Horizontal visibility of Lambertian object submerged in seawater

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Abstract — A simple algorithm to calculate horizontal visibility of submerged Lambertian object is proposed. This algorithm is based on the knowledge of the three major parameters: seawater absorption coefficient, seawater forward scattering coefficient, and the albedo of the object. The algorithm is derived from the self-consistent approach to the radiative transfer theory published earlier by the author. This approach is valid for all possible values of absorption and forward scattering coefficients and may be applied without restrictions to any type of coastal water. A FORTRAN code to calculate horizontal visibility is included.

INTRODUCTION

In many predictive visibility models, such as PVM-CWC developed recently by the SAIC and the Scripps Oceanographic Institution [1, 2], the horizontal visibility of a submerged object is estimated only through the beam attenuation coefficient of modeled water. These models ignore such important factors as the forward scattering coefficient by seawater, and the albedo of the object. These omitted properties play a significant role in determining the horizontal visibility of submerged object. This model includes dependence on backscattering coefficient but ignores effects of blurring of the target image associated with the point spread function [3, 4].

APPROACH

The horizontal contrast between Lambertian object with surface albedo A and surrounding seawater background may be expressed as:

\[ k_{LO} = \frac{|R_A - R_\infty|}{R_\infty} \]  

(1)

where \( R_A \) is a horizontal diffuse reflectance of Lambertian object and the layer of water between this object and a viewer, who is supposed to be on the same level with the object, \( R_\infty \) is a horizontal diffuse reflectance of the aqueous background.

The basic formulas for horizontal diffuse reflectances may be found in previous papers by the author [5-8]. Some insights on the connection between backscattering coefficient \( b_b \) with scattering \( b \) and beam attenuation \( c \) coefficients may be found in Refs. [8-11].

\[ R_A = \frac{R_\infty + \xi \exp(-x_f)}{1 + R_\infty \xi \exp(-x_f)}, \quad \xi = \frac{A - R_\infty}{1 - R_\infty A} \]  

(2)

\[ R_\infty = \left(1 - \frac{v}{1 + v}\right)^2, \quad R_\infty = \left(\frac{2 + \mu}{2 - \mu}\right) R_\infty \]  

(3)

\[ v = a \left(\frac{7 + 2 \mu^2 - \mu^4}{\mu (3 - \mu^2)}\right) \]  

(4)

here \( x_f \) is a distance between Lambertian target and viewer, \( a = c - b \) is an absorption coefficient and \( \mu \) is an average cosine determined by the formula [5]:

\[ \mu = \left[\frac{a}{a + 3b_a + b_b (4a + 9b_b)}\right] \]  

(5)

In case when only the values of scattering and absorption coefficients are available, we can use the following expression that connects \( \mu \) with a single scattering albedo \( \omega_\alpha \) [8]:

\[ \mu = \sum_{\omega=0}^{\omega_m} c_\omega (1 - \omega_\alpha)^\omega \]  

(6)

coefficients \( c_\omega \) are given in Ref. [8] or can be fetched from the function \( \eta_{\mu_\omega a_\beta} \) listed in the APPENDIX.

The object is visible when \( k_{LO} \geq k_h \), here \( k_h \) is a threshold contrast for a human eye [12, 13]. By denoting as \( d_v \) a maximum distance from which an object can be detected and solving Eq. (1) in respect to \( x_f = d_v \), we have the following equation for \( d_v \):

\[ d_v = \frac{\mu (3 - \mu^2)}{a (7 + 2 \mu^2 - \mu^4)} \times \ln \left[\frac{A - R_\infty}{(1 - R_\infty R_\infty) - R_\infty R_\infty k_h (1 - A R_\infty)}\right] \]  

(7)

Equation (7) is coded in the APPENDIX of this paper.

CONCLUSION

It is shown that the horizontal visibility of a Lambertian object submerged in seawater may be computed on the basis of self-consistent approach in radiative transfer theory [5]. This theory is valid for any arbitrary values of optical properties \( a, b, \) and \( b_b \). It means that the approach of this paper can be used in waters of arbitrary turbidity including very turbid coastal waters and waters of lakes and rivers.

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APPENDIX: FORTRAN FUNCTION HORVIS TO CALCULATE CONTRAST OF LAMBERTIAN OBJECT SUBMERGED IN WATER

c ***************************************
real*8 function horvis

c ***************************************
c calculates horizontal visibility
of an object with Lambertian albedo At placed in water with
absorption coefficient a and
backscattering coefficient bb.
c written by Vladimir I. Haltrin
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c The following code is based on the
equations proposed in papers:
c V. I. Haltrin, (See Refs. [5],[8]).
c input parameters:
c k, Visibility contrast limit for the human eye (about 3%)
c At, target albedo (0 ≤ At ≤ 1.)
c a, absorption coefficient in 1/m (arbitrary value)
c bb, backscattering coefficient in 1/m (arbitrary value)
c b, scattering coefficient in 1/m (arbitrary value)
c output parameter:
c horvis, horizontal visibility
c distance in m
implicit none
real*8 a,bb,At,k
real*8 fdvis

call getinput(a,bb,At,k)
horvis = fdvis(a,bb,At,k)
return
end

real*8 function fmu(a,bb)
c based on Eq. (37) in Ref. [5]
imPLICIT none
real*8 a,bb,q
q = a+3*bb+SQRT(bb*(4*a+9*bb))
fmu = SQRT(a/q)
return
end

real*8 function fRb(mu)
c based on Eq. (41) in Ref. [5]
imPLICIT none
real*8 mu,r
r = (1.-mu)/(1.+mu)
fRb = rr
return
end

real*8 function fR0(Rb,mu)
c based on Eq. (42) in Ref. [5]
imPLICIT none
real*8 Rb,mu
fR0 = (2.+mu)*Rb/(2.-mu)
return
end

real*8 function frnu(a,mu)
c frnu = 1./nu; Eq.(53) in Ref.[5] for nu
implicit none
real*8 a,mu,m2
m2 = mu*mu
frnu = mu*(3.-mu)/
& (a*7.81*2.65)
return
end

real*8 function fdvis(a,bb,At,k)
c based on Eq.(62) in Ref.[5] and formula
c for the contrast: k = (Rt-Rb)/Rb
implicit none
real*8 a,bb,Rb,R0,mu,R2,Rk,At
real*8 k,Q,Rq,rnu,dvis
real*8 fm,frb,fR0,frnu
mu = fm(a,bb)
Rb = frb(mu)
R0 = fR0(Rb,mut)
R2 = R0*Rb
if (At.ge.Rb) then
if (Rk.ge.1.) then
fdvis = 0.
c fdvis is a horizontal visibility
c distance in m
c else
Rk = (1.+k)*R2
Q = k*(1.-R0*At)/(1.-Rk)
Rq = Rb*Q
Q = (At-Rb)/Rq
if ((At.le.Rq).or.(Q.le.1.)) then
fdvis = 0.
c end if
else
rnu = frnu(a,mu)
fdvis = rnu*LOG(Q)
end if
end if
else
Rk = (1.-k)*R2
Q = k*(1.-R0*At)/(1.-Rk)
Rq = Rb*Q
Q = (Rb-At)/Rq
if (Q.le.1.) then
fdvis = 0.
c else
rnu = frnu(a,mu)
fdvis = rnu*LOG(Q)
end if
end if
return
end
subroutine getinput(a,bb,At,k)
implicit none
real*8   a,bb,At,k,b,fbb
logical  a_and_b
open(11, file='horvis.in',
     &         status='old')
read(11,*) a_and_b
read(11,'(/)') k
at
Visibility contrast limit
for the human eye
read(11,*) At    ! target albedo
read(11,*) a     ! absorption coefficient in 1/m
read(11,*) bb    ! backscattering coeff. in 1/m
if (a_and_b) then
read(11,*) b   ! scattering coefficient in 1/m
  bb = fbb(a,b)
end if
close(11)
return
end
real*8 function fmuab(a,b)
  based on Eq.(6) in Ref. [8]
implicit none
real*8     a,b,q
q = SQRT(a/(a+b))
fmuab = q*(2.6178398+q*
     &       (-4.6024180+q*(9.0040600+
     &         q*(-14.59994+q*
     &           (14.83909+q*(-8.117954+
     &             1.8593222*q)))))
return
end
real*8 function fgord(mu)
  based on reversed Eq.(37) in Ref. [5]
implicit none
real*8     mu,m2,q
m2 = mu*mu
q = 1.-m2
fgord = q*q/(1.+m2*(4.-m2))
return
end
real*8 function fbb(a,b)
calculates backsc. coeff. via a and bb
implicit none
real*8     a,b,mu,g,fmuab,fgord
mu = fmuab(a,b)    ! average cosine
  g = fgord(mu)    ! Gordon's parameter
  fbb = a*g/(1.-g)    ! backscattering coefficient; see p.3778 in Ref. [5]
return
end
input file "horvis.in"
.false. a_and_b (if .true. a and b
are used to calculate bb)
0.03 k, human eye visib. contr. limit
0.5 At, target albedo (0 ≤ At ≤ 1.)
0.2 a, absorption coefficient in 1/m
0.05 bb, backscattering coeff. in 1/m
0.3 b, scattering coeff. in 1/m

REFERENCES

[1]. R. R. Hammond, S. A. Jenkins, J. S. Cleveland et al.,