

# Software Package for Optical Propagation in the Ocean

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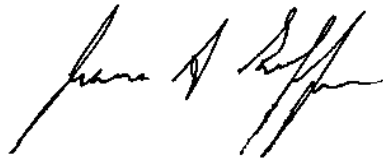
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Newport, Rhode Island**

## **PREFACE**

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**This report describes a Monte Carlo simulation of image point spread functions in an absorbing and scattering water environment. A parallel processing MATLAB software package that implements the simulation is presented.**

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# SOFTWARE PACKAGE FOR OPTICAL PROPAGATION IN THE OCEAN

## 1. INTRODUCTION

When light travels in water, it experiences beam steering, diffraction, scattering due to inhomogeneities along with polarization effects, and absorption. Full wave propagation and ray tracing software are available to determine the effects of relatively smooth variations in the water index of refraction caused by thermal, salinity, and pressure variations. This report describes a ray-based Monte Carlo software package that ignores polarization effects and simulates light propagation in the presence of absorption and scattering due to particles and molecular fluctuations. While the main focus of the software is to produce a point spread function (PSF) that can be used to model imaging, the results include propagation times so that the bandwidth of the optical channel when used for communication is also generated. While some commercial software packages exist that accomplish these results, this report presents a slightly different point of view, as well as a parallel processing MATLAB software package that implements the Monte Carlo simulation.

## 2. THEORY

The model presented makes use of the following inherent optical properties to describe the optical environment:

$a \equiv$  optical absorption coefficient,

$\beta \equiv$  volume scattering coefficient,

$$b \equiv \text{optical scattering coefficient} = \int_{4\pi \text{ steradians}} d\Omega \beta = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin(\theta) \beta(\phi, \theta). \quad (1)$$

Based on these definitions, a derived inherent optical property is the coherent beam attenuation coefficient, defined as

$$c = a + b. \quad (2)$$

All of the parameters defined in equations (1) and (2) are wavelength dependent.

In the case of a collimated laser beam with wavelength  $\lambda$  and power  $P_0$ , the coherent portion of the beam after propagating a distance  $R$  is given by

$$P(z) = P_0 \exp(-c_\lambda R). \quad (3)$$

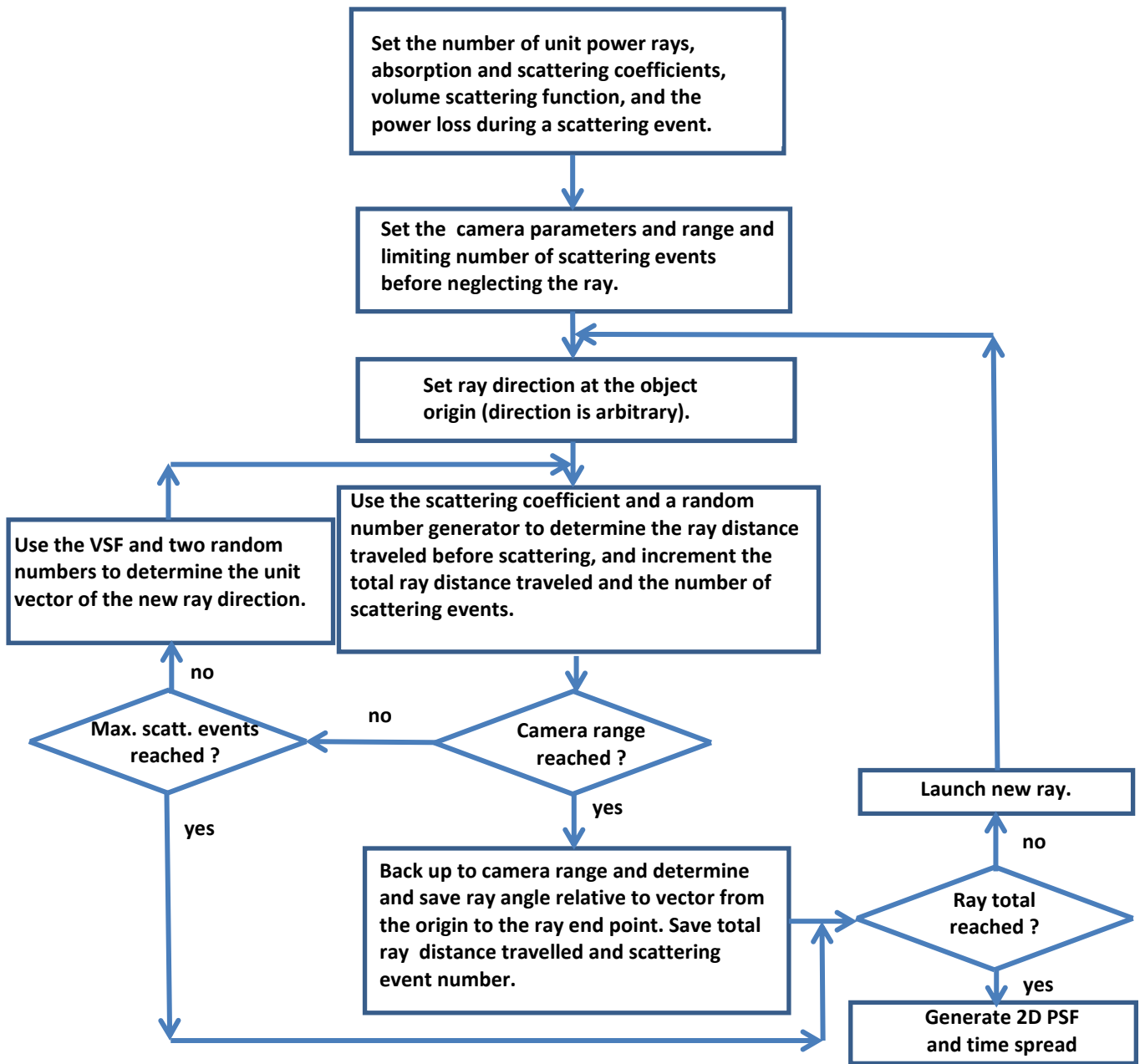
In the case of a single wavelength point source with power  $P_0$ , the irradiance at a range  $R$  is given by

$$I(R) = P_0 \frac{\exp(-K_\lambda R)}{4\pi R^2}, \quad (4)$$

where  $K_\lambda$  is the diffuse attenuation coefficient, which is greater than the absorption coefficient because some of the light undergoes scattering before it arrives at a range  $R$  and must therefore travel a longer distance in the absorbing environment to arrive at  $R$ . The value of  $K_\lambda$  is determined by fitting the results generated by the Monte Carlo simulation of a point source to equation (4). Defined in this way, the value of  $K_\lambda$  increases slightly with range. The difference in travel range causes a corresponding spread in travel times. In addition, the point source light that arrives at  $R$  is spread over a range of angles because of the different scattering experience of each ray. This spread in angles is recorded in the Monte Carlo simulation and used to determine the image PSF seen by a camera located at range  $R$  and aimed at the point source.

The process outlined above is only an approximation of what occurs when a picture is taken of an object in the absorbing and scattering medium that lies between the camera and the object. For instance, it does not account for light that leaves the object and is backscattered to re-illuminate the object. It also does not account for light that leaves the object and reaches behind the camera to be scattered in front of the camera and then scattered into the camera. While these events occur, they are higher order events that are reasonably neglected.

Within the approximations described above, the process used to determine a PSF is presented in the flowchart in figure 1. As indicated in the third block of the flowchart, the initial ray direction is arbitrary for the assumed point source that demands statistical angular symmetry.

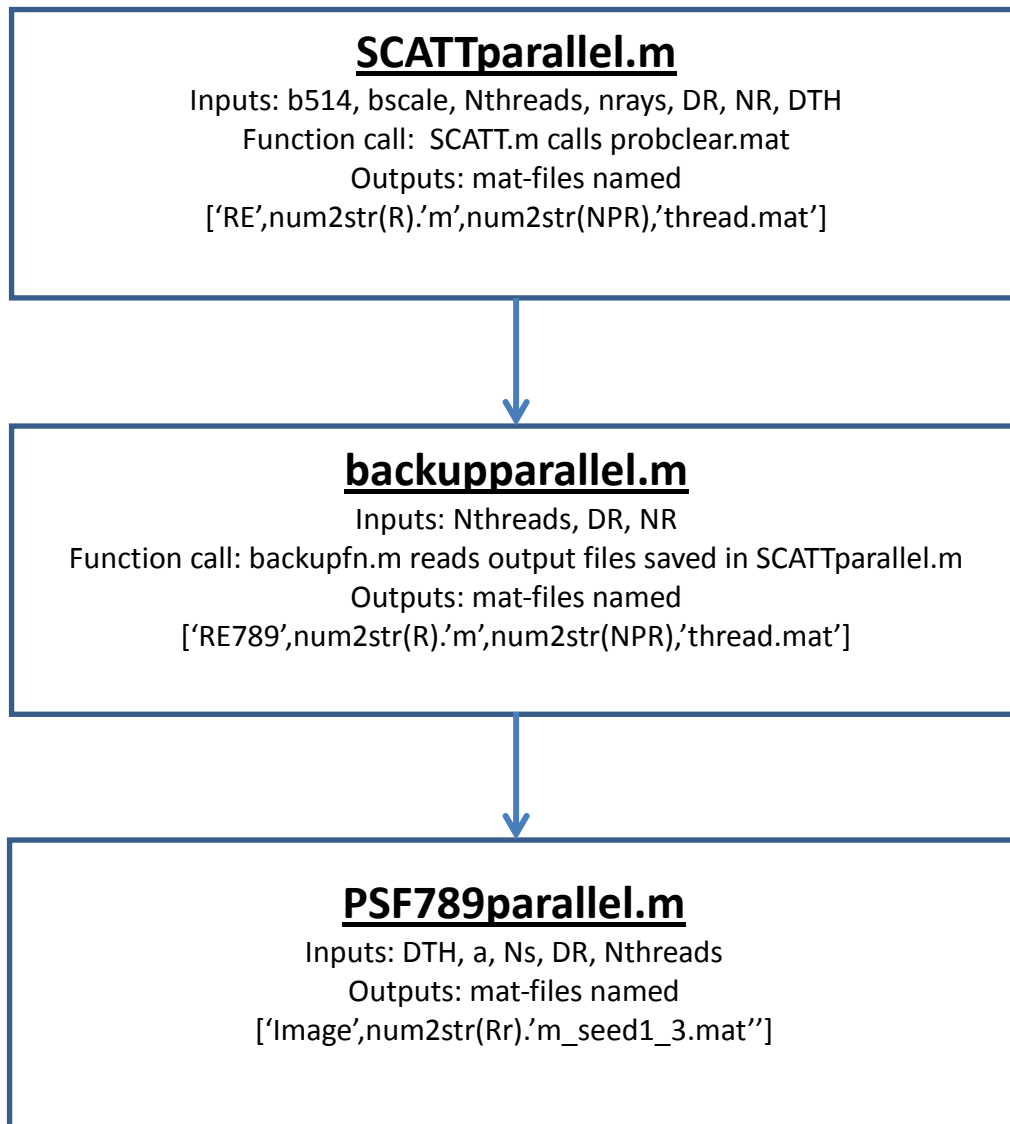


*Figure 1. Flowchart for Simulation of Ray Propagation in the Presence of Scattering and Absorption*



### 3. MATLAB CODE

The flowchart in figure 1 is implemented with three m-files that call two functions and import one mat-file that contains the needed volume scattering function data. The code uses parallel processing to determine the point spread function out to a selectable maximum range and at selected periodic intermediate ranges. Figure 2 depicts the software modules with their names, inputs, and outputs. Reference is made to the m-files presented in the appendix, where the input variables are defined at the beginning of each m-file. The contents of the output mat-files are defined in the two function and the PSF789parallel m-files.



*Figure 2. Parallel Processing MATLAB m-files Used to Implement the Monte Carlo Simulation Flow Charted in Figure 1 for a Periodic Sequence of Ranges*



#### **4. SUMMARY**

The ray-based Monte Carlo software package described in this report ignores polarization effects and simulates light propagation in the presence of absorption and scattering due to particles and molecular fluctuations. While the main focus of the software is to produce a point spread function (PSF) that can be used to model imaging, the results include propagation times so that the bandwidth of the optical channel when used for communication is also generated. Some commercial software packages exist that accomplish these results, but this report has presented a slightly different point of view, as well as a parallel processing MATLAB software package that implements the simulation.



## APPENDIX MATLAB CODE

```
%SCATTparallel
L. Estes
clc;clear;close all
%function[kout]=SCATT(b514,DR,NR,nrays,DTH,NPR)%SCATT.m
%seedoffset=input('seed offset [use 0 to (2^32-1)] =');
b514=0.037;
    bscale=input('bscale=');
    Nthreads=input('# of parallel threads =? ');
    nrays=input('total # of rays=');
    nrays=ceil(nrays/Nthreads);%for parallel processing
    DR=input('sphere radius step size=?');
    NR=input(' number of range steps=?');
    DTH=input('initial source cone angle (deg, 0+:180)=?');
    b514=bscale*b514;
    %c530=b514+a;
        %rand('state',seed)
    DTH=DTH*pi/180;
    maxstep=4*ceil(b514*DR*NR+12*((b514*DR*NR)^0.5))
    Omega=2*pi*(1-cos(DTH));%cone steradians
    OTH=Omega/(2*pi);

tic
%matlabpool close force local
matlabpool close
%matlabpool open
matlabpool(Nthreads)
    parfor NPR = 1:Nthreads
        %c(:,i) = eig(rand(1000));
        %c(:, :, i)=stat2(1:i);
        %K(NPR)=SCATT(.04,17,3,10000,180,NPR)
        K(NPR)=SCATT(b514,DR,NR,nrays,DTH,NPR)
    end
toc
%x=1:10;
%stat2(x)
%function [mean,stdev] = stat2(x)
%STAT Interesting statistics.
```

```

%backupperparallel
%L. Estes
clc;clear
%K=backupfn(22,2,2)

%function[kout]=backupfn(DR,NR,NPR)

    Nthreads=input('# of parallel threads =? ')
    %nrays=input('total # of rays=');
    %nrays=ceil(nrays/Nthreads');%for prallel processing
    DR=input('sphere radius step size =?');
    NR=input(' number of range steps=?');

tic
%matlabpool close force local
matlabpool close
%matlabpool open
matlabpool(Nthreads)
    parfor NPR = 1:Nthreads
        %c(:,i) = eig(rand(1000));
        %c(:, :, i)=stat2(1:i);
        %K(NPR)=SCATT(.04,17,3,10000,180,NPR)
        K(NPR)=backupfn(DR,NR,NPR)
    end
toc

```

```

%PSF789parallel.m
%L. Estes
clc
clear all
close all
format compact
a=input('absorption coef m^-1=? ')
Ns=input('number of range steps=? ')
DR=input('range step size m=?')
Nthreads=input('number of threads =')
r=(1:Ns)*DR;
ANGLEbarA=zeros(1,Ns);
ANGLErmsA=zeros(1,Ns);
toc1=zeros(1,Ns);
toc2=zeros(1,Ns);
toc3=zeros(1,Ns);
KdiffA=zeros(1,Ns);
KcoefA=zeros(1,Ns);
tic
for Nr=1:Ns

    Rr=Nr*DR
    tic
    for NPR=1:Nthreads
        Nfile=['RE789_',num2str(Rr),'_m_',num2str(NPR),'threadHIT.mat'];
        load (Nfile)
        if NPR==1
            R789t=RE789;
        else
            R789t=[R789t;RE789];
        end
    end

    RE789=R789t;
    clear R789t
    nrays=nrays*Nthreads;
    toc

    %RE(ray pos vector, output ray unit vector, travel length in m', # of
    %scatterings, output angle relative to position vector), R=range'
    %N=range steps, seed, b514, nrays=launched ray number, TOC1=scatt
    %compute time, TOC2=backup time')
    c530=a+b514;
    sz=size(RE789);
    krays=sz(1);
    raypower=exp(-a*RE789(:,1));powsum=sum(raypower);
    ANGLEbarA(Nr)=sum(RE789(:,3).*raypower)/powsum;
    ANGLEBAR=ANGLEbarA(Nr);
    ANGLErmsA(Nr)=(sum((RE789(:,3).^2).*raypower)/powsum)^0.5;
    ANGLErms=ANGLErmsA(Nr);
    toc1(Nr)=TOC1;
    toc2(Nr)=TOC2;
    %get diffuse attenuation coef
    KdiffA(Nr)=(log(nrays/powsum))/R;%DiffuseAttenuationCoef
    DiffuseAttenuationCoef=KdiffA(Nr);
    KcoefA(Nr)=KdiffA(Nr)/a;
    Kcoef=KcoefA(Nr);

```

```

%construct diffuse images assuming f/theta(deg)lens
DTH=0.0547;%deg
DTHairDeg=DTH*1.34;
THETA=(0:DTH:90);
LTH=length(THETA)
DENOM=zeros(1,LTH-1);
PDIF=0;
for NL=1:LTH-1
    DENOM(NL)=2*pi*((THETA(NL+1)+THETA(NL))/2)*DTH;
end
Image=zeros(1,LTH-1);
COHpower=0;
Nnoscatterings=0;
for K=1:krays
    if RE789(K,2)>0
        NTH=ceil(RE789(K,3)/DTH);
        if NTH==0
            NTH=1
        end
        Image(NTH)=Image(NTH)+raypower(K)/DENOM(NTH);
        PDIF=PDIF+raypower(K);
    else
        COHpower=COHpower+raypower(K);
        Nnoscatterings=Nnoscatterings+1;
    end
end
end
COHpower=COHpower/nrays
Nnoscatterings
Image=Image/PDIF;
ImageFinalOnSphereOneWattSource=Image*PDIF/nrays;
savefile=['Image',num2str(Rr),'m_seed1_3.mat']
TOC3=toc
toc3(Nr)=TOC3;

save(savefile,'Image','DENOM','THETA','R','PDIF','nrays','ImageFinalOnSphereOneWattSource','DiffuseAttenuationCoef','Kcoef','a','b514','ANGLErms','ANGLEBAR','c530','COHpower','Nnoscatterings','DTHairDeg','TOC1','TOC2','TOC3')
figure(Nr);plot(THETA(2:length(THETA)),Image);xlabel('theta degrees')
title(['PSF range =',num2str(R)]);grid on
ylabel(['PSF range =',num2str(R)]);
%save Image500sd1 Image DENOM THETA R PDIF nrays
%ImageFinalOnSphereOneWattSource DiffuseAttenuationCoef Kcoef a b514 ANGLErms
ANGLEBAR AngleRMSfirstOrderScatt c530 COHpower Nnoscatterings DTHairDeg
%figure(1600)
%plot(THETA(2:LTH),Image);xlabel('degrees');grid on
%ylabel('total normalized diffuse image radial slice')

end
toc
NF=0
if NF==0
figure(51);plot(r,KdiffA);grid on;xlabel('range');ylabel('Kdiff')
figure(52);plot(r,KcoefA);grid on;xlabel('range');ylabel('Kcoef')
figure(53);plot(r,ANGLEbarA);grid on;xlabel('range');ylabel('ANGLEbar deg')
figure(54);plot(r,ANGLErmsA);grid on;xlabel('range');ylabel('ANGLErms deg')
figure(55);plot(r,toc1);xlabel('range');ylabel('toc1 sec');grid on
figure(56);plot(r,toc2);xlabel('range');ylabel('toc2 sec');grid on
figure(57);plot(r,toc3);xlabel('range');ylabel('toc3 sec');grid on
save KdKcAbArSeed1 KdiffA KcoefA ANGLEbarA ANGLErmsA a b514 r toc1 toc2 toc3
end

```

```

function[kout]=SCATT(b514,DR,NR,nrays,DTH,NPR)%SCATT.m
%L. Estes
%format compact
%Pt spread function simulation of 3D scattering of a light at
    %depth z propagating upward
    %loc=point location in [x y z]
    %dir=direction as unit vector [x y z]
%clc
%clear all
%close all

%Data from deep water at Autec by Petzold(24 deg 29.0 min N, 77 deg 33 min
west)
%c530=0.151; b514=0.037;%*10;
%a=0.114;%=c530-b514 all m-1
nw=1.34;%water index of refraction
na=1;%air index of refraction
ca=(3e8)/na;%m/sec speed of light in air
cw=(3e8)/nw;%m/sec speed of light in water
can=pi/180;nac=1/can;

load probclear% loads prob dist pb , angles th, VSF B, bscatt
lb=length(pb);
%Data from deep water at Autec by Petzold(24 deg 29.0 min N, 77 deg 33 min
%west)
%b514=0.037;%Petzold Autec clear
%c530=0.151;a=0.114;%=c530-b514 all m-1

% user input
    %seedoffset=input('seed offset [use 0 to (2^32-1)] =');
    %bscale=input('bscale=');
    %Nthreads=input('# of parallel threads =? ');
    %nrays=input('total # of rays=');
    %nrays=ceil(nrays/Nthreads);%for prallel processing
    %DR=input('sphere radius step size =?');
    %NR=input(' number of range steps=?');
    %DTH=input('initial source cone angle (deg, 0+:180))= ?');
    %b514=bscale*b514;
    %c530=b514+a;
        %rand('state',seed)
    DTH=DTH*pi/180;
    maxstep=2*ceil(b514*DR*NR+12*((b514*DR*NR)^0.5));
    Domega=2*pi*(1-cos(DTH));%cone steradians
    OTH=Domega/(2*pi);
    RE=zeros(nrays,9); % ray results array
    %RE=[location vector,direction unit vector,length traveled, # of
    %scatterings, exit angle relative to position vector]
    xc=[1 0 0]; %unit x vector
    yc=[0 1 0]; %unit y vector
    zc=[0 0 1]; %unit z vector
    %matlabpool

RE=zeros(nrays,9);
seed=NPR;

```

```

rand('state',seed)

for N=1:NR
    tic;
    R=N*DR;
    %total path length to the surface
    k=0; %hit the surface ray counter
    sz=size(RE);
    krays=sz(1);
    for m=1:krays
        re1=RE(m,1:3); % source ray location in meters
        re2=re1;
        r=norm(re2);
        if r>=R
            k=k+1;
            RE(k,:)=RE(m,:);
        else
            re1=re2;
            ST=RE(m,7);
            nend=0;

        for n=1:maxstep,

            if N==1 & n==1
                %get source direction
                phis=2*pi*rand;sp=sin(phis);cp=cos(phis);
                ths=acos(1-OTH*rand);st=sin(ths);ct=cos(ths);
                ne=[st*cp st*sp ct];
                RE(m,4:6)=ne;
                RE(m,8)=-1;%initialize # of scatterings
            else
                %get ne
                if n==1
                    ne=RE(m,4:6);
                end
                pang=rand;
                np = find(pb>=pang,1); % SBD replacement of while loop below
                %np=1;
                %while pb(np)<pang,
                % np=np+1;
                %end
                if pang==1
                    theta=180;%degrees
                elseif np==1
                    theta=(th(1))*(pang)/(pb(1));
                else
                    theta=th(np-1)+(th(np)-th(np-1))*(pang-pb(np-1))/(pb(np)-
pb(np-1));
                end
            end
        end
    end
end

```

```

        %theta
        theta=can*theta;
        % determine azimuth angle relative to current direction
        phi=2*pi*rand;
        %scatter
        %get unit vector in xc,ne plane perpendicular to ne
        np1dot = xc-ne*(dot(ne,xc));
        np1=np1dot/norm(np1dot);
        %get unit vector perp to np1,ne plane
        np2=cross(ne,np1);% unit vector perp to ne and np1
        % now scatter the ray
        ne=ne*cos(theta)+sin(theta)*(np1*cos(phi)+np2*sin(phi));
    end

    %get s
    s=(-log((1-rand)))/b514;%step size to scattering event
    ST=ST+s;
    %step
    re2=re1+s*ne; %step before scattering
    r=norm(re2,2);

    if r<R%test if surface has been reached
        re1=re2;
        %surface not reached
    else
        alpha=nac*real(acos(dot(ne,re2)/r));
        nend=1;
        k=k+1;
        nn=RE(m,8)+n;
        RE(k,:)=[re2,ne,ST,nn,alpha];

    end

    if nend==1,break,end

end

end

end
kout=k;
TOC1=toc;
%save range result
RE=RE(1:k,:);
savefile=['RE',num2str(R),'m_',num2str(NPR),'thread.mat'];
save(savefile,'RE','R','N','seed','b514','nrays','TOC1')
end

```

```

function[kout]=backupfn(DR,NR,NPR)
%backupfn.m
%L. Estes
format compact
clc
%clear all
%close all
nac=180/pi;
%NR=input('number of ranges = ?')
%DR=input('range step size m =?')
for Nr=1:NR
    tic
    Rr=Nr*DR;
    Nfile=['RE',num2str(Rr),'m_',num2str(NPR),'thread.mat'];
    load(Nfile);
    %RE(ray pos vector,output ray unit vector, travel length, #of
    %scatterings,output angle relative to position vector),R=range,N=range
    %step, seed,b514,nrayslaunched, TOC1=compute time
    sz=size(RE);
    krays=sz(1);
    RE789=zeros(krays,3);%ST,n,alpha=distance,scatt #,angle deg

    for m=1:krays
        %back up to surface
        ST=RE(m,7);
        ne=RE(m,4:6);
        re=RE(m,1:3);
        r=norm(re);
        dnr=dot(ne,re);
        dels=dnr-(dnr^2-r^2+R^2)^0.5;
        % dels
        re=re-dels*ne;
        ST=ST-dels;%correct travel distance to surface
        %tim_of_flight=ST/cw;%time of flight to surface
        alpha=real((acos(dot(ne,re)/R))*nac);
        %account for absorption
        %raypower=raypower*(scatEff^(n-1))*exp(-ST*a); %account for
scatterer absorption scatEff
        %raypower=raypower*exp(-ST*a);
        %nend=1;
        RE(m,1:3)=re;
        RE(m,7)=ST;
        RE(m,9)=alpha;
    end
    TOC2=toc;
    % savefile=['RE',num2str(Rr),'m_seed1_3HIT.mat'];
    savefile=['RE',num2str(Rr),'m_',num2str(NPR),'threadHIT.mat'];
    save(savefile,'RE','R','N','seed','b514','nrays','TOC1','TOC2')
    RE789=RE(:,7:9);
    savefile2=['RE789_',num2str(Rr),'m_',num2str(NPR),'threadHIT.mat'];
    save(savefile2,'RE789','R','N','seed','b514','nrays','TOC1','TOC2')
    kout=krays;
end

```

The probclear .mat file is loaded from the SCATT function and loads the probability distribution pb, angles th, volume scattering function B, and scattering coefficient bscatt. The size and character of these variables are:

B	1x55	440 double
th	1x55	440 double
pb	1x55	440 double
bscatt	1x1	8 double

The variable B is the volume scattering function data obtained by Petzold\* from deep water at AUTECH (24° 29.0' N, 77° 33' W). The variable values are

```
B = 53.1800 40.4200 30.7300 23.7400 18.1400 13.6000 9.9540
7.1790 5.1100 3.5910 2.4980 1.7190 1.1710 0.7758
0.5087 0.3340 0.2196 0.1446 0.0952 0.0628 0.0416
0.0204 0.0110 0.0062 0.0039 0.0027 0.0019 0.0014
0.0010 0.0008 0.0006 0.0005 0.0004 0.0003 0.0003
0.0003 0.0002 0.0002 0.0002 0.0002 0.0002 0.0002
0.0002 0.0003 0.0003 0.0003 0.0003 0.0003 0.0003
0.0003 0.0004 0.0004 0.0005 0.0005 0.0005
```

```
th= 0.1000 0.1260 0.1580 0.2000 0.2510 0.3160 0.3980
0.5010 0.6310 0.7940 1.0000 1.2590 1.5850 1.9950
2.5120 3.1620 3.9810 5.0120 6.3100 7.9430 10.0000
15.0000 20.0000 25.0000 30.0000 35.0000 40.0000 45.0000
50.0000 55.0000 60.0000 65.0000 70.0000 75.0000 80.0000
85.0000 90.0000 95.0000 100.0000 105.0000 110.0000 115.0000
120.0000 125.0000 130.0000 135.0000 140.0000 145.0000 150.0000
155.0000 160.0000 165.0000 170.0000 175.0000 180.0000
```

```
pb= 0.0139 0.0209 0.0292 0.0397 0.0521 0.0671 0.0847
0.1050 0.1281 0.1539 0.1826 0.2141 0.2482 0.2846
0.3226 0.3622 0.4033 0.4462 0.4910 0.5377 0.5865
0.6798 0.7473 0.7948 0.8288 0.8547 0.8753 0.8917
0.9048 0.9153 0.9239 0.9311 0.9372 0.9426 0.9473
0.9515 0.9553 0.9589 0.9623 0.9655 0.9687 0.9718
0.9748 0.9779 0.9809 0.9838 0.9865 0.9891 0.9915
0.9937 0.9957 0.9974 0.9988 0.9997 1.0000
```

bscatt= 0.0367 .

For the data presented the units are: B in 1/(steradian-meters), th in degrees, pb is unitless, and bscatt in 1/m.

---

\*Curtis D. Mobley, *Light and Water Radiative Transfer in Natural Waters*, Academic Press, San Diego, 1994, pp. 110-111.

```

%petzoldclear.m
%L. Estes
%Creates probclear.mat
%Data from deep water at Autec by Petzold(24 deg 29.0min N, 77 deg 33min W)
%c(530)=0.151, b(514)=0.037, a=c(530)-b(514)=0.114 all m-1

close all
th=zeros(1,55);%angle in degrees
B=zeros(1,55);%m-1sr-1 volume scattering function
th(1:8)=[0.1,0.126,0.158,0.2,0.251,0.316,0.398,0.501];
B(1:8)=[5.318,4.042,3.073,2.374,1.814,1.360,0.9954,0.7179]*10;

th(9:16)=[0.631,0.794,1,1.259,1.585,1.995,2.512,3.162];
B(9:16)=[5.11,3.591,2.498,1.719,1.171,0.7758,0.5087,0.334];

th(17:24)=[3.981,5.012,6.31,7.943,10,15,20,25];
B(17:24)=[2.196,1.446,0.9522,0.6282,0.4162,0.2038,0.1099,0.06166]*0.1;

th(25:32)=[30,35,40,45,50,55,60,65];
B(25:32)=[3.888,2.68,1.899,1.372,1.02,0.7683,0.6028,0.4883]*0.001;

th(33:40)=[70,75,80,85,90,95,100,105];
B(33:40)=[4.069,3.457,3.019,2.681,2.459,2.315,2.239,2.225]*0.0001;

th(41:48)=[110,115,120,125,130,135,140,145];
B(41:48)=[2.239,2.265,2.339,2.505,2.629,2.662,2.749,2.896]*0.0001;

th(49:55)=[150,155,160,165,170,175,180];
B(49:55)=[3.088,3.304,3.627,4.073,4.671,4.845,5.019]*0.0001;

figure(1)
plot(th,log10(B));grid;xlabel('angle in degrees')
ylabel('log10 (Ptezold clear(AUTEC 24 deg 29.0min N, 77 deg 33min W)
scattering function m-1sr-1)')

b=zeros(1,55);%=integrated scattering coef
g=pi/180;
w=g*th;I=B.*sin(w);
b(1)=pi*I(1)*w(1);
for n=2:55,
    b(n)=b(n-1)+pi*(I(n)+I(n-1))*(w(n)-w(n-1));
end

figure(2)
plot(th,b);grid;xlabel('angle in degrees')
ylabel('integrated scat coef m-1 (Ptezold clear(AUTEC 24 deg 29.0min N, 77
deg 33min W)')
bscatt=b(55)
pb=b/bscatt;
save probclear pb th B bscatt

```

```

figure(3)
plot(th,pb);grid;xlabel('angle in degrees')
ylabel('probability distribution (Ptezold clear(AUTEC 24 deg 29.0min N, 77
deg 33min W) scattering function m-lsr-1)')

%calculate the rms theta
w=g*th;I2=B.*w.*w.*(sin(w))/bscatt;an2=zeros(1,55);

an2(1)=pi*I2(1)*w(1);
NMAX=55;
for n=2:NMAX,
    an2(n)=an2(n-1)+pi*(I2(n)+I2(n-1))*(w(n)-w(n-1));
end
anglerms=(180/pi)*((an2(NMAX))^0.5)%rms angle in degrees

%calculate the avg of cos(theta)
w=g*th;I3=B.*(cos(w)).*(sin(w))/bscatt;cs=zeros(1,55);

cs(1)=pi*I3(1)*w(1);
NMAX=55;
for n=2:NMAX,
    cs(n)=cs(n-1)+pi*(I3(n)+I3(n-1))*(w(n)-w(n-1));
end
costhetabar=cs(NMAX)%rms angle in degrees

%calculate the avg of (cos(theta))^2
w=g*th;I5=B.*((cos(w)).^2).*(sin(w))/bscatt;cs2=zeros(1,55);

cs2(1)=pi*I5(1)*w(1);
NMAX=55;
for n=2:NMAX,
    cs2(n)=cs2(n-1)+pi*(I5(n)+I5(n-1))*(w(n)-w(n-1));
end
costhetasqbar=cs2(NMAX)%rms angle in degrees

%calculate the avg theta
w=g*th;I4=B.*w.*(sin(w))/bscatt;an=zeros(1,55);

an(1)=pi*I4(1)*w(1);
NMAX=55;
for n=2:NMAX,
    an(n)=an(n-1)+pi*(I4(n)+I4(n-1))*(w(n)-w(n-1));
end
avgbangle=(180/pi)*(an(NMAX))%avg angle in degrees

```



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