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An algorithm to restore spectral signatures of all inherent optical properties of seawater using a value of one property at one wavelength

Vladimir I. Haltrin

Naval Research Laboratory, Ocean Sciences Branch, Code 7331
Stennis Space Center, MS 39529-5004, USA, e-mail: <haltrin@nrlssc.navy.mil>

ABSTRACT

A one-parameter chlorophyll-based optical model of inherent optical properties of seawater is used to develop an algorithm to expresses the whole set of spectral inherent optical properties through the one optical parameter – the beam attenuation coefficient at one wavelength. This model is valid for the beam attenuation coefficient between 0 and 10 m^{-1} in visible part of spectrum (400-720 nm). The FORTRAN code to compute optical properties of seawater through a beam attenuation coefficient at one wavelength is released for public use.

Keywords: Ocean optics, inherent optical properties, scattering, absorption, seawater.

1.0 INTRODUCTION

This work is based on a one-parameter optical model of inherent sea optical properties presented previously at the Ocean Optics XIV meeting in Hawaii (Haltrin, 1998a). The one-parameter optical model expresses the whole set of spectral inherent optical properties, the absorption and scattering coefficients and the phase function of scattering, through one parameter – the concentration of chlorophyll. The model is valid for the values of chlorophyll concentration ranging from 0 to 12 $\mathrm{mg/m^3}$. The model was used to obtain values of inherent optical properties in the range of wavelengths between 400 and 720 nm over the range of chlorophyll concentrations cited. The resulting data sets were statistically processed to obtain wavelength-dependent regressions that couple different inherent optical properties with the beam attenuation coefficient.

2.0. MODEL OF SEAWATER OPTICAL PROPERTIES

All optical properties of seawater are divided into two groups: inherent optical properties and apparent optical properties. Inherent optical properties depend only on processes of absorption and single scattering in seawater. Apparent optical properties depend on inherent optical properties, geometry of illumination, and processes of transmission and reflection by the sea surface and sea bottom.

There are only two major inherent optical properties: the absorption coefficient a and the angular scattering coefficient $\beta(\vartheta)$ (which is a function of a scattering angle ϑ). All other inherent optical properties, the phase function of scattering $p(\vartheta) \equiv \beta(\vartheta)/b$, the scattering coefficient $b = 0.5\int_0^{\pi} \beta(\vartheta)\sin\vartheta\, d\vartheta$, the beam attenuation coefficient $c = a + b$, the single scattering albedo $\omega_0 = b/c$, the backscattering coefficient $b_B = 0.5\int_{\pi/2}^{\pi} \beta(\vartheta)\sin\vartheta\, d\vartheta$, the probability of backscattering $B = 0.5\int_{\pi/2}^{\pi} p(\vartheta)\sin\vartheta\, d\vartheta$, are derivatives of these two major inherent optical properties (Haltrin and

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Kattawar, 1993). The model presented here is based on timer-proven parts proposed by different researchers (See Refs. in Haltrin, 1998a).

The absorption coefficient $a(\lambda)$, (m^{-1}) is taken to be:

$$a(\lambda) = a_w(\lambda) + a_c^0(\lambda)\left(C_c/C_c^0\right)^{0.602} + a_f^0\, C_f \exp(-k_f\,\lambda) + a_h^0\, C_h \exp(-k_h\,\lambda)\,, \tag{1}$$

where $a_w(\lambda)$ is the pure water absorption coefficient in m^{-1}, λ is the wavelength of light in nm, $a_0^c(\lambda)$ is the specific absorption coefficient of chlorophyll in m^2/mg , C_c is the total concentration of chlorophyll in mg/m^3 $(C_c^0 = 1\,\mathrm{mg}/\mathrm{m}^3)$ (Prieur and Satyendranath, 1981), $a_f^0 = 35.959\,\mathrm{m}^2/\mathrm{mg}$ is the specific absorption coefficient of fulvic acid; $k_f = 0.0189\,\mathrm{nm}^{-1}$; $a_h^0 = 18.828\,\mathrm{m}^2/\mathrm{mg}$ is the specific absorption coefficient of humic acid; $k_h = 0.01105\ \mathrm{nm}^{-1}$; C_f and C_h are, respectively, concentrations of fulvic and humic acids in mg/m^3 (Carder *et al.*, 1989).

The scattering $b(\lambda)$ and backscattering $b_B(\lambda)$ coefficients are calculated according to:

$$b(\lambda) \;=\; b_w(\lambda) + b_s^0(\lambda)\, C_s + b_l^0(\lambda)\, C_l\,, \qquad b_B(\lambda) \;=\; 0.5\, b_w(\lambda) + B_s\, b_s^0(\lambda)\, C_s + B_l\, b_l^0(\lambda)\, C_l\,, \tag{2}$$

here

$$B_s = 0.5\int_{\pi/2}^{\pi} p_s(\vartheta)\sin\vartheta\, d\vartheta = 0.039\,, \qquad B_l = 0.5\int_{\pi/2}^{\pi} p_l(\vartheta)\sin\vartheta\, d\vartheta = 0.00064\,, \tag{3}$$

B_s is a probability of backscattering by small particles, B_l is a probability of backscattering by large particles, $b_w(\lambda)$ is the scattering coefficient by pure water in m^{-1}, $b_s^0(\lambda)$ and $b_l^0(\lambda)$ are, respectively, the specific scattering coefficients in m^2/g for small and large particulate matter, C_s and C_l are, respectively ,concentrations in g/m^3 of small and large particles. The equation for $b_w(\lambda)$ is derived by interpolating the data published by Morel and Prieur (1977):

$$b_w(\lambda) \;=\; \left(5.826\cdot 10^{-3}\,\mathrm{m}^{-1}\right)\left(400/\lambda\right)^{4.322}. \tag{4}$$

The spectral dependencies for scattering coefficients of small and large particulate matter are given by the following equations (Kopelevich, 1983; Haltrin 1985):

$$b_s^0(\lambda) \;=\; \left(1.1513\,\mathrm{m}^2/\mathrm{g}\right)\left(400/\lambda\right)^{1.7}, \qquad b_l^0(\lambda) \;=\; \left(0.3411\,\mathrm{m}^2/\mathrm{g}\right)\left(400/\lambda\right)^{0.3}. \tag{5}$$

The phase function of scattering is derived by Kopelevich (1983) from results of *in situ* measurements. The Kopelevich model expresses the total hydrosol scattering function as a linear combination of two phase functions p_s and p_l. The phase function p_s describes scattering by small terrigenic fraction of particles with the density $\rho_s = 2\,\mathrm{g}/\mathrm{cm}^3$. The phase function p_l describes scattering by large particles associated with a biogenic fraction of marine hydrosol with the density $\rho_l = 1\,\mathrm{g}/\mathrm{cm}^3$. The total hydrosol angular scattering coefficient is expressed as follows:

$$\beta_H(\lambda,\vartheta) = b_s^0(\lambda)\, p_s(\vartheta)\, C_s + b_l^0(\lambda)\, p_l(\vartheta)\, C_s\,. \tag{6}$$

The phase functions in Eq. (6) can be expressed by the following regressions (Haltrin, 1997):

$$p_S(\vartheta) = 5.61746\exp\left(\sum_{n=1}^{5} s_n\, \vartheta^{3n/4}\right), \qquad p_L(\vartheta) = 188.381\exp\left(\sum_{n=1}^{5} l_n\, \vartheta^{3n/4}\right), \tag{7}$$

here ϑ is the scattering angle in degrees. The coefficients s_n and l_n are given in Haltrin (1997, 1998a) and are built into functions `fpsmall` and `fplarge` of APPENDIX A.

The seawater angular scattering coefficient is a linear combination of a Rayleigh phase function of scattering p_R and a hydrosol phase functions p_s and p_l:

$$\beta(\lambda,\vartheta) \;=\; b_w(\lambda)\, p_R(\vartheta) + b_s^0(\lambda)\, p_s(\vartheta)\, C_s + b_l^0(\lambda)\, p_l(\vartheta)\, C_l\,, \quad p_R(\vartheta) = 0.7823 + 0.6531\cos^2\vartheta \tag{8}$$

Equations (1)–(11) allow us to compute inherent optical properties of seawater as functions of wavelength and five concentrations C_c, C_h, C_f, C_s, C_l of dissolved and suspended matter.

Results of *in situ* measurements of seawater optical properties show that in a majority of cases any two formally independent optical properties correlate with each other (case I waters). Morel (1980) and Gordon and Morel (1983) propose the following correlation to estimate the chlorophyll concentration C_r in the upper ocean layer:

$$C_r = 1.92\ I_c^{1.8}, \quad I_c = R(550)/R(440), \tag{9}$$

here $R(\lambda)$ is a diffuse reflectance of the sea at wavelength λ. All these dependencies indicate that we can choose a single parameter to characterize all inherent optical properties. The optical model given by Eqs. (1)-(8) depends on five parameters: C_c, C_h, C_f, C_s, C_l The one-parameter model implies that we can express any four of these concentrations through a chosen fifth one. It is convenient to choose the chlorophyll concentration C_c as our main parameter. To derive four dependencies that express four concentrations C_c, C_f, C_s, C_l through a chlorophyll concentration C_c we minimized the following five-dimensional functional:

$$\Delta(C_c, C_f, C_h, C_s, C_l) = \left|C_c - C_r\right| \equiv \left|C_c - 1.92\left[R_\infty(550)/R_\infty(440)\right]^{1.8}\right|. \tag{10}$$

The dependence of R_∞ on a and b_B in Eq. (9) was taken from Haltrin (1998b). Two additional stabilizing relationships were used to restrict a number of solutions. For chlorophyll concentrations in the range of $0 \le C_c \le 12\,\mathrm{mg/m^3}$ several solutions were found. The single physically meaningful solution to this problem is given in a form of the four dependencies (Haltrin 1998a):

$$\left.\begin{aligned} C_f &= 1.74098 \cdot C_c \cdot \exp(0.12327 \cdot C_c), \quad C_s = 0.01739 \cdot C_c \cdot \exp(0.11631 \cdot C_c), \\ C_h &= 0.19334 \cdot C_c \cdot \exp(0.12343 \cdot C_c), \quad C_l = 0.76284 \cdot C_c \cdot \exp(0.03092 \cdot C_c). \end{aligned}\right\} \tag{11}$$

These dependencies allow calculation of the concentrations of dissolved organic matter (C_f, C_h) and concentrations of suspended particles (C_s, C_l) through the concentration of chlorophyll C_c. Eqs. (11) and Eqs. (1)-(8) constitute a one-parameter model of seawater optical properties. The validation of this model based on independent experimental data is given in Haltrin (1998a).

3.0. ALGORITHM TO CALCULATE INHERENT OPTICAL PROPERTIES THROUGH A VALUE OF BEAM ATTENUATION COEFFICIENT AT ONE WAVELENGTH

Equations (11) give a one-parameter model of seawater optical properties. Existence of a solution to Eq. (11) means that any chosen inherent optical property may be used as a parameter. For example, if we choose the beam attenuation, we can formulate a one-parameter model of sea optical properties based on a $c(\lambda)$. For example, let us use $\Delta c(\lambda)$, the difference between beam attenuation coefficients of seawater and pure water,

$$\Delta c(\lambda) = c(\lambda) - a_w(\lambda) - b_w(\lambda), \quad 0 \le \Delta c \le 10\,\mathrm{m}^{-1}, \tag{12}$$

as a regression parameter, here $a_w(\lambda)$ is taken from Pope and Fry (1997) and $b_w(\lambda)$ is given by Eq. (5). In this case it is possible to derive the following regression relationships between $\Delta c(\lambda)$ and wavelength λ and chlorophyll concentration C_c and other optical properties a, b, and b_B:

$$C_c = \Delta c\,(c_1 + \Delta c\,(c_2 + c_3\,\Delta c)), \quad c_j = \sum_{n=0}^{5} c_{jn} \left(\frac{\lambda - 400}{350}\right)^n, \ j = 1, 2, 3, \tag{13}$$

$$a = a_w + \Delta c\,(a_1 + \Delta c\,(a_2 + a_3\,\Delta c)), \quad a_j = \sum_{n=0}^{5} a_{jn} \left(\frac{\lambda - 400}{350}\right)^n, \ j = 1, 2, 3, \tag{14}$$

$$b = b_w + \Delta c\,(b_1 + \Delta c\,(b_2 + b_3\,\Delta c)), \quad b_j = \sum_{n=0}^{5} b_{jn} \left(\frac{\lambda - 400}{350}\right)^n, \ j = 1, 2, 3, \tag{15}$$

$$b_b = 0.5\,b_w + \Delta c\,(g_1 + \Delta c\,(g_2 + g_3\,\Delta c)), \quad g_j = \sum_{n=0}^{5} g_{jn} \left(\frac{\lambda - 400}{350}\right)^n, \ j = 1, 2, 3. \tag{16}$$

Equations (13)-(16) are derived and valid for the wavelengths in the interval $410 \le \lambda \le 715$ nm. The coefficients c_j, a_j, b_j, g_j, $j = 1,2,3$ are given in file "`coef.in`" of APPENDIX B. Equations (13)-(16) allow us to derive a chlorophyll concentration C_c, absorption, scattering, and backscattering coefficients a, b, and b_B for the same wavelength λ that corresponds to the value of c used to derive parameter Δc. To restore the whole set of spectral and angular optical properties we should use the approach given in Section 2.

4.0 ACKNOWLEDGMENT

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APPENDIX A: A PROGRAM TO COMPUTE OPTICAL PROPERTIES OF SEAWATER THROUGH A BEAM ATTENUATION COEFFICIENT AT ONE WAVELENGTH

```
!     program    IOPregr (written by Vladimir I. Haltrin <haltrin@nrlssc.navy.mil>
!     this program is free for any non-commercial use, a reference to this article is required
      implicit   none
      integer    i,j,Nang,Nan
      parameter  (Nang=361)
      real*8     c,lam,cw,bw,dc,x,Cc,Cf,Ch,Cs,Cl,a,b,bB,wl
      real*8     ai,bi,bBi,bpw,btot,thet,A0,bs,bl,gi,ci
      real*8     c1s,c2s,c3s, a1s,a2s,a3s,b1s,b2s,b3s, g1s,g2s,g3s
      real*8     c1(0:5),c2(0:5),c3(0:5), a1(0:5),a2(0:5),a3(0:5)
      real*8     b1(0:5),b2(0:5),b3(0:5), g1(0:5),g2(0:5),g3(0:5)
      real*8     lm(35),aw(35),Ac0(35),at(35),bt(35),bBt(35)
      real*8     p(35,Nang),ang(Nang),fawater,fbwater,fphfunct
      logical    warning,fbadinput
      character  tb

      open(11, file = 'IOPregr.in', status='old')
         read(11,*) c
         read(11,*) lam
      close(11)

      open(12, file = 'coef.in', status='old')
         read(12,*) (c1(i), i=0,5)
         read(12,*) (c2(i), i=0,5)
         read(12,*) (c3(i), i=0,5)
         read(12,*) (a1(i), i=0,5)
         read(12,*) (a2(i), i=0,5)
         read(12,*) (a3(i), i=0,5)
         read(12,*) (b1(i), i=0,5)
         read(12,*) (b2(i), i=0,5)
         read(12,*) (b3(i), i=0,5)
         read(12,*) (g1(i), i=0,5)
         read(12,*) (g2(i), i=0,5)
         read(12,*) (g3(i), i=0,5)
      close(12)
      open (13, file='lawac35.in', status='old')
         read(13,'(//)')
         do i = 1, 35
            read(13,*) lm(i),aw(i),Ac0(i)
         end do
      close (13)

      open (14, file='ang.in', status='old')
         read(14,*) Nan             ! Nan < Nang
         read(14,*) (ang(j), j=1,Nan)
      close (14)

      cw = fawater(aw,lam) + fbwater(lam)
      warning = fbadinput(cw,lam,c)
```

```
      dc = c-cw
      x  = (lam-400.)/350.
      bw = fbwater(lam)
      call scoeff(c1,c2,c3,x, c1s,c2s,c3s)
      Cc = dc*(c1s+dc*(c2s+c3s*dc))        ! chlorophyll concentration
      call scoeff(a1,a2,a3,x, a1s,a2s,a3s)
      a = fawater(aw,lam)+dc*(a1s+dc*(a2s+a3s*dc)) ! absorption coefficient
      call scoeff(b1,b2,b3,x, b1s,b2s,b3s)
      b = bw + dc*(b1s+dc*(b2s+b3s*dc))    ! scattering coefficient
      call scoeff(g1,g2,g3,x, g1s,g2s,g3s)
      bB = 0.5*bw+dc*(g1s+dc*(g2s+g3s*dc)) ! backscattering coefficient
      call scalcons(Cc, Cf,Ch,Cs,Cl)
      do i = 1,35
        wl = lm(i)
        A0 = Ac0(i)
        call siopsi(Cc,Cf,Ch,Cs,Cl,wl,A0, bs,bl,ai,bi,bBi)
        at(i) = aw(i) + ai
        bpw = fbwater(wl)
        btot = bpw + bi
        bt(i) = btot
        bBt(i) = 0.5*bpw + bBi
        do j=1,Nan
           thet = ang(j)
           p(i,j) = fphfunct(bpw,bs,bl,btot,thet)
         end do
      end do
      tb = CHAR(9)
      open(21, file='iopr.out', status='new')
         if (warning) then
            write(21,8)
            write(21,9)
         end if
         write(21,30) 'Attenuation coefficient, c = ',c, ' 1/m'
         write(21,30) 'Input wavelength, lam = ',lam, ' nm'
         write(21,30) 'Computed Chlorophyll concentration, Cc = ',Cc
     &              ,' mg/m^3'
         write(21,30) 'Computed absorption coefficient, a = ',a,' 1/m'
         write(21,30) 'Computed scattering coefficient, b = ',b,' 1/m'
         write(21,30) 'Computed backscattering coefficient, bB = ',bB
     &              ,' 1/m'
      close(21)
      open(22, file='iops.out', status='new')
         write(22,40) 'lam',tb,'c',tb,'a',tb,'b',tb,'bB',tb,'g'
         do i = 1, 35
            ai = at(i)          ! absorption coefficient
            bi = bt(i)          ! scattering coefficient
            ci = ai+bi          ! attenuation coefficient
            bBi = bBt(i)        ! backscattering coefficient
            gi = bBi/(ai+bBi)   ! Gordon's parameter
            write(22,50) lm(i),tb,ci,tb,ai,tb,bi,tb,bBi,tb,gi
         end do
      close(22)
      open(23, file='phfs.out', status='new',recl=465)
         write(23,60) 'ang\lam',(tb,lm(i),i=1,35)
         do j = 1, Nan
            write(23,70) ang(j),(tb,p(i,j),i=1,35)
         end do
      close(23)
   8  format(' Bad input parameters in the file "IOPregr.in"')
   9  format(' ---------------------------------------------')
```

```
30  format(a42, f10.6,a7)
40  format(a5,   5(a1,a12))
50  format(f5.1, 5(a1,g12.5))
60  format(a7,   35(a1,f12.1))
70  format(f7.3, 35(a1,g12.5))
    end

    subroutine scalcons(Cc, Cf,Ch,Cs,Cl)
    implicit   none
    real*8     Cc, Cf,Ch,Cs,Cl
    Cf = 1.74098*Cc*EXP(0.12327*Cc)
    Ch = 0.19334*Cc*EXP(0.12343*Cc)
    Cs = 0.01739*Cc*EXP(0.11631*Cc)
    Cl = 0.76284*Cc*EXP(0.03092*Cc)
    return
    end

    real*8 function fbwater(lam)
    implicit  none
    real*8    lam
    fbwater = 5.826E-3*(400./lam)**4.322
    return
    end

    real*8 function fawater(aw,lam)
    implicit  none
    integer   i
    real*8    aw(35),lam,lm
    i = INT(lam-370.)/10
    lm = 370.+ 10.*i
    fawater = aw(i) + 0.1*(aw(i+1)-aw(i))*(lam-lm)
    return
    end

    logical function fbadinput(cw,lam,ce)
    implicit  none
    real*8    ce,lam,cw
    fbadinput = .false.
    if (ce.lt.cw) then
       ce = cw
       fbadinput = .true.
    end if
    if (lam.lt.410.) then
       lam = 410.
       fbadinput = .true.
    end if
    if (lam.gt.715.) then
       lam = 715.
       fbadinput = .true.
    end if
    return
    end

    subroutine scoeff(v1,v2,v3,x, w1,w2,w3)
    implicit  none
    real*8    v1(0:5),v2(0:5),v3(0:5),x, w1,w2,w3
    w1 = v1(0)+x*(v1(1)+x*(v1(2)+x*(v1(3)+x*(v1(4)+x*v1(5)))))
    w2 = v2(0)+x*(v2(1)+x*(v2(2)+x*(v2(3)+x*(v2(4)+x*v2(5)))))
    w3 = v3(0)+x*(v3(1)+x*(v3(2)+x*(v3(3)+x*(v3(4)+x*v3(5)))))
    return
    end

    subroutine siopsi(Cc,Cf,Ch,Cs,Cl,lam,A0, bs,bl,ai,bi,bBi)
    implicit  none
    real*8    Cc,Cf,Ch,Cs,Cl,lam,A0, bs,bl,ai,bi,bBi,r,la
    r = 400./lam
```

```
      bl = 0.3410739*Cl*(r**0.3)  ! scattering coeff. by large fraction
      bs = 1.1513020*Cs*(r**1.7)  ! scattering coeff. by small fraction
      la = 450.-lam
      ai = A0*0.06*(Cc**0.602) + Cf*0.00728*EXP(0.01890*la)
     &   + Ch*0.13040*EXP(0.01105*la)    ! absorption coeff. by species
      bi =  bs + bl                   ! total scattering by suspensions
      bBi = 0.039*bs + 0.00064*bl     ! total backscatt. by suspensions
      return
      end

      real*8 function fphfunct(bpw,bs,bl,btot,ang)
      implicit  none
      real*8    bpw,bs,bl,btot,ang,beta
      real*8    fpwater,fpsmall,fplarge
      beta = bpw*fpwater(ang)+bs*fpsmall(ang)+bl*fplarge(ang)
      fphfunct = beta/btot
      return
      end

      real*8 function fpwater(ang)         ! ang in degrees
      implicit  none
      real*8    ang,mu
      mu = COSD(ang)
      fpwater = 0.7823 + 0.6531*mu*mu
      return
      end

      real*8 function fpsmall(ang)         ! ang in degrees
      implicit  none
      real*8    ang,x
      x = ang**0.75
      x = x*(-2.957089e-2+x*(-2.78294e-2+x*(1.255406e-3+x
     &                     *(-2.15588e-5+1.356632e-7*x))))
      fpsmall = 52.39389*EXP(x)        ! corrected 6/14/00
      return
      end

      real*8 function fplarge(ang)         ! ang in degrees
      implicit  none
      real*8    ang,x
      x = ang**0.75
      x = x*(-1.604327+x*(8.157686e-2+x*(-2.150389e-3+x
     &                  *(2.419323e-5-6.578455e-8*x))))
      fplarge = 7653.704*EXP(x)         ! corrected 6/14/00
      return
      end
```

APPENDIX B: INPUT FILES TO THE PROGRAM IOPREGR

File "coef.in":

```
 2.422697E+0   3.857256E+0  -1.578237E+1   6.585905E+1  -1.051054E+2   5.427571E+1
-1.877098E-1  -9.457076E-1   8.166927E+0  -3.267484E+1   4.923368E+1  -2.459349E+1
 5.642058E-3   1.237942E-1  -1.166176E+0   4.416329E+0  -6.444667E+0   3.163730E+0
 2.885964E-1  -6.317607E-1   3.383521E+0  -1.538335E+1   2.537777E+1  -1.331364E+1
 1.697134E-2   1.295791E-2  -1.476434E+0   6.401668E+0  -9.702480E+0   4.841352E+0
 2.505272E-5  -1.152725E-2   2.177258E-1  -8.421014E-1   1.219591E+0  -5.943660E-1
 7.114036E-1   6.317610E-1  -3.383523E+0   1.538335E+1  -2.537777E+1   1.331364E+1
-1.697134E-2  -1.295790E-2   1.476434E+0  -6.401669E+0   9.702482E+0  -4.841353E+0
-2.505272E-5   1.152725E-2  -2.177258E-1   8.421014E-1  -1.219591E+0   5.943660E-1
  2.497181E-3  -1.861928E-3  -5.878085E-5   2.063419E-2  -4.438652E-2   2.562029E-2
 2.772841E-4   1.384905E-3  -1.299578E-3  -3.868762E-3   8.154464E-3  -4.274115E-3
-1.109959E-5  -5.498079E-5  -6.231651E-5   9.251807E-4  -1.554635E-3   7.728582E-4
```

file "IOPregr.in":

```
0.2            <-- beam attenuation coefficient in 1/m (0 ≤ c ≤ 10 1/m)
450.           <-- wavelength in nm (410 ≤ lam ≤ 715)
```

File “ang.in”:

```
30     <-- Nan, a number of angles for phase function (in degrees); ang(Nan) (Nan < 362):
0.   .1   0.3   0.5   1.0   1.5   3.0   5. 10   15.   20.   25.   30.   35.   40.   45.
50.   60.   70.  80.   90.   100.   110.   120.   130.   140.   150.   160.   170.   180.
```

File “lawac35.in”:

```
  Aw according to Pope & Fry (1997)
  Ac0 according to Prieur & Satyendranath
  lam     Aw             Ac0
  380.0       0.01137       0.538
  390.0       0.00851       0.618
  400.0       0.00663       0.687
  410.0       0.00473       0.828
  420.0       0.00454       0.913
  430.0       0.00495       0.973
  440.0       0.00635       1.000
  450.0       0.00922       0.944
  460.0       0.00979       0.917
  470.0       0.01060       0.870
  480.0       0.01270       0.798
  490.0       0.01500       0.750
  500.0       0.02040       0.668
  510.0       0.03250       0.618
  520.0       0.04090       0.528
  530.0       0.04340       0.474
  540.0       0.04740       0.416
  550.0       0.05650       0.357
  560.0       0.06190       0.294
  570.0       0.06950       0.276
  580.0       0.08960       0.291
  590.0       0.13510       0.282
  600.0       0.22240       0.236
  610.0       0.26440       0.252
  620.0       0.27550       0.276
  630.0       0.29160       0.317
  640.0       0.31080       0.334
  650.0       0.34000       0.356
  660.0       0.41000       0.441
  670.0       0.43900       0.595
  680.0       0.46500       0.502
  690.0       0.51600       0.329
  700.0       0.62400       0.215
  710.0       0.82700       0.160
  720.0       1.23100       0.112
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