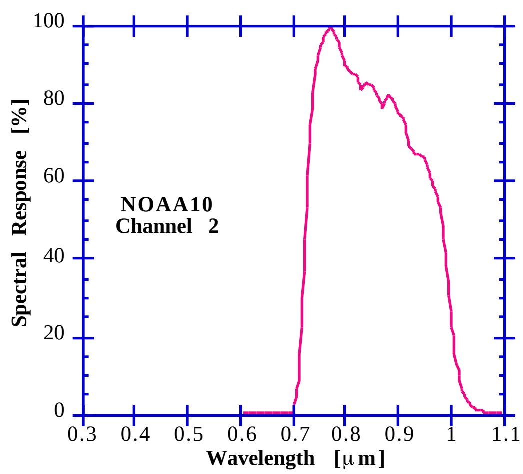

NOAA8
Channel 1
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

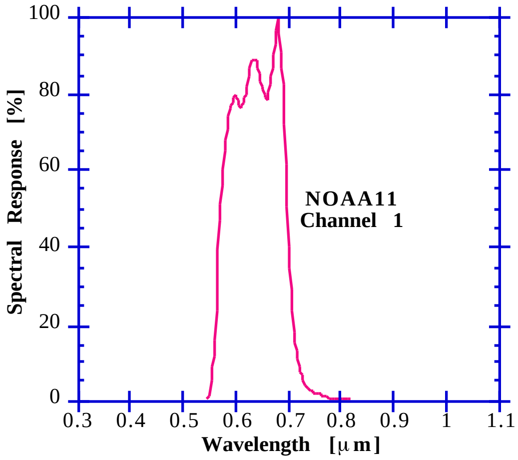

NOAA8
Channel 2
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

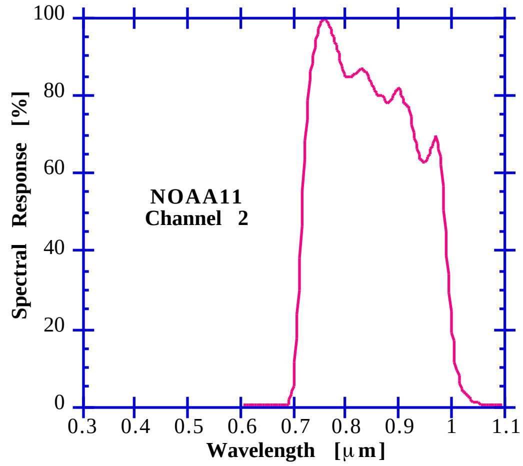

NOAA9
Channel 1
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

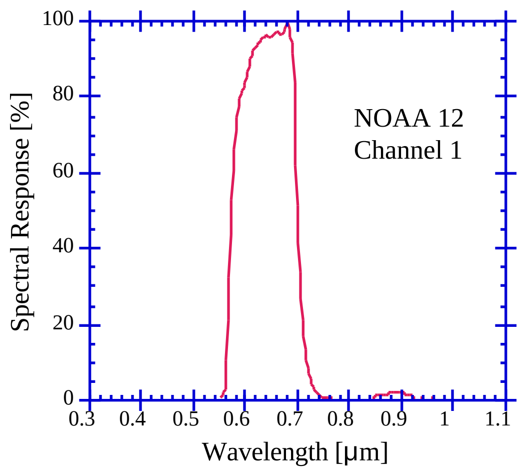

NOAA9
Channel 2
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

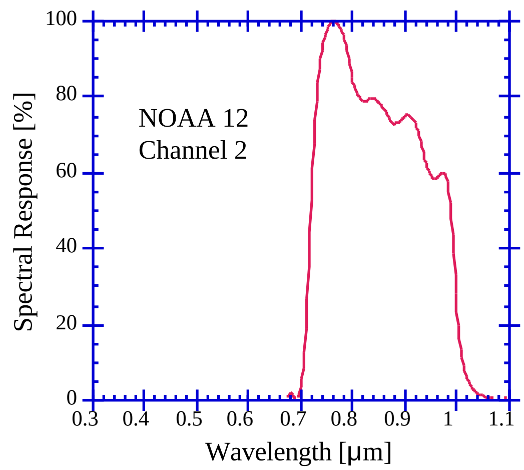

NOAA10
Channel 1
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

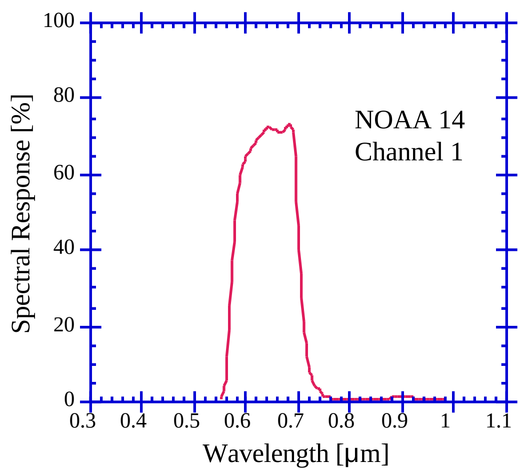

NOAA10
Channel 2
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

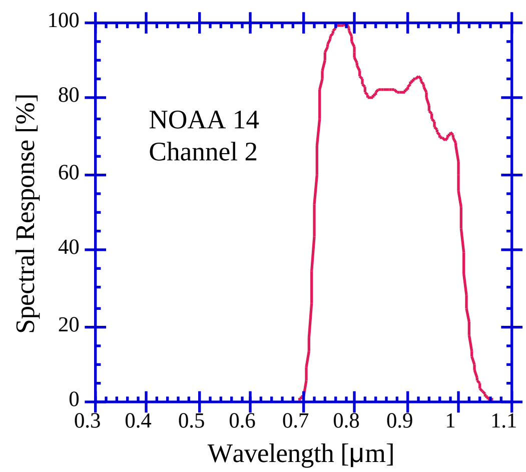

NOAA11
Channel 1
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1


NOAA11
Channel 2
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1


NOAA 12
Channel 1
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1


NOAA 12
Channel 2
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1


NOAA 14
Channel 1
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1


NOAA 14
Channel 2
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

References:

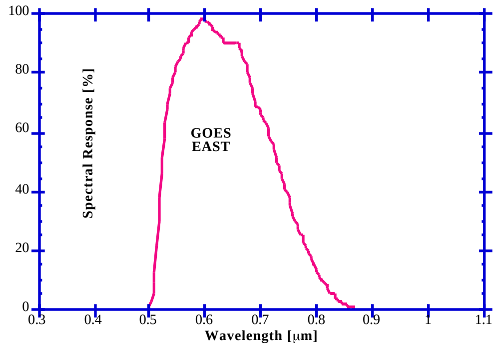
NOAA POLAR ORBITER DATA USERS GUIDE, (1985) U.S. Dept. of Commerce, NOAA, National Environment Satellite, National Climatic Data Center, Satellite Data Service Division, World Weather Building, Room 100, Washington D.C., 202333, U.S.A.

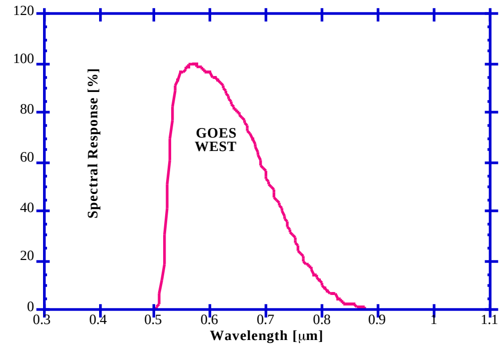
DUE C.T., 1982, Optical-Mechanical Active/passive imaging Systems - Volume II, Report number 153200-2-TIII- ERIM Infrared information and Analysis Center, P.O. BOX 8518, Ann. Arbor., MI.98107.

SCHNEIDER S.R. and Mc GINNIS D.F., 1982, The NOAA/AVHRR: A new satellite sensor for monitoring crop growth, Proc. 8th Inter. Symp.on Machine Processing of Remotely Sensed data, Purdue University, Indiana, p. 250-281.

SUBROUTINE GOES

Function: To read the visible spectral bands of the Visible Infrared Spin-Scan Radiometer (VISSR) on GOES 5 (East) and GOES 4 (West), (extreme wavelengths and spectral response of the filter function).





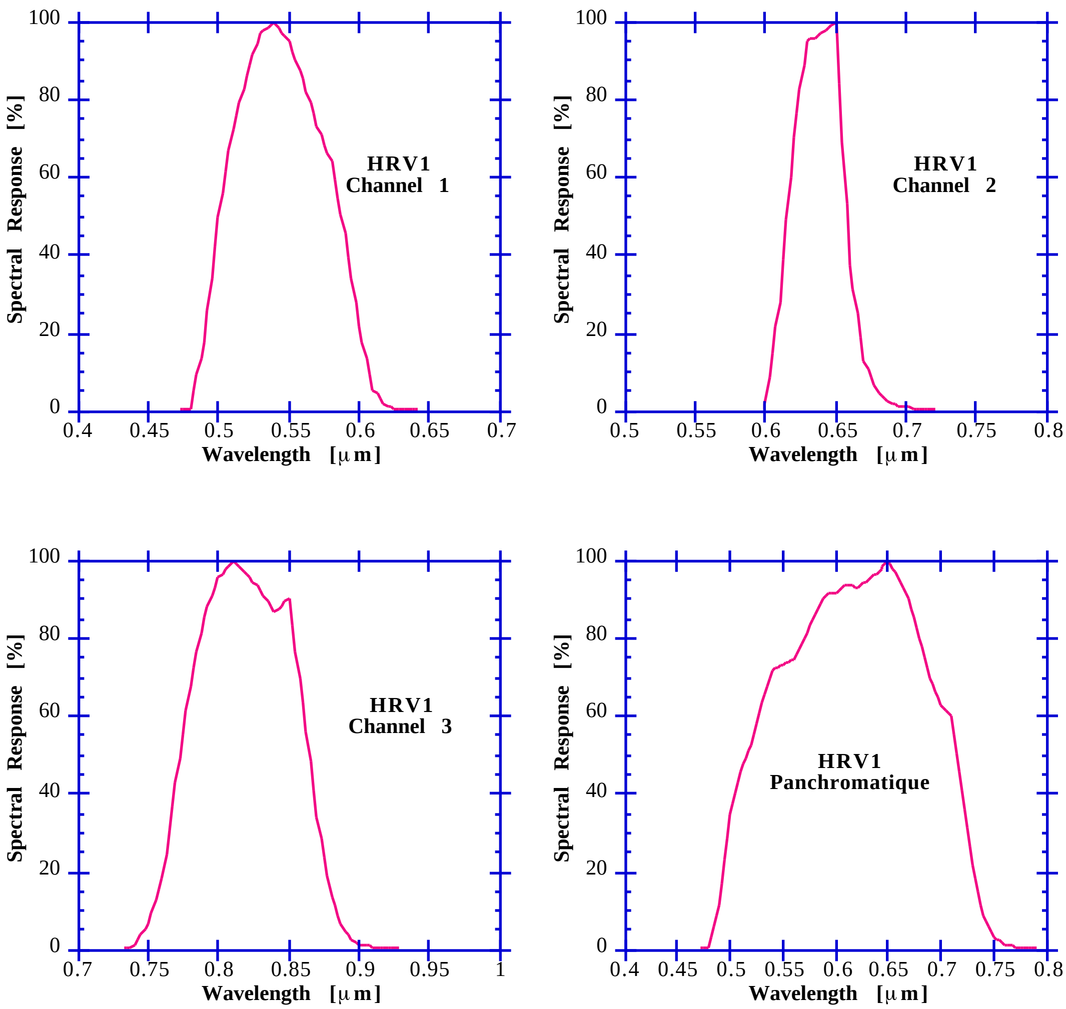
References:

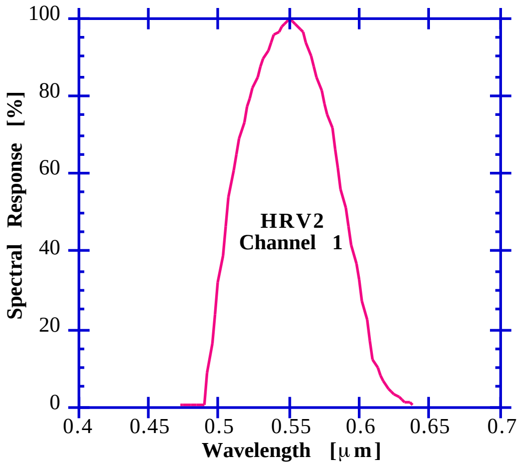
STAFF MEMBERS, 1980, Visible infrared Spin Scan Radiometer Atmospheric sounder system description, Santa Barbara Research center, Goleta, Cali., U.S.A.

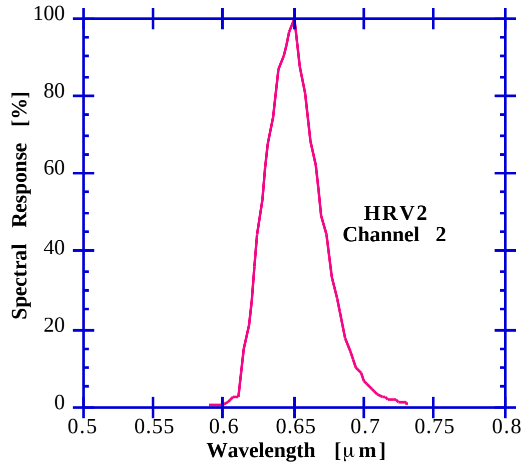
CORBELL R.P., C.J. CULLAHAN and W.J. KOTSCH, 1976, The GOES/SMS user's Guide: U.S. Dept. of Commerce, NOAA, NESS, Washington D.C., U.S.A.

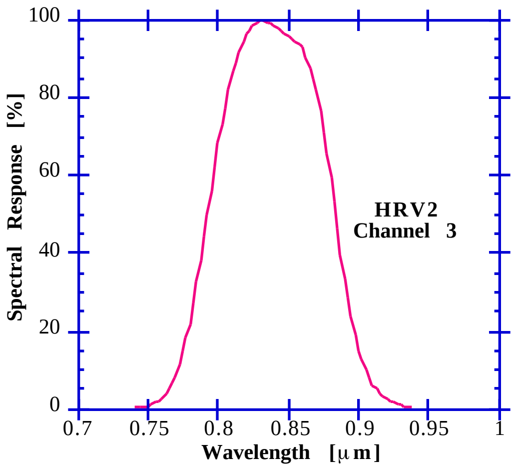
SUBROUTINE HRV

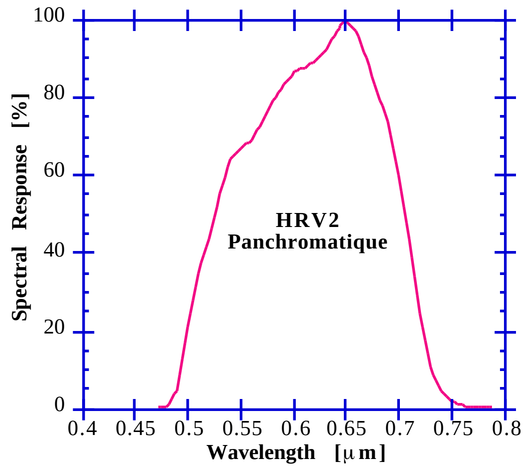
Function: To read the four spectral bands of High Resolution Visible (HRV1 and 2) on Spot 1 (extreme wavelengths and spectral response of the filter function).









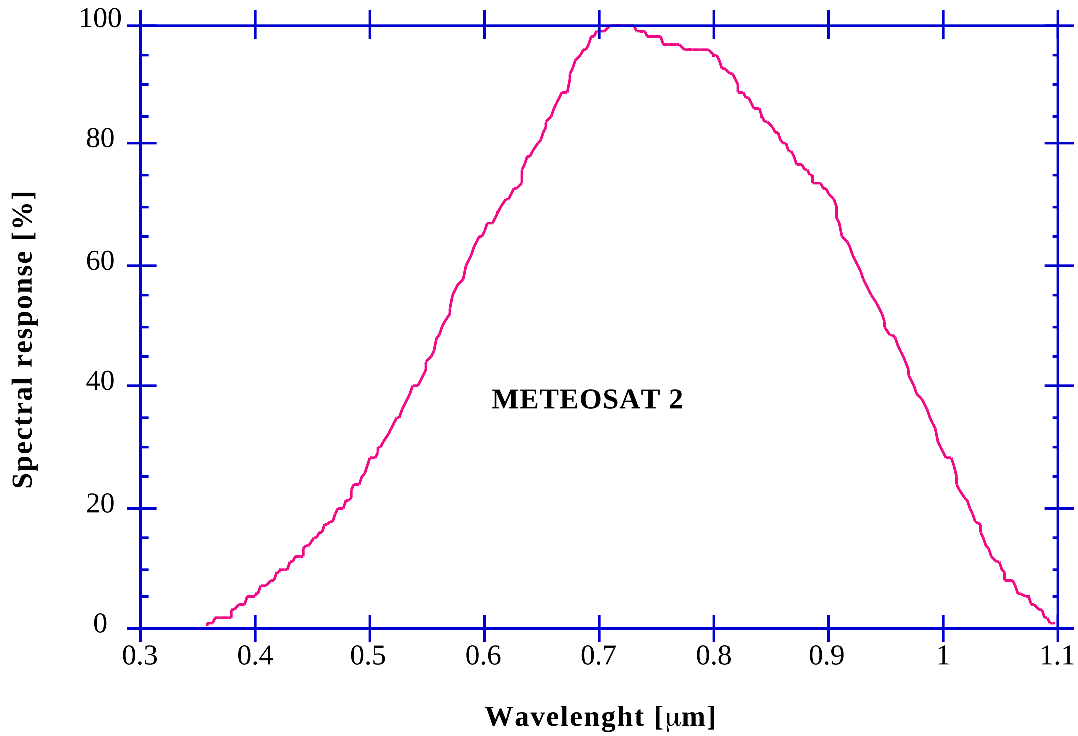


Reference:

CHEVREL M., M. COURTOIS, and G. WEILL, 1981, The Spot Satellite Remote Sensing Mission Photogrammetric Engineering and Remote Sensing, Vol. 47, no 8, p. 1163-1171.

SUBROUTINE METEO

Function: To read the visible spectral band of the radiometer on Meteosat 2 (extreme wavelengths and spectral response of the filter function).

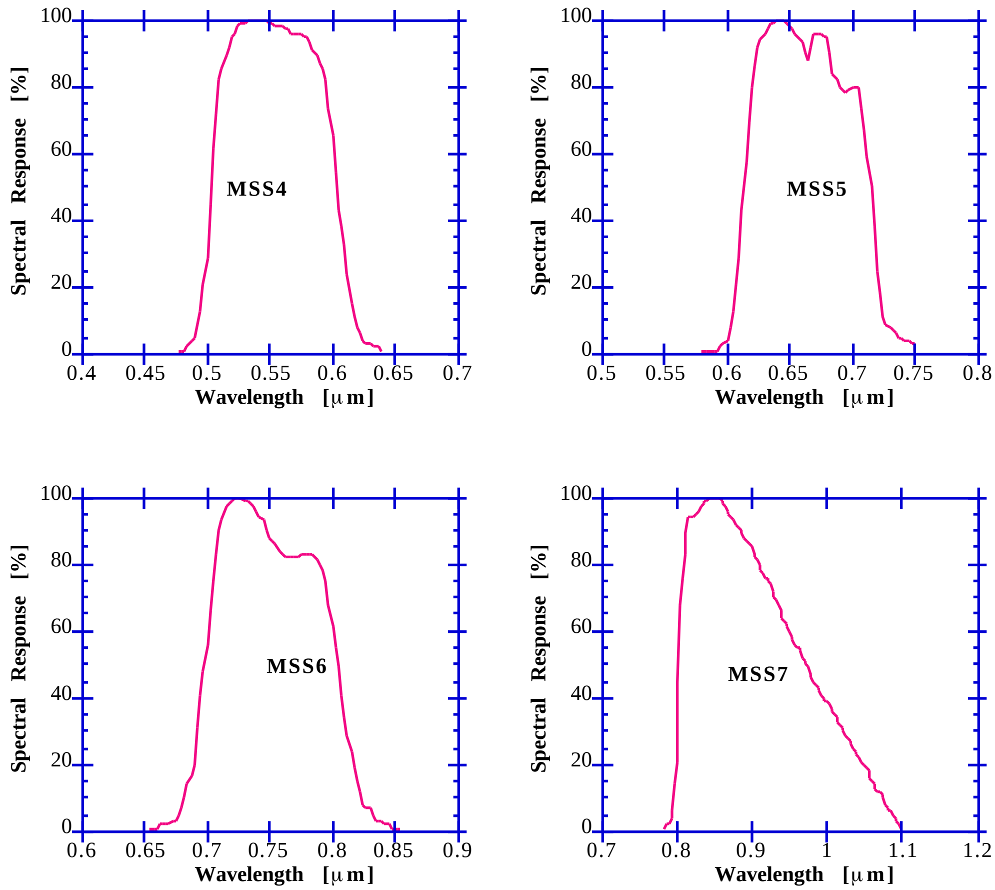


Reference:

MORGAN, 1981, Introduction to the Meteosat System, *ESOC, Darmstadt, R.F.A.*

SUBROUTINE MSS

Function: To read the four spectral bands of the Multispectral Scanner System (MSS) on Landsat 5 (extreme wavelengths and spectral response of the filter function).



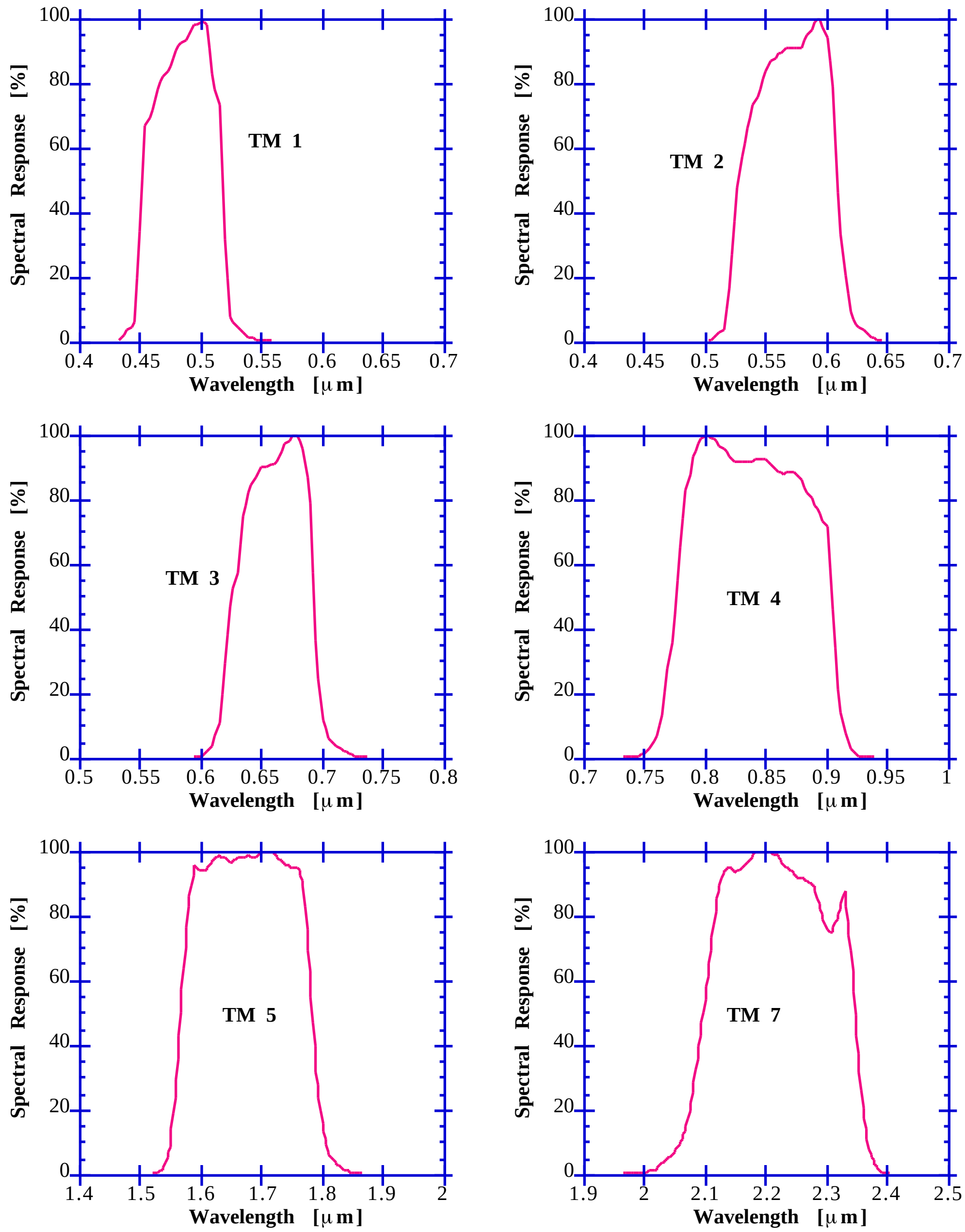
References:

LANDSAT DATA USERS HANDBOOK (revised) (1979), U.S. Geol. Survey, EROS Data Center, Sioux Falls, SD 57198.

LANDSAT DATA USERS NOTES (1982), International Land Satellite programs, ibid.

SUBROUTINE TM

Function: To read the six visible spectral bands of Thematic Mapper (TM) on Landsat 5 (extreme wavelengths and spectral response of the filter function).

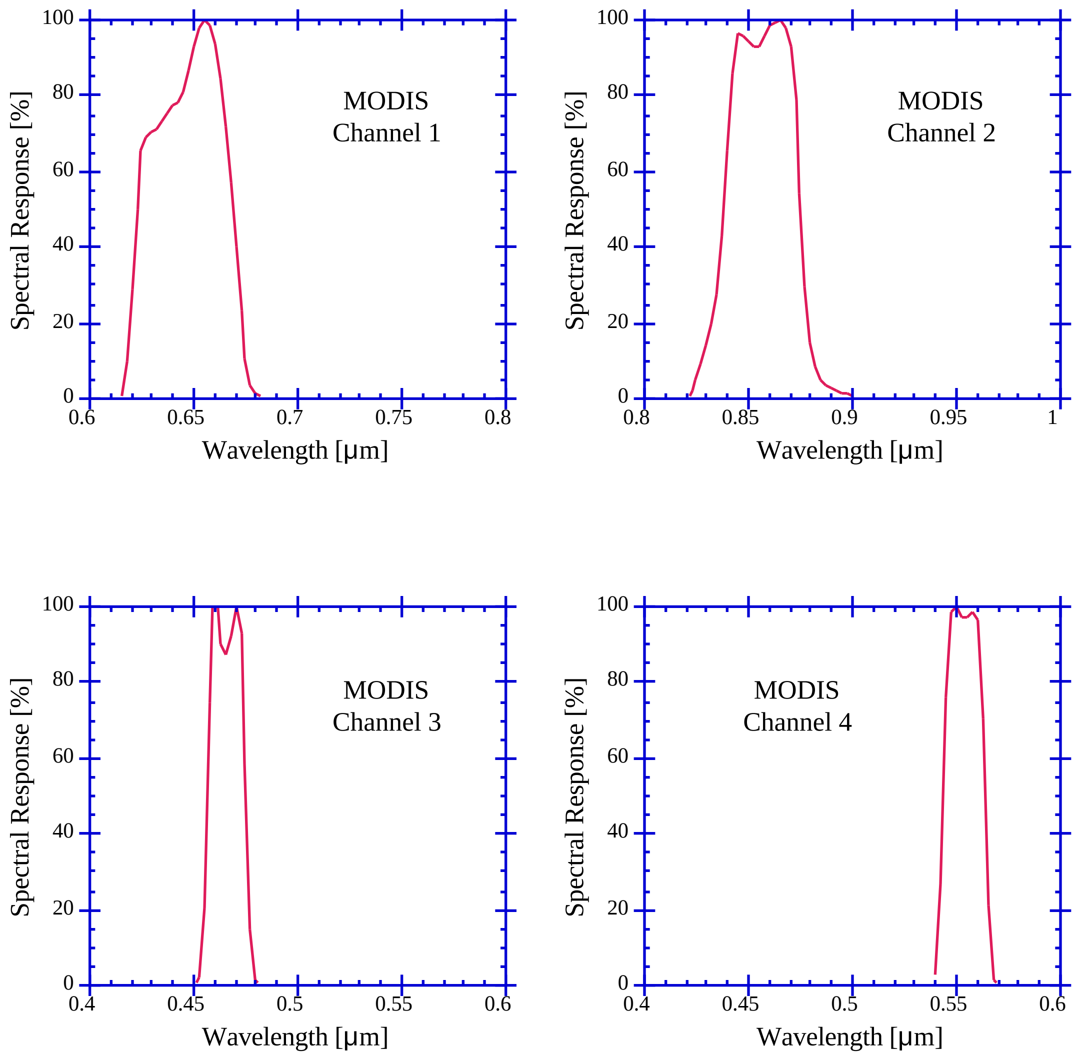


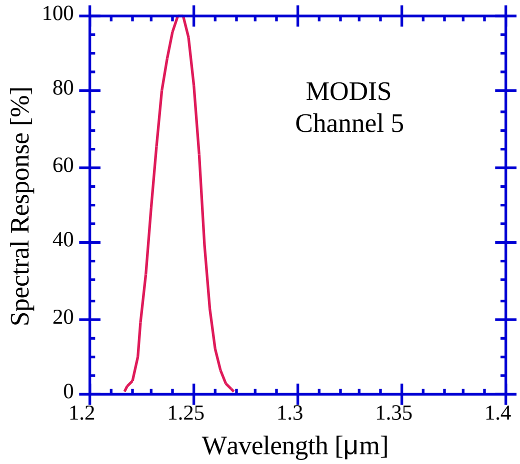
Reference:

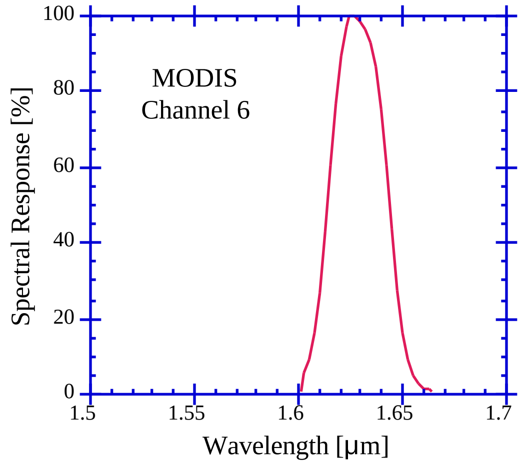
MARKHAM B.L. and J.L. BARKER, 1985, Spectral Characterization of the LANDSAT thematic Mapper sensors, Int. J. Remote Sensing

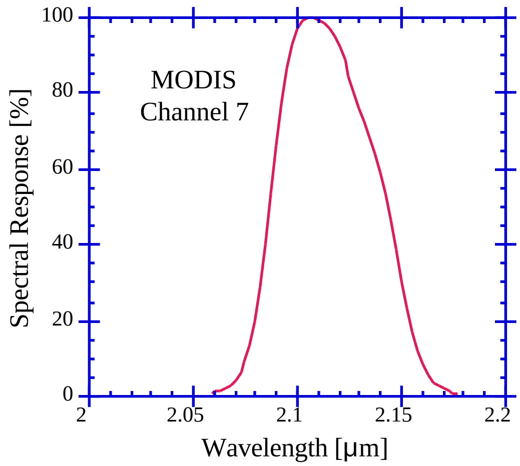
SUBROUTINE MODIS

Function: To read the seven first visible and near-infrared spectral bands of MODIS (MODerate resolution Imaging Spectroradiometer) scheduled for launch on Earth Observing System (EOS) spacecraft in June 1998 (extreme wavelengths and spectral response of the filter function).




MODIS
Channel 5
Spectral Response [%]
Wavelength [µm]
100
80
60
40
20
0
1.2
1.25
1.3
1.35
1.4

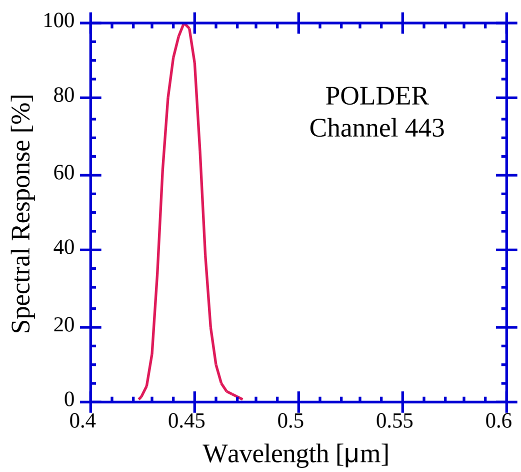

MODIS
Channel 6
Spectral Response [%]
Wavelength [µm]
100
80
60
40
20
0
1.5
1.55
1.6
1.65
1.7

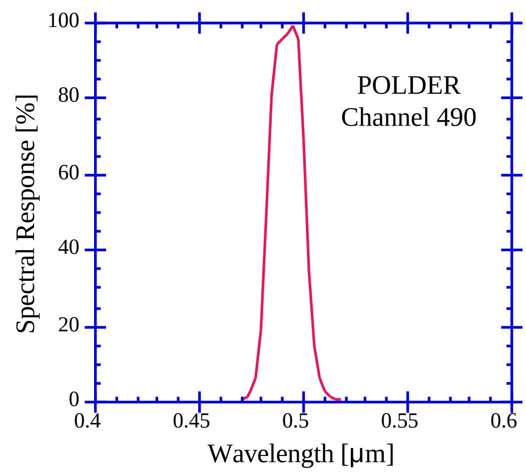

MODIS
Channel 7
Spectral Response [%]
Wavelength [µm]
100
80
60
40
20
0
2
2.05
2.1
2.15
2.2

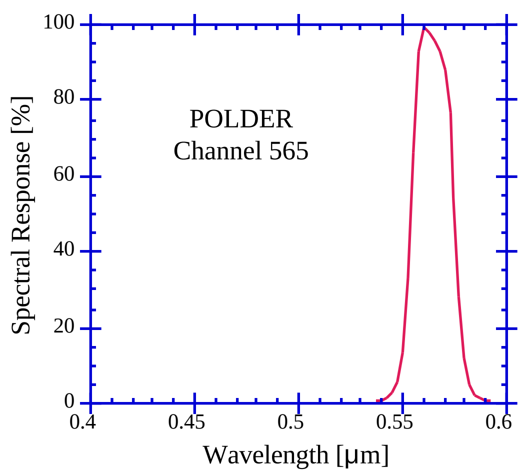
References:

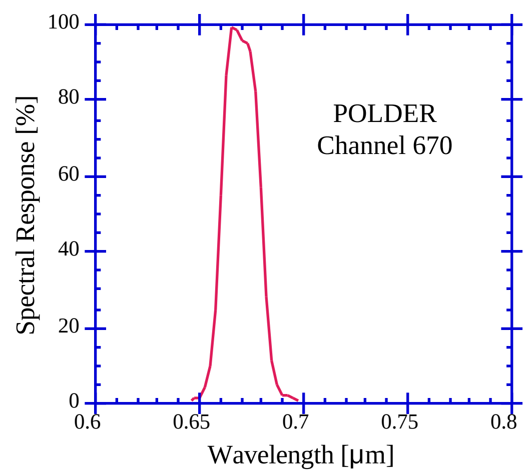
SUBROUTINE POLDER

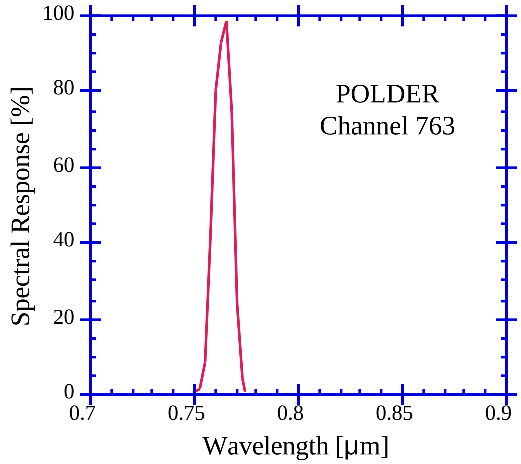
Function: To read the eight visible and near-infrared spectral bands of POLDER (POLarization and Directionality of Earth's Reflectances) on ADEOS (Advanced Earth Observing Satellite) (extreme wavelengths and spectral response of the filter function). For the spectral bands with polarization measurements (0.443, 0.670 and 0.865 µm), only one spectral response is tabulated.

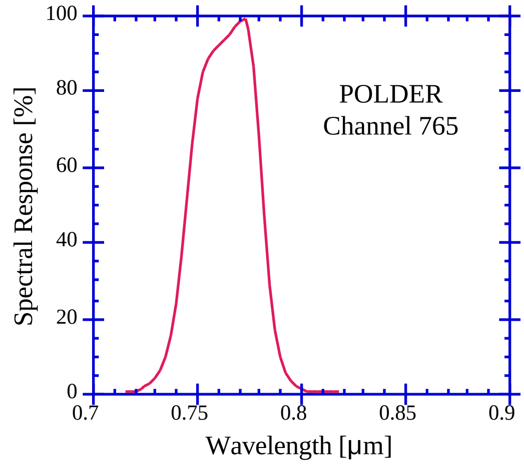


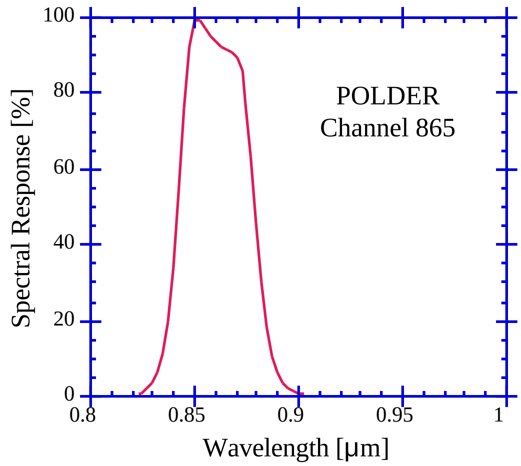


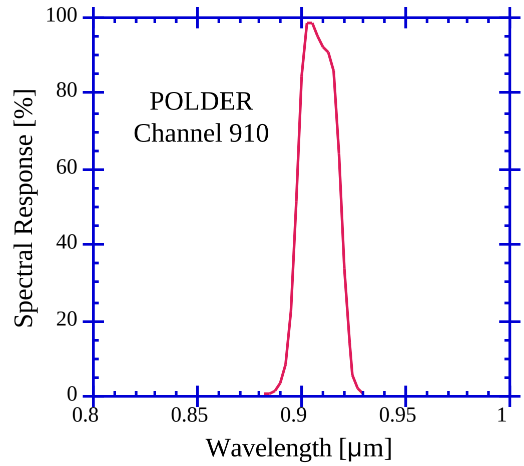





POLDER
Channel 763
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.7
0.75
0.8
0.85
0.9


POLDER
Channel 765
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.7
0.75
0.8
0.85
0.9

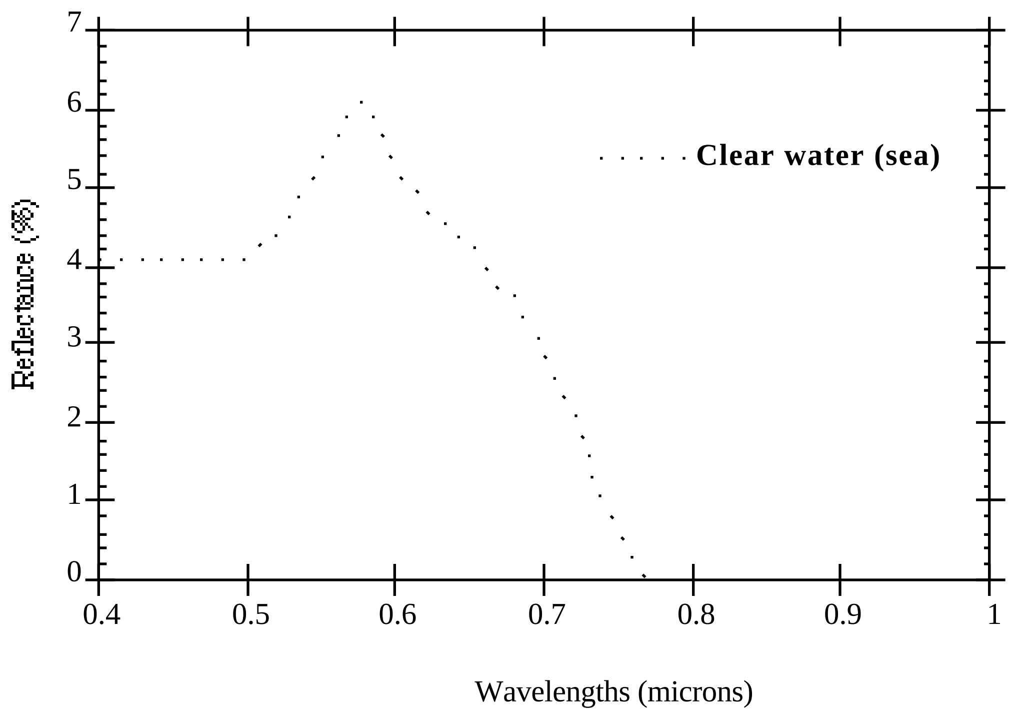

POLDER
Channel 865
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.8
0.85
0.9
0.95
1


POLDER
Channel 910
Spectral Response [%]
Wavelength [µm]
0
20
40
60
80
100
0.8
0.85
0.9
0.95
1

References:

SUBROUTINE CLEARW

Function: To read a typical spectral reflectance of clear water (sea) from 250 to 4000 *nm* by steps of 2.5 *nm*.

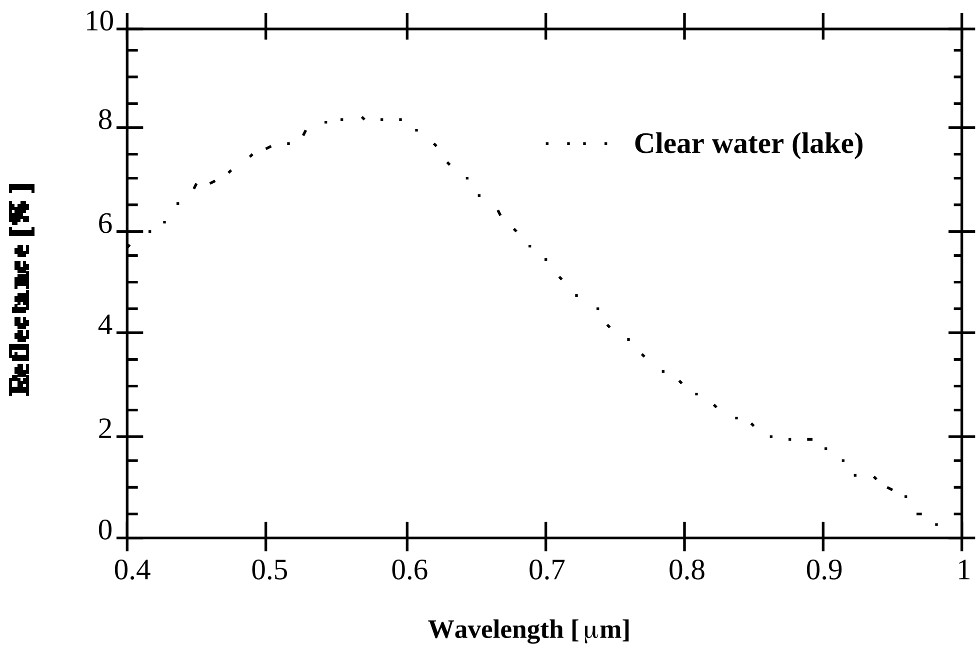


Reference:

M. VIOLLIER, Télédétection des concentrations de seston et pigments chlorophylliens contenus dans l'Océan, *Thèse de Doctorat d'Etat, no 503*, 1980.

SUBROUTINE LAKEW

Function: To read a typical spectral reflectance of water (lake) from 250 to 4000 *nm* by steps of 2.5 *nm*.

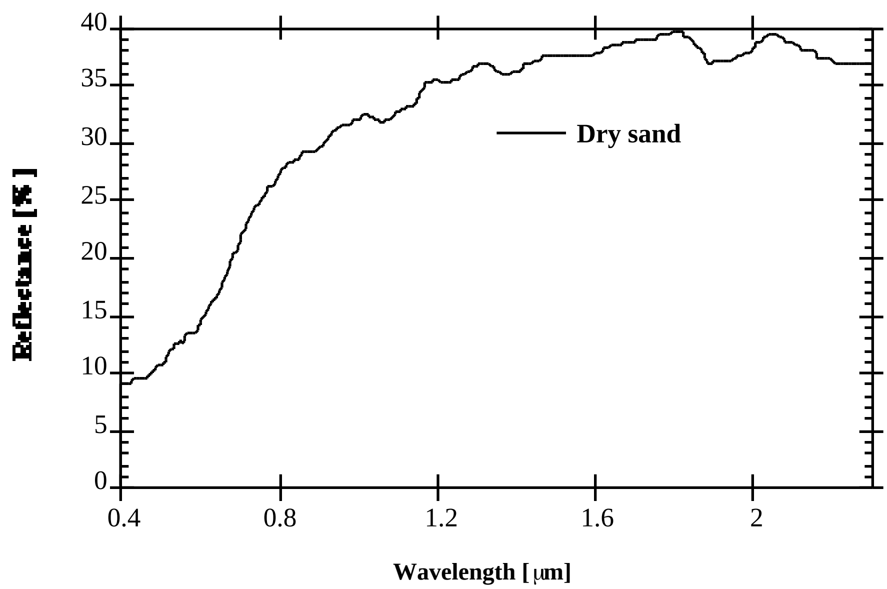


Reference:

KONDRATYEV K. Ya (1969), Radiation in the atmosphere, *Academic Press*, N.Y. 10003, U.S.A.

SUBROUTINE SAND

Function: To read a typical spectral reflectance of sand from 250 to 4000 nm by steps of 2.5 *nm*.

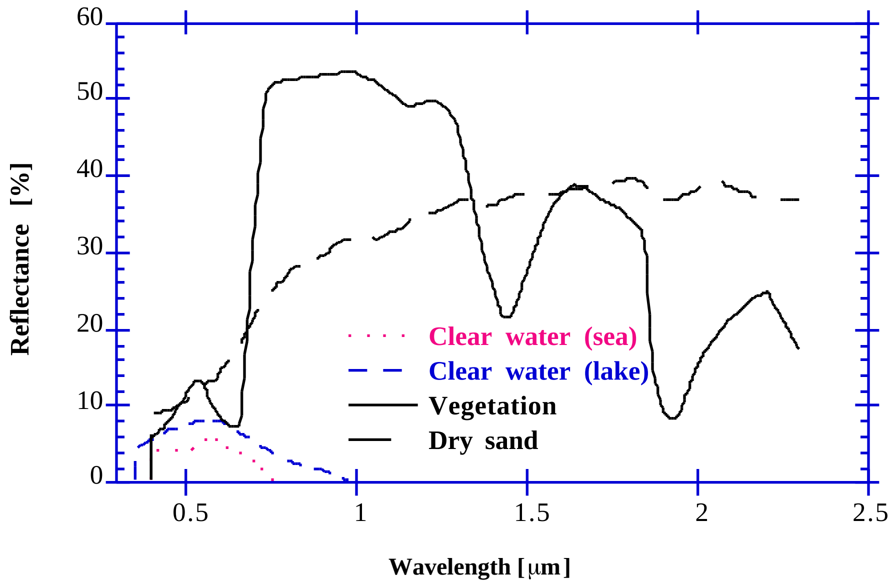


Reference:

R. STAETTER, M. SCHROEDER, Spectral characteristics of natural surfaces, *Proceeding of ten Int. Conf. on Earth Obs. from Space*, 6-11 March 1978, (ESA-SP, 134).

SUBROUTINE VEGETA

Function: To read a typical spectral reflectance of a mean green vegetation surface from 250 to 4000 nm by steps of 2.5 nm.



Reference:

Manual of Remote Sensing, Falls Church, Virginia, American Society of Photogrammetry, 1983.

SUBROUTINE DICA1

Function: To read the eight coefficients necessary to compute the CO_2 transmission according to the Malkmus model (see the text). The frequency interval is 2500-5050 cm^{-1}, step of 10 cm^{-1}.

SUBROUTINE DICA2

Function: Same as DICA1 but for frequency interval 5060-7610 cm^{-1}.

SUBROUTINE DICA3

Function: Same as DICA1 but for frequency interval 7620-10170 cm^{-1}.

SUBROUTINE METH1

Function: To read the eight coefficients necessary to compute the methane transmission according to the Malkmus model (see the text). The frequency interval is 2500-5050 cm^{-1}, step of 10 cm^{-1}.

SUBROUTINE METH2

Function: Same as METH1 but for frequency interval 5060-7610 cm^{-1}.

SUBROUTINE METH3

Function: Same as METH1 but for frequency interval 7620-10170 cm^{-1}.

SUBROUTINE METH4

Function: Same as METH1 but for frequency interval 10180-12730 cm^{-1}.

SUBROUTINE METH5

Function: Same as METH1 but for frequency interval 12740-15290 cm^{-1}.

SUBROUTINE METH6

Function: Same as METH1 but for frequency interval 15300-17870 cm^{-1}.

SUBROUTINE MOCA1

Function: To read the eight coefficients necessary to compute the CO transmission according to the Malkmus model (see the text). The frequency interval is 2500-5050 cm^{-1}, step of 10 cm^{-1}.

SUBROUTINE MOCA2

Function: Same as MOCA1 but for frequency interval 5060-7610 cm^{-1}.

SUBROUTINE MOCA3

Function: Same as MOCA1 but for frequency interval 7620-10170 cm^{-1}.

SUBROUTINE MOCA4

Function: Same as MOCA1 but for frequency interval 10180-12730 cm^{-1}.

SUBROUTINE MOCA5

Function: Same as MOCA1 but for frequency interval 12740-15290 cm^{-1}.

SUBROUTINE MOCA6

Function: Same as MOCA1 but for frequency interval 15300-17870 cm^{-1}.

SUBROUTINE NIOX1

Function: To read the eight coefficients necessary to compute the nitrous oxyde transmission according to the Malkmus model (see the text). The frequency interval is 2500-5050 cm^{-1}, step of 10 cm^{-1}.

SUBROUTINE NIOX2

Function: Same as NIOX1 but for frequency interval 5060-7610 cm^{-1}.

SUBROUTINE NIOX3

Function: Same as NIOX1 but for frequency interval 7620-10170 cm^{-1}.

SUBROUTINE NIOX4

Function: Same as NIOX1 but for frequency interval 10180-12730 cm^{-1}.

SUBROUTINE NIOX5

Function: Same as NIOX1 but for frequency interval 12740-15290 cm^{-1}.

SUBROUTINE NIOX6

Function: Same as NIOX1 but for frequency interval 15300-17870 cm^{-1}.

SUBROUTINE OXYG3

Function: To read the eight coefficients necessary to compute the O_2 transmission according to the Malkmus model (see the text). The frequency interval is 2500-5050 cm^{-1}, step of 10 cm^{-1}.

SUBROUTINE OXYG4

Function: Same as OXYG3 but for frequency interval 10180-12730 cm^{-1}.

SUBROUTINE OXYG5

Function: Same as OXYG3 but for frequency interval 12740-15290 cm^{-1}.

SUBROUTINE OXYG6

Function: Same as OXYG3 but for frequency interval 15300-17870 cm^{-1}.

SUBROUTINE OZON 1

Function: To read the eight coefficients necessary to compute the O_3 transmission according to the Malkmus Model (see the text). The frequency interval is 2500-5050 cm^{-1}, steps of 10 cm^{-1}.

SUBROUTINE WAVA1

Function: To read the eight coefficients necessary to compute the H_2O transmission according to the Goody Model (see the text). The frequency interval is 2500-5050 cm^{-1}, steps of 10 cm^{-1}.

SUBROUTINE WAVA2

Function: Same as WAVA1 but for frequency interval 5060-7610 cm^{-1}.

SUBROUTINE WAVA3

Function: Same as WAVA1 but for frequency interval 7620-10170 cm^{-1}.

SUBROUTINE WAVA4

Function: Same as WAVA1 but for frequency interval 10180-12730 cm^{-1}.

SUBROUTINE WAVA5

Function: Same as WAVA1 but for frequency interval 12740-15290 cm^{-1}.

SUBROUTINE WAVA6

Function: Same as WAVA1 but for frequency interval 15300-17860 cm^{-1}.

SUBROUTINE DUST

Function: To read the scattering phase function for the Dust-Like component. Computations have been performed for 83 phase angles (80 Gauss Angles and 0°, 90°, 180°) and 10 wavelengths, 0.400, 0.515, 0.550, 0.633, 0.694, 0.860, 1.536, 2.250, 3.750 μm.

SUBROUTINE OCEA

Function: Same as DUST but for the oceanic component.

SUBROUTINE SOOT

Function: Same as DUST but for the soot component.

SUBROUTINE WATE

Function: Same as DUST but for the water-soluble component.

SUBROUTINE BBM

Function: Same as DUST but for biomass burning model.

SUBROUTINE BDM

Function: Same as DUST but for desertic background model.

SUBROUTINE STM

Function: Same as DUST but for stratospheric model.

Reference:

R.A. Mc CLATCHEY, M.J. BOLLE, K.Ya. KONDRATYEV, "A preliminary cloudless standard atmosphere for radiation computation", Boulder, Colorado, U.S.A. (1982).

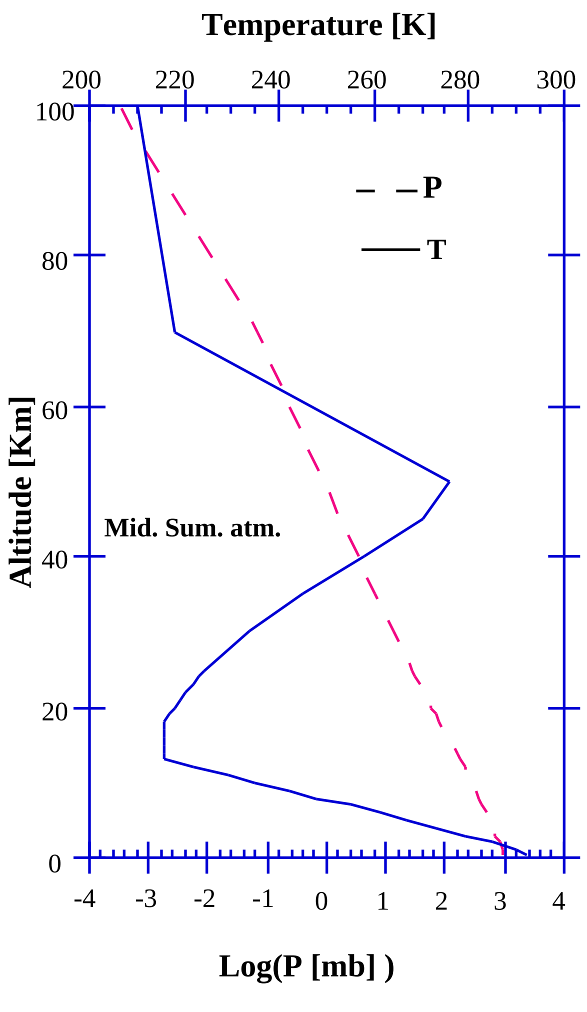
E. P. SHETTLE, Optical and radiative properties of a desert aerosol model. *Symposium of Radiation in the atmosphere,* 1 Deepak publishing), pp. 74-77, 1984.

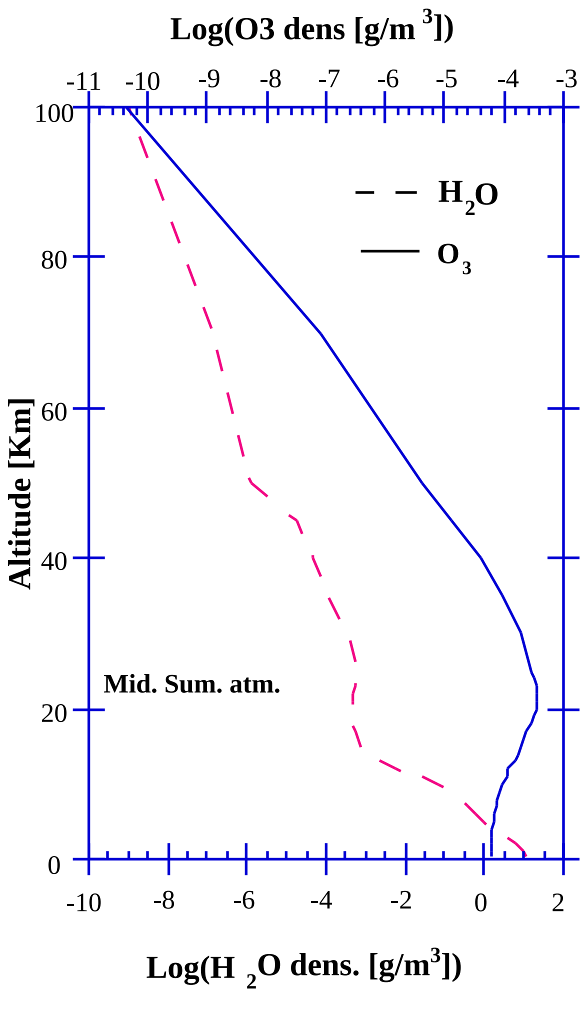
M. KING, HARSHVARDHAN, and ARKING, A, A model of the Radiative Properties of the El Chichon Stratospheric Aerosol Layer, *J. Appl. Meteor.*, 23, (7), pp. 1121-1137, 1984.

SUBROUTINE MIDSUM

Function: To read the midlatitude summer model atmosphere, i.e.pressure (*mb*), temperature (*K*), water vapor and ozone concentrations (g/m^3) as a function of the altitude (34 levels)

- $Z = 1$ *km* for $0 < Z_{km} < 25$
- $Z = 5$ *km* for $25 < Z_{km} < 50$
- $Z = 70$, 100 *km* and ∞ (p = 0).





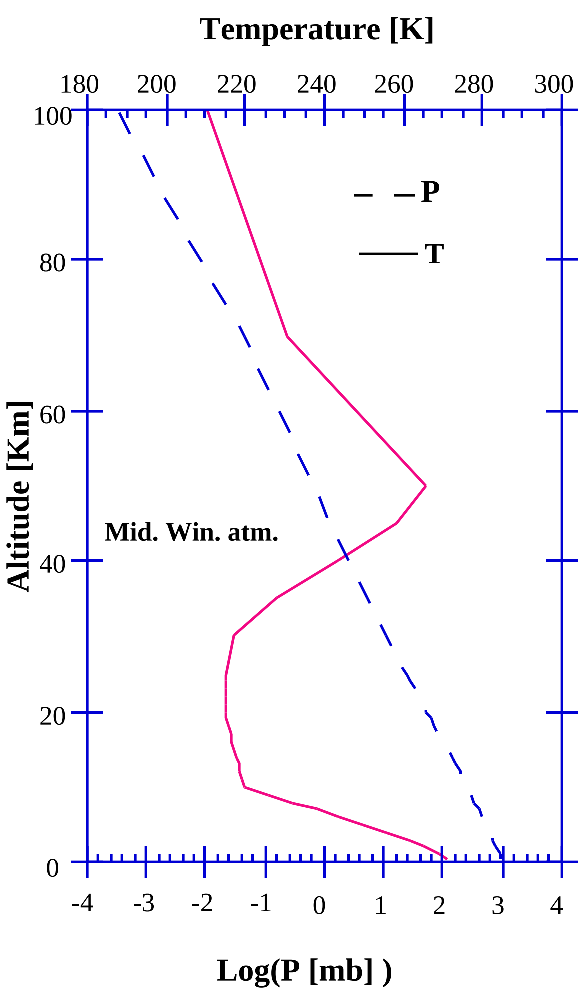
Reference:

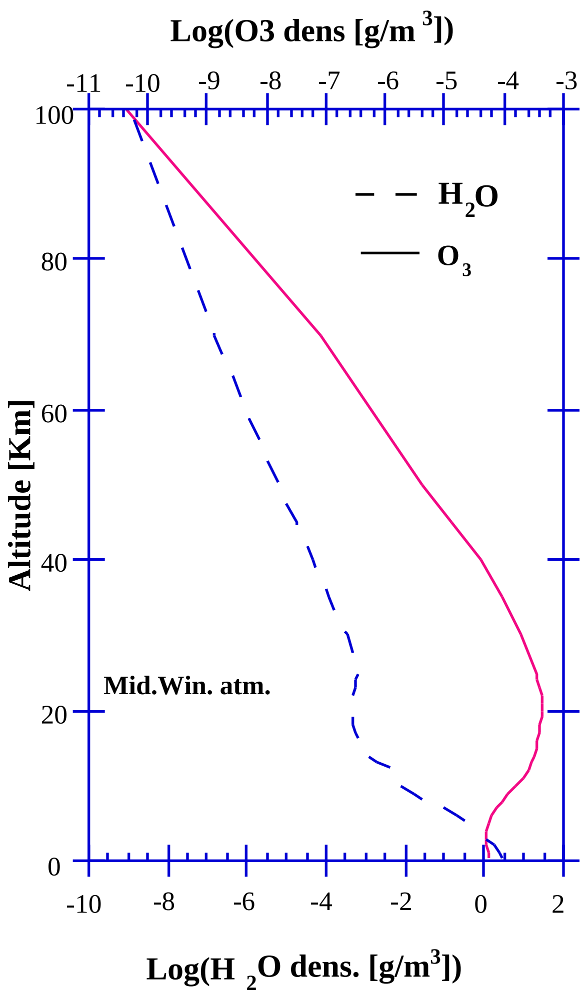
Mc CLATCHEY R.A., FENN R.W., SELBY J.E.A., VOLZ F.E.and GARING J.S., Optical properties of the Atmosphere, AFCRL-TR- 71-0279, Enviro. Research papers, No 354, L.G. HANCOM FIEL Bedford, Mass. U.S.A., 1971.

SUBROUTINE MIDWIN

Function: To read the midlatitude winter model atmosphere, i.e., pressure (*mb*), temperature (*K*), water vapor and ozone concentrations (g/m^3) as a function of the altitude (34 levels)

- $Z = 1\ km$ for $0 < Z_{km} < 25$
- $Z = 5\ km$ for $25 < Z_{km} < 50$
- $Z = 70, 100\ km$ and ∞ (p = 0).



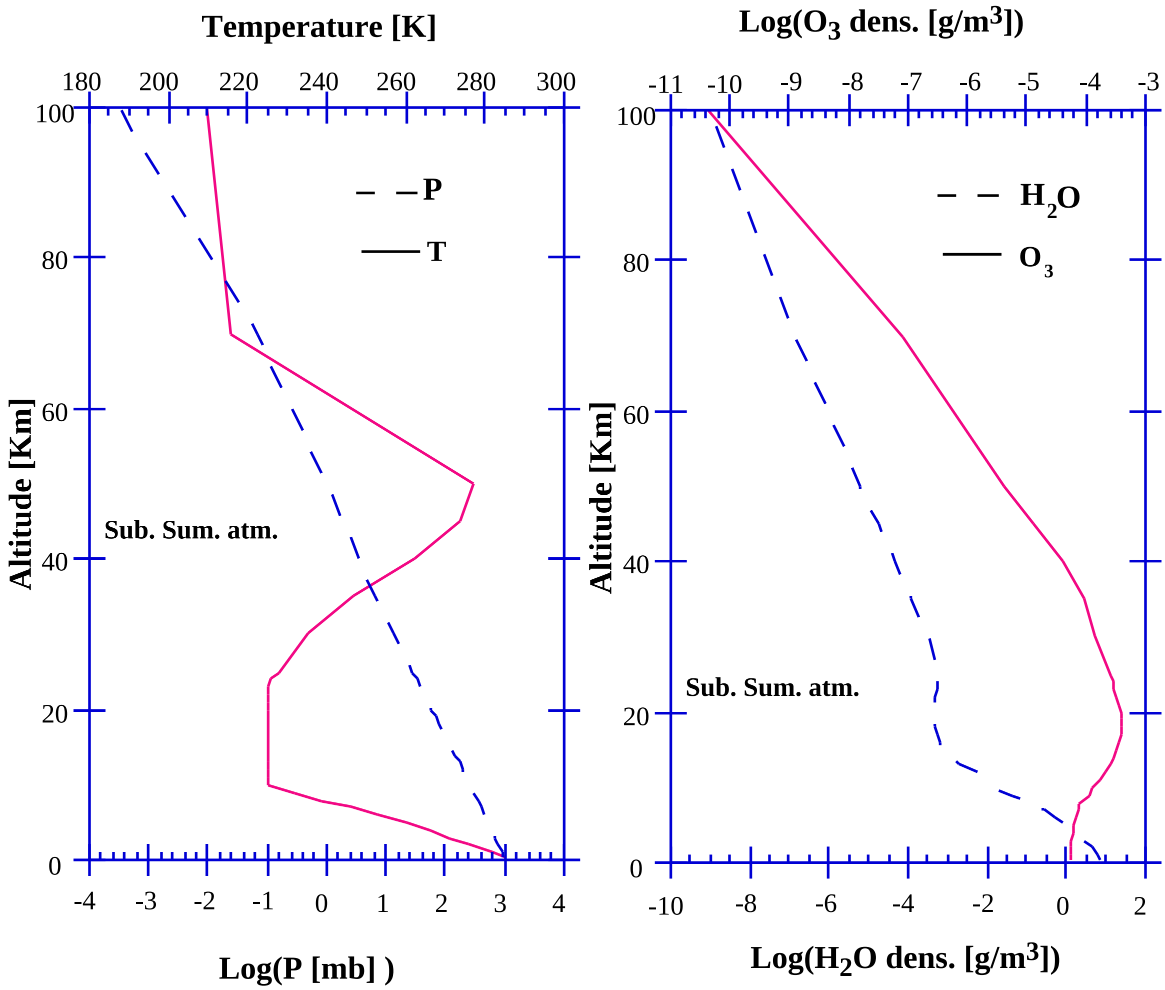


Mc CLATCHEY R.A., FENN R.W., SELBY J.E.A., VOLZ F.E.and GARING J.S., Optical properties of the Atmosphere, AFCRL-TR- 71-0279, *Enviro. Research papers*, No 354, L. G. HANCOM FIEL Bedford, Mass. U.S.A., 1971.

SUBROUTINE SUBSUM

Function: To read the subarctic summer model atmosphere, i.e., pressure (*mb*), temperature (*K*), water vapor and ozone concentrations (g/m^3) as a function of the altitude (34 levels)

• $Z = 1$ *km* for $0 < Z_{km} < 25$
• $Z = 5$ km for $25 < Z_{km} < 50$
• $Z = 70$, 100 *km* and ∞ (p = 0).



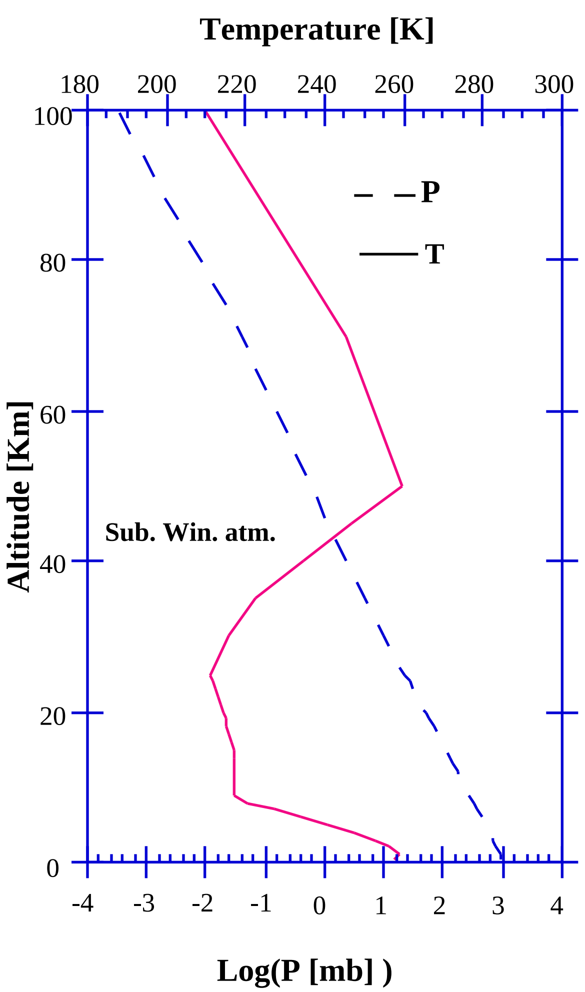
Reference:

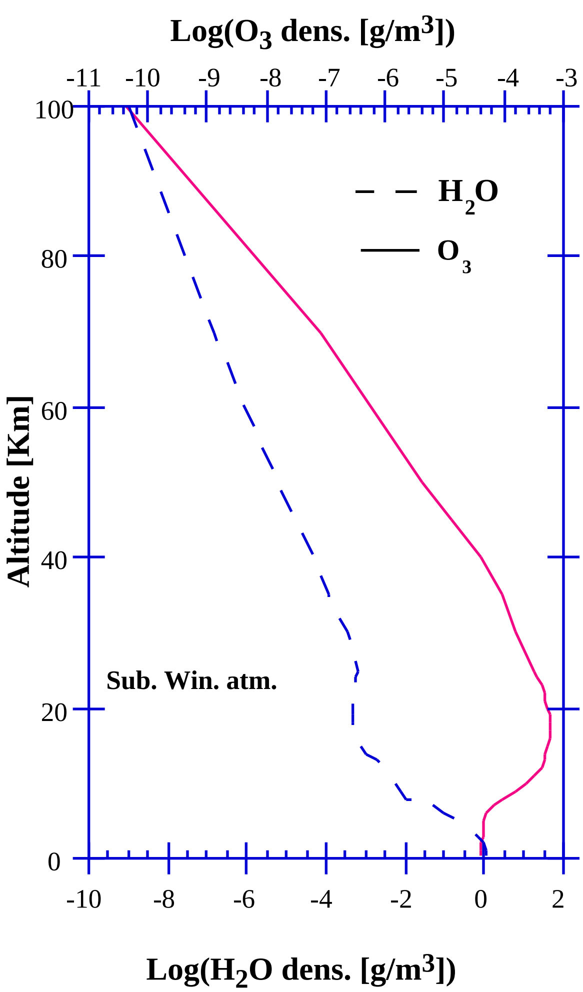
Mc CLATCHEY R.A., FENN R.W., SELBY J.E.A., VOLZ F.E. AFCRL-TR- 71-0279, *Enviro. Research papers*, No 354, L.G. HANCOM FIEL Bedford, Mass. U.S.A., 1971.

SUBROUTINE SUBWIN

Function: To read the subarctic model atmosphere, i.e., pressure (*mb*), temperature (*K*), water vapor and ozone concentrations (g/m^3) as a function of the altitude (34 levels)

- $Z = 1$ *km* for $0 < Z_{km} < 25$
- $Z = 5$ *km* for $25 < Z_{km} < 50$
- $Z = 70$, 100 *km* and ∞ (p = 0).





Reference:

Mc CLATCHEY R.A., FENN R.W., SELBY J.E.A., VOLZ F.E. and GARING J.S., Optical properties of the Atmosphere, *AFCRL-TR- 71-0279, Enviro. Research papers,* No 354, L.G. HANCOM FIEL Bedford, Mass. U.S.A., 1971.

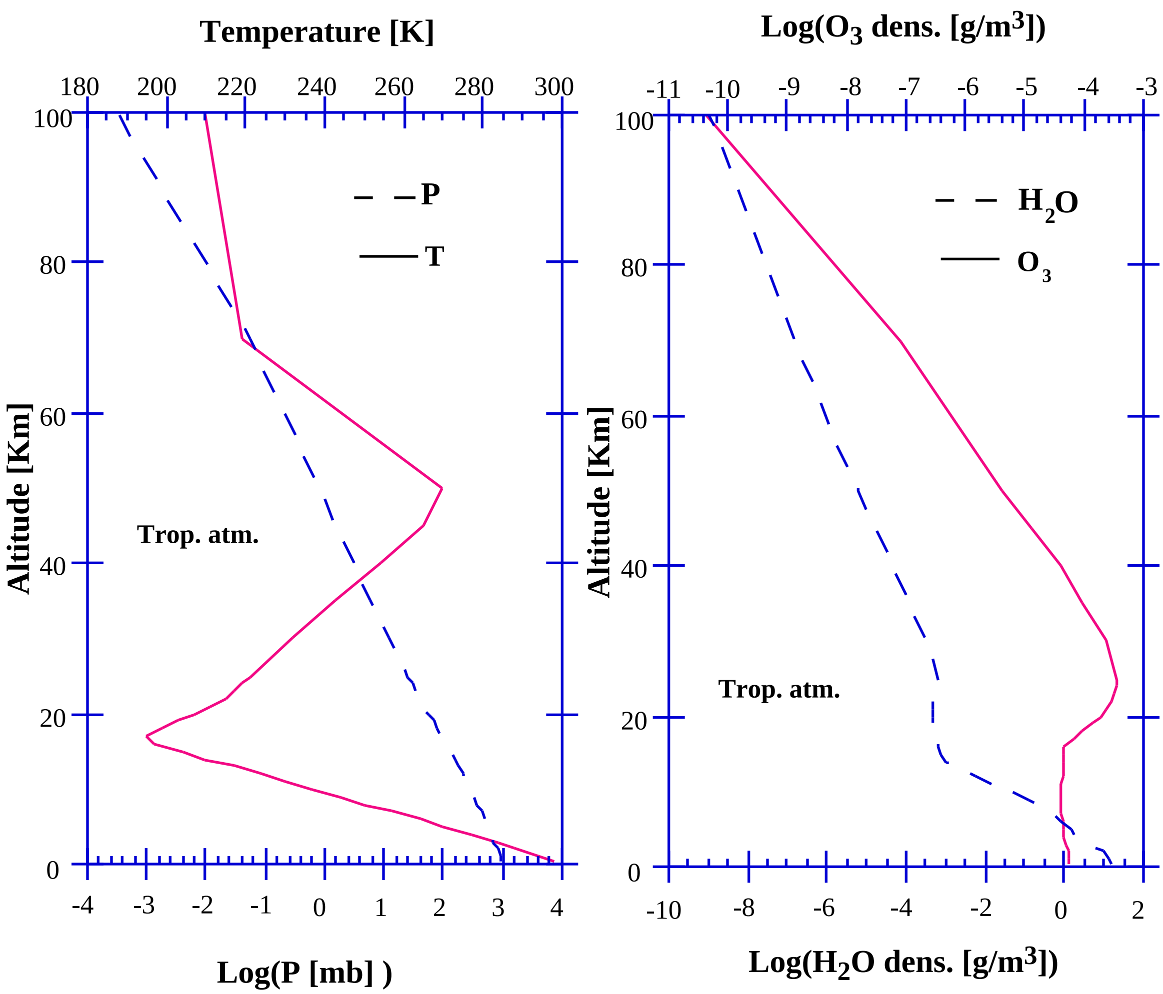
SUBROUTINE TROPIC

Function: To read the tropical model atmosphere, i.e., pressure (*mb*), temperature (*K*), water vapor and ozone concentrations (g/m^3) as a function of the altitude (34 levels)

• Z = 1 *km* for 0 < Z_{km} < 25

• Z = 5 km for 25 < Z_{km} < 50

• Z = 70, 100 *km* and ∞ (p = 0).



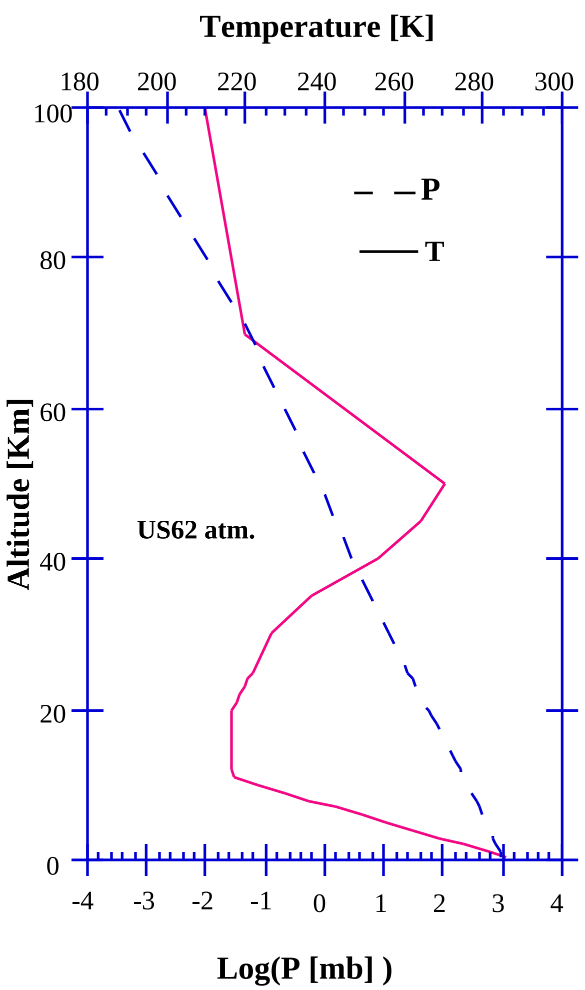
Reference:

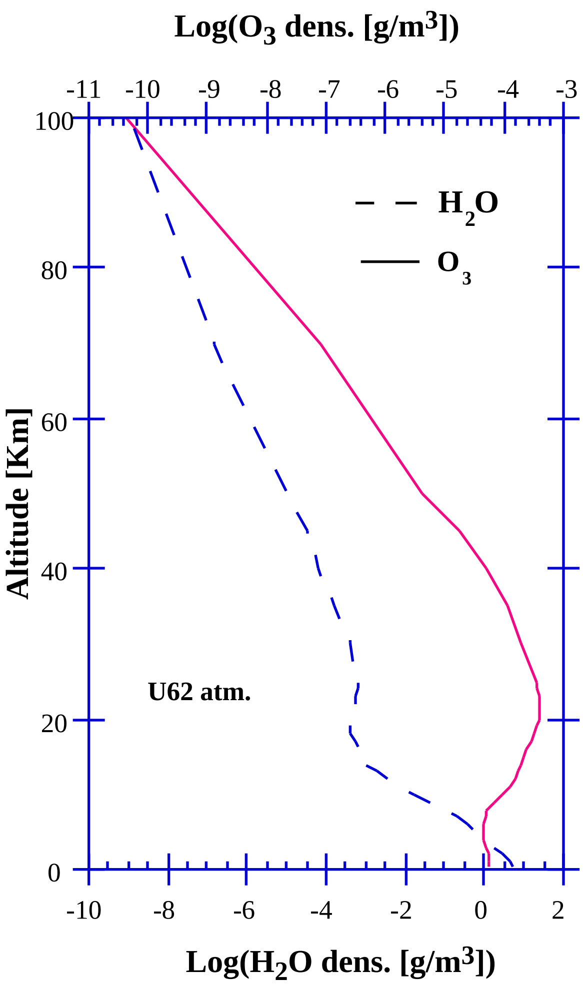
Mc CLATCHEY R.A., FENN R.W., SELBY J.E.A., VOLZ F.E.and GARING J.S., Optical properties of the Atmosphere, AFCRL-TR- 71-0279, *Enviro. Research papers*, No 354, L.G. HANCOM FIEL Bedford, Mass. U.S.A., 1971.

SUBROUTINE US 62

Function: To read the U.S. Standard Atmosphere, i.e., pressure (*mb*), temperature (*K*), water vapor and ozone concentrations (g/m^3) as a function of the altitude (34 levels)

- $Z = 1$ *km* for $0 < Z_{km} < 25$
- $Z = 5$ *km* for $25 < Z_{km} < 50$
- $Z = 70$, 100 *km* and ∞ (p = 0).





Reference:

Mc CLATCHEY R.A., FENN R.W., SELBY J.E.A., VOLZ F.E. and GARING J.S., Optical properties of the Atmosphere, AFCRL-TR- 71-0279, *Enviro. Research papers*, No 354, L.G. HANCOM FIEL Bedford, Mass. U.S.A., 1971.

MISCELLANEOUS

SUBROUTINE EQUIVWL

Function: To compute the equivalent wavelength needed for the calculation of the downward radiation field used in the computation of the non lambertian target contribution (main.f).

Description: The input is the spectral response of the selected sensor as well as the solar irradiance spectrum. The output is the equivalent wavelength which is computed by averaging the spectral response of the sensor over the solar irradiance using increment of 2.5nm,

SUBROUTINE PRINT_ERROR

Function: provide centralized error handling for the code and output specific error messages.

SUBROUTINE SPECINTERP

Function: To compute the atmospheric properties at the equivalent wavelength (see EQUIVWL.f) needed for the calculation of the downward radiation field used in the computation of the non lambertian target contribution (main.f).

Description: The input is the equivalent wavelength for which coupling between BRDF and atmosphere is to be computed. Using the actual aerosol model, the ouput are the atmospheric properties at this wavelength that is the aerosol optical thickness, the aerosol single scattering albedo and the aerosol phase function. In addition, this routine modifies the thickness and single scattering albedo of the aerosol layer below an aircraft.

SUBROUTINE SPLIE2,SPLIN2,SPLINE,SPLINT

Function: Perform interpolation of a furnished BDRF discrete dataset (BRDFGRID.f, option 1 of BRDF model) to compute the albedo ($\bar{\bar{\rho}}$) as well as the BRDF value at the gaussian quadrature points.