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Technical Report
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SeaRad, A Sea Radiance Prediction Code

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EXECUTIVE SUMMARY

OBJECTIVE

Develop a computer code to predict sea radiance (brightness).

APPROACH

Sea radiance is modeled by combining the methods of geometrical optics with the Cox-Munk statistical description of ocean capillary waves. The model is incorporated into the atmospheric transmittance/radiance code MODTRAN2 to provide numerical sea radiance predictions.

In this model each individual capillary wave facet is allowed to reflect the sky or sun and emit thermal radiation. The total radiance from the sea is obtained by applying the proper statistical weight to each facet and integrating it over all facets within the observer's field-of-view.

RESULTS

The modified MODTRAN2 code, called *SeaRad*, calculates sea radiance for any viewing geometry in the spectral range from 52.63 cm^{-1} to 25000 cm^{-1}. Typical execution speeds are approximately 10 s per pixel on a Pentium/90 MHz personal computer. Preliminary comparisons show that *SeaRad* agrees to within several degrees Celsius (°C) with actual sea radiance measurements in the mid-wave and long-wave infrared bands.

CONTENTS

FIGURES

1. Introduction.

SeaRad is a FORTRAN computer code that predicts the radiance (brightness) of the ocean surface. *SeaRad* is based on the Cox-Munk statistical model (Cox and Munk, 1954, 1956) for wind-driven capillary wave facets. An individual facet is chosen and assigned a specific slope with respect to the local horizon. The facet is allowed to reflect the sky and sun and emit thermal black body radiation toward an observer. The total radiance is obtained by applying the proper statistical weight to the facet and integrating over all facets within the observer's field-of-view.

SeaRad is valid for a spectral range extending from the visible to the far infrared. Preliminary comparisons show that *SeaRad* agrees to within several °C with actual sea radiance measurements in the mid-wave and long-wave infrared bands.

In its current form, *SeaRad* is a self-contained, DOS-compatible program that runs on a personal computer and computes radiance for a single pixel (rather than an entire image). It is a modified version of the Air Force program MODTRAN2 (Berk, et al., 1989; Kneizys, et al., 1988) that computes atmospheric transmittance and radiance. *SeaRad* operates exactly like the original MODTRAN2 code[1] except that a new logical parameter, "SeaSwitch", is required in the input file. Sun glint is included in the sea radiance prediction provided that the user has chosen to execute *SeaRad* in radiance mode with solar scattered radiance included (IEMSCT = 2).

2. Hardware Considerations.

The size of the FORTRAN source code is 1.8 MB. When assembled by version 5.01 of the Lahey F77L/EM-32 DOS compiler, the size of the executable code is 0.8 MB. When run[2] on a Pentium/90 at low spectral resolution (LOWTRAN7) in multiple scattering mode, execution times are 4 s for a typical thermal long-wave case (830 to 1250 cm^{-1} in 21 spectral steps) and 17 s for a typical solar mid-wave case (2000 to 3340 cm^{-1} in 67 spectral steps). Source and executable codes are available on disk through correspondence with the author.

We take this occasion to point out that although the program will execute faster in single scattering mode, this mode results in a radiance corresponding to clear (aerosol-free) air even when aerosols are present in the model atmosphere. Hence, we do not recommend the single scattering mode when aerosol effects are desired.

3. An Example.

[1] This report assumes that the reader is familiar with MODTRAN2 operation.
[2] The compiler requires the Lahey/Phar Lap 386 DOS Extender program (0.2 MB) to run on a personal computer.

This section provides an example of how *SeaRad* is used to predict ocean radiance. An input file called "Tape5Rad.Std" (Appendix A, page 2) employs a 1976 U. S. standard atmosphere to calculate ocean radiance observed at a zenith angle of 100° (a depression angle of 10°) from a height of 23 m. The Navy aerosol model is used. The calculation is done with multiple scattering at low spectral resolution (LOWTRAN7) for a single wave number (945 cm^{-1}) in the long-wave band.

With this file present, the following three DOS commands will calculate ocean radiance and print results:

```
Copy   Tape5Rad.Std   Tape5
SeaRad
Type  Out
```

These commands[3] produce the output file "Out"(Appendix A, page 3). Band-integrated radiance values in W m^{-2} sr^{-1} are listed at the end of the output file for each of four contributions to ocean radiance: path to footprint, sea emission, sky reflection, and sun glint. (In fact, no sun glint has been calculated in this instance since the input file specifies IEMSCT = 1 rather than IEMSCT = 2.) Please note that the parameter "TBOUND" in the input file has been reinterpreted by *SeaRad* as the sea temperature.

The input file shown in Appendix A page 2 contains two new parameters at the end of the third line: "90.000" and "T". These will be discussed in reverse order of their appearance.

The "T", which may appear anywhere in columns 76 through 80 of the third line of the input file (at the end of Card 3), is a new logical parameter "SeaSwitch". It is required; that is, a fatal error will be generated if it is not present in the input file. "SeaSwitch" controls the sea radiance calculation. When "SeaSwitch" is equal to "T", the sea radiance calculation will be allowed provided certain other conditions are met. When "SeaSwitch" is equal to "F", the sea radiance calculation will be prevented under all conditions and the program will execute as originally released by the Air Force.

The "90.000", which may appear anywhere in columns 66 through 75 of the third line of the input file (near the end of Card 3), is a new floating point parameter, "Psi". It is optional; that is, the program will run whether this parameter is included in the input file or not. "Psi" is the azimuth of the upwind direction[4] measured from the line-of-sight in degrees positive East of North. If it is omitted (if the field is blank), and if all conditions for a sea radiance calculation are met, that calculation will proceed under the assumption that the value of "Psi" is zero, meaning that the observer is looking directly into the wind.

[3] The time for this particular test case was 3 s on a 486/50 MHz personal computer.
[4] This information is required because the Cox-Munk capillary wave slope statistics are different in the upwind and crosswind directions.

For the input file in Appendix A, “Psi” is 90°, meaning that the wind is blowing from right to left, perpendicular to the direction of observation.

The modified version of Card 3 used by SeaRad is:

H1, H2, ANGLE, RANGE, BETA, R0, LEN, Psi, SeaSwitch
Format (6F10.3, I5, F10.3, L5)

4. The Model.

The primary assumption of the model is that the strength of interaction between an optical ray and a capillary wave facet is given by the facet area projected normal to the ray. A feature (Zeisse, 1994) of the equations contained in *SeaRad* is that they predict a finite horizon radiance. *SeaRad* does not include multiple reflections, shadowing, or gravity waves. Polarization is ignored.

The model computes four contributions to sea radiance. Each of the four contributions is shown in figure 1. (For purposes of clarity, only two dimensions have been used in figure1; however, all three dimensions are used in the actual calculation.)

The first contribution is path radiance, shown at the top of figure 1. The footprint of a single pixel in an image of the sea is indicated by the wavy line. The footprint is observed by a receiver at the end of a ray whose zenith angle at the footprint is θ_r. Let N_{path} designate the spectral radiance in W m^{-2} sr^{-1} $(cm^{-1})^{-1}$ along the path[5] from the footprint to the receiver.

The second contribution is reflected sky radiance. Spectral radiance N_s from a portion of the sky arrives at the footprint along a ray whose zenith angle there is θ_s. The footprint contains wave facets of different slopes, many that reflect the incoming sky radiance away from the receiver toward other parts of the sky. These facets are ignored. However, the footprint will also contain some facets whose slope is correct for reflecting the incoming sky radiance toward the receiver along the path defined by the zenith angle θ_r. These facets are retained. The contributions from all portions of the sky are summed together after specular reflection by the appropriate facets within the footprint, and the sum leaving the footprint at zenith angle θ_r is designated N_{sky}. During its path to the receiver, the reflected sky radiance is attenuated by the path transmission τ_{path}.

The third contribution is reflected solar radiance, sun glint. The calculation is analogous to the calculation of sky radiance. Spectral radiance N_o from the solar center arrives at the footprint along a path whose zenith angle there is θ_o. Within the footprint most facets deflect the solar ray away from the receiver and are rejected, but some facets are retained because they deflect the ray specularly toward the receiver along a path with zenith angle θ_r. N_{sun} is the spectral radiance leaving the footprint after summation over rays arriving from all portions of the solar disk. The reflected solar radiance is also attenuated by the path transmission τ_{path} before final reception.

[5] In this report, the word path refers only to the optical path between the footprint and the receiver.

The fourth contribution is thermal black body emission. Each facet emits a spectral radiance N_{bb} given by Planck's equation for a black body whose temperature is equal to the value of TBOUND in the input file. The spectral emissivity of a given facet in the direction of the receiver is specified by the slope of that facet and the value of θ_r. N_{sea} is the thermal spectral radiance leaving the footprint for the receiver after summation over all facets within the footprint. As before, N_{sea} is attenuated by path transmission after leaving the footprint.

Optical reflection governs the second and third contributions and optical emission governs the fourth. By application of Kirchoff's Law to sea water, an opaque medium, the spectral emissivity is one minus the spectral reflectivity. Throughout figure 1, the symbol ρ represents the reflectivity of sea water. The reflectivity is calculated from Fresnel's equations (Stratton, 1941) with a complex optical index taken from the literature (Hale & Querry, 1973; Querry, et al., 1977). These data for the index, available between 52.63 cm^{-1} and 25000 cm^{-1}, set the spectral range of *SeaRad*.

The total spectral radiance N received at wave number ν (cm^{-1}) is given by

$$N(n) = N_{path}(n)\ f(n) + \left[N_{sky}(n) + N_{sun}(n) + N_{sea}(n) \right] t_{path}(n)\ f(n)\,, \qquad (1)$$

where $f(\nu)$ has been introduced to represent the spectral responsivity of the receiver.

The design of *SeaRad* is such that path (N_{path},, τ_{path},) and source (N_s, N_o, N_{bb}) values are taken from the original MODTRAN2 while Fresnel reflection (ρ) and slope integrated values (N_{sky}, N_{sun},, N_{sea}) are introduced in new subroutines. Integration of (1) over the wave number band specified in the input file is carried out in a modification of subroutine "TRANS" to produce the band-integrated values for sea radiance given in the output file.

5. The Coordinate System.

The previous description has neglected the azimuthal dependence of rays arriving and leaving the footprint. The full three-dimensional geometry will now be introduced.

Figure 2 shows the geometry of reflection. A coordinate system was chosen whose origin is the point of reflection with the X-axis pointing upwind, the Z-axis pointing toward the zenith, and the Y-axis pointing crosswind such that a right-handed system is formed. The X-Y plane is therefore horizontal at the point of reflection. The tilted facet passes through the origin.

Define a unit vector $\mathbf{U} \equiv (q,\ f)$ with polar coordinates q, the zenith angle, and f, the azimuth. If we denote the Cartesian coordinates of $\mathbf{U}$ by (a, b, c), then we have

$$
\begin{aligned}
a &= \sin\theta \,\cos\phi \\
b &= \sin\theta \,\sin\phi \\
c &= \cos\theta
\end{aligned}
\tag{2}
$$

for the Cartesian coordinates of **U** in terms of its spherical coordinates and

$$
\begin{aligned}
\theta &= \cos^{-1}(c) \\
\phi &= \tan^{-1}(b/a)
\end{aligned}
\tag{3}
$$

for the spherical coordinates of **U** in terms of its Cartesian coordinates. Two unit vectors are shown in figure 2: $\mathbf{U}_s$, pointing from the origin to the source, and $\mathbf{U}_r$, pointing from the origin to the receiver. A third unit vector, $\mathbf{U}_n$,, is normal to the facet at the point of reflection but was removed from the figure for clarity[6].

The facet slope in the upwind direction, ζ_x , is given by the slope of the line formed at the intersection of the facet with the *X-Z* plane. The facet slope in the crosswind direction, ζ_y, is given by the slope of the line formed at the intersection of the facet with the *Y-Z* plane. In Cartesian coordinates these slopes are

$$
\begin{aligned}
\zeta_x &= -a_n/c_n \\
\zeta_y &= -b_n/c_n .
\end{aligned}
\tag{4}
$$

6. Specular Reflection.

If a specular reflection occurs, the three vectors for source, receiver, and facet normal will be connected by the law of reflection:

$$\mathbf{U}_s + \mathbf{U}_r = 2\cos\omega\ \mathbf{U}_n , \tag{5}$$

where ω is the angle of incidence and the angle of reflection.

7. The Occurrence Probability.

Following Cox and Munk, let P stand for the probability

$$P \equiv p(\zeta_x, \zeta_y, W)\, d\zeta_x d\zeta_y \tag{6}$$

[6] The zenith angle of $\mathbf{U}_n$ is the same as the tilt of the facet. The tilt is the angle of the steepest ascent within the facet.

that a wave facet will occur with a slope within $\pm dz_x/2$ of z_x and $\pm dz_y/2$ of z_y when the wind speed is W. The wave slope occurrence probability density is p. It is proportional to the horizontal projection of the facet. Cox and Munk obtained an expression for p whose lowest order term is

$$p(z_x, z_y, W) \approx \frac{1}{2p s_u s_c} \exp\left\{ -\frac{1}{2}\left(\frac{z_x^2}{s_u^2} + \frac{z_y^2}{s_c^2} \right) \right\},$$

$$s_u^2 = 0.000 + 3.16 \cdot 10^{-3} W, \tag{7}$$

$$s_c^2 = 0.003 + 1.92 \cdot 10^{-3} W.$$

Here $s_u{}^2$ and $s_c{}^2$ are the variances in z_x and z_y respectively and W is the wind speed in m s^{-1}. Figure 3 shows the dependence of p throughout slope space for a wind speed of 10 m s^{-1}. The coordinate system of figure 2 has been inserted at the top of the figure to illustrate the relation between coordinates and slopes. Note that the first *X*-*Y* quadrant corresponds to negative slopes.

8. The Interaction Probability.

Following a suggestion of Plass, et al. (1976), let Q stand for the (different) probability

$$Q \equiv q(z_x, z_y, q, f, W) dz_x dz_y \tag{8}$$

that a facet whose slope is within $\pm\, dz_x/2$ of z_x and $\pm\, dz_y/2$ of z_y will interact with a ray arriving from the arbitrary direction $\mathbf{U} = (q,\ f)$ when the wind speed is W. The wave slope interaction probability density is q. It is proportional to the facet area projected normal to the ray. It has previously been shown (Zeisse, 1994)[7] that

$$q(z_x, z_y, q, f, W) = \frac{\frac{\cos w}{\cos q_n} p}{\iint\limits_{\substack{w \le p/2 \\ \mathbf{U} = const.}} \frac{\cos w}{\cos q_n} p \, dz_x dz_y}. \tag{9}$$

[7] Equation (6) is only defined for $w \le \frac{p}{2}$.

Figure 4 is a graph of equation (9), also for a wind speed of 10 m s^{-1}, showing how facets with a specified slope interact with a ray pointing in the direction (80°, 270°), that is, with a ray elevated by 10° along an azimuth in the negative-Y direction.

9. The Equations.

The capillary wave contributions to sea radiance are

$$N_{sky}(q_r, f_r, W, n) = \iint\limits_{\substack{q_s,\, w \le p/2 \\ U_r = const}} N_s(q_s, f_s, n)\; r(w,n)\; q(z_x, z_y, q_r, f_r, W)\; dz_x dz_y \tag{10}$$

$$N_{sun}(q_o, f_o, q_r, f_r, W, n) \approx \frac{N_o(q_o, f_o, n)}{4} \cdot \iint\limits_{\substack{disk \\ U_r = const}} r(w,n)\, \sec w\, \sec^3 q_n\; q(z_x, z_y, q_r, f_r, W)\; dq_s df_s \tag{11}$$

$$N_{sea}(q_r, f_r, W, T_{sea}, n) = N_{bb}(T_{sea}, n) \iint\limits_{\substack{w \le p/2 \\ U_r = const}} [1 - r(w,n)]\, q(z_x, z_y, q_r, f_r, W)\; dz_x dz_y \tag{12}$$

In each of the integrals (10) through (12), *q* plays the role of a weighting function attached to the facet. The weight is applied to the ray leaving the footprint and propagating toward the receiver, and that ray and those receiver coordinates are held constant in all of the integrals. A physical description and some mathematical details of each equation will now be presented.

In the integrand of (10), the product of N_s and ρ represents the radiance leaving a single facet when $N_s(\theta_s, \phi_s, \nu)$ is the spectral sky radiance incident on that facet at zenith angle θ_s and azimuth ϕ_s. This product is weighted by *q* and integrated over all slopes in the ocean. During integration, a specular reflection occurs at one facet after another inside the footprint with the outgoing (receiver) ray held fixed. The incoming (source) ray is swept across the sky and sun. Equation (10) will require explicit expressions for each of its variables in terms of slopes and receiver coordinates. From (3) and (4) it can be shown that the facet tilt is given in terms of the facet slopes by

$$\cos q_n = c_n = \frac{1}{\sqrt{1 + z_x^2 + z_y^2}} \tag{13}$$

while the fact that *w* is the angle between the facet normal and the receiver ray implies that

$$
\begin{aligned}
\cos\omega &= \mathbf{U}_n \cdot \mathbf{U}_r \\
&= a_n a_r + b_n b_r + c_n c_r \\
&= \{-\zeta_x a_r - \zeta_y b_r + c_r\}\, c_n \\
&= \frac{\{-\zeta_x \sin\theta_r \cos\phi_r - \zeta_y \sin\theta_r \sin\phi_r + \cos\theta_r\}}{\sqrt{1+\zeta_x^2+\zeta_y^2}}.
\end{aligned} \tag{14}
$$

Equations (13) and (14) hold at all times, regardless of whether a specular reflection is taking place. When a specular reflection does occur, the Z component of the law of reflection

$$
\mathbf{U}_s = 2\cos\omega\, \mathbf{U}_n - \mathbf{U}_r \tag{15}
$$

gives

$$
\begin{aligned}
\cos\theta_s &= 2\cos\omega\, c_n - c_r \\
&= \frac{2\{\,\} - c_r/c_n^2}{1/c_n^2} \\
&= \frac{-2\sin\theta_r(\zeta_x \cos\phi_r + \zeta_y \sin\phi_r) + \cos\theta_r(1-\zeta_x^2-\zeta_y^2)}{1+\zeta_x^2+\zeta_y^2}
\end{aligned} \tag{16}
$$

where { } represents the expression within curly braces in (14). Finally, the X and Y components of (15) give

$$
\begin{aligned}
\tan\phi_s &= \frac{b_s}{a_s} \\
&= \frac{2\cos\omega\, b_n - b_r}{2\cos\omega\, a_n - a_r} \\
&= \frac{2\zeta_y\{\,\} + b_r/c_n^2}{2\zeta_x\{\,\} + a_r/c_n^2} \\
&= \frac{(1+\zeta_x^2-\zeta_y^2)\sin\phi_r - (2\zeta_x\zeta_y)\cos\phi_r + (2\zeta_y)\cot\theta_r}{(1-\zeta_x^2+\zeta_y^2)\cos\phi_r - (2\zeta_x\zeta_y)\sin\phi_r + (2\zeta_x)\cot\theta_r}
\end{aligned} \tag{17}
$$

for the source azimuth during specular reflection by a facet (ζ_x, ζ_y) into a receiver at (θ_r, ϕ_r).

Expressions (13), (14), (16), and (17) should be used in (10) [and in equation (9) when using (10)]. The Cartesian expressions are convenient for computer calculation while the spherical expressions are consistent with the form of equations (10) through (12).

In the integrand of (11), the product of N_o and ρ represents the spectral radiance leaving a single facet when $N_o(\theta_o, \phi_o, \nu)$ is the spectral radiance arriving at that facet from the sun whose center is at $(\theta_o, \phi_o.)$. The remaining factors in (11) are the Jacobian of the transformation from ocean slopes to sky coordinates (Zeisse, 1994). As before, the integrand is weighted by *q* but now the integration is over the solar disk in the sky. (It is assumed in (11) that $N_o(\theta_o, \phi_o, \nu)$ does not vary during integration because the sun is a Lambertian source and size of the solar disk is small.) During integration, a specular reflection from the sun to the receiver occurs at those facets within the footprint with the correct slope. Explicit expressions for each of the variables in terms of source and receiver coordinates will be required in (11). The law of reflection

$$2\cos w\,\mathbf{U}_n = \mathbf{U}_s + \mathbf{U}_r \qquad (18)$$

gives the facet position in terms of the source and receiver positions whenever a specular reflection occurs. The components of (18) give

$$\begin{aligned} z_x &= -\frac{a_n}{c_n} \\ &= -\frac{a_s + a_r}{c_s + c_r} \qquad (19) \\ &= -\frac{\sin q_s \cos f_s + \sin q_r \cos f_r}{\cos q_s + \cos q_r} \end{aligned}$$

and

$$\begin{aligned} z_x &= -\frac{a_n}{c_n} \\ &= -\frac{a_s + a_r}{c_s + c_r} \qquad (20) \\ &= -\frac{\sin q_s \cos f_s + \sin q_r \cos f_r}{\cos q_s + \cos q_r} \end{aligned}$$

while its square gives

$$2 \qquad + \mathbf{U}_s \cdot \mathbf{U}$$
$$1 + a_s a_r + b\,b_r \quad c_s c \qquad (21$$
$$= 1 + \sin \quad {}_s \sin \quad {}_r \qquad {}_r + \cos \quad {}_s \cos$$

Finally, from (4) we have

$$\begin{aligned}\tan^2\theta_n &= \zeta_x^2 + \zeta_y^2 \\ &= \frac{\left(a_s + a_r\right)^2 + \left(b_s + b_r\right)^2}{\left(c_s + c_r\right)^2} \\ &= \frac{\sin^2\theta_s + \sin^2\theta_r + 2\sin\theta_s \sin\theta_r \cos\left(\phi_s - \phi_r\right)}{\left(\cos\theta_s + \cos\theta_r\right)^2}\end{aligned} \quad . \qquad (22)$$

Expressions (19) through (22) should be used in (11) [and in (9) when using (11)]. They apply only when there is a specular reflection.

In (12) there is no incident ray or specular reflection, and integration is over all slopes in the ocean. The integral in (12) is the effective spectral emissivity of the ocean. Explicit expressions in terms of slopes and receiver coordinates will also be required for each of the variables in (12) [and in (9) when using (12)]. Equation (13) is the expression for θ_n and equation (14) is the expression for ω.

10. SeaRad.

SeaRad consists of new routines added to MODTRAN2 to compute the spectral values of N_{sky}, N_{sun}, and N_{sea} according to equations (10), (11), and (12), respectively. Through modifications to subroutine “TRANS”, these values are assembled according to (1) and integrated over wave number after obtaining proper path radiance and transmittance spectral values. *SeaRad* also introduces minor changes in subroutine “DPFNMN” and major changes in subroutine “DRIVER”. These changes will now be considered in more detail.

The modifications to “DRIVER” are briefly shown in figure 5. See Appendix B for a detailed flowchart of the modifications to “DRIVER” as well as the complete source code for the modified version of “DRIVER”. After the normal call to “GEO”, a test is conducted to see whether the ray chosen by the user has hit the surface of the sea. If so, geometry cards required for the sea calculation are issued by subroutine “Card” to file “Tape5.Sea”, and input is temporarily redirected to “Tape5.Sea”. An example of “Tape5.Sea” is given in Appendix A, page A-4, for the run initiated by the input file of Appendix A, page A-2. After the final card has been read from “Tape5.Sea”, sea radiance is calculated in “TRANS”. Then “TAPE5” is restored as the active input file and normal program execution is resumed.

Conditions in “DPFNMN” determine whether or not the sea has been hit. “DPFNMN” is a subroutine reached by a sequence of calls beginning in the driver with a call to subroutine “GEO”. Modifications to “DPFNMN” are summarized in figure 6. A logical variable “Sea”, initially set false, is set true in “DPFNMN” if the following four conditions are met:

1. The program has reached the section of code following the comment line “Tangent path intersects earth”.

2. The variable “HMIN” is equal to zero.

3. The user has chosen a radiance mode.

4. The variable “SeaSwitch” is true.

The variable “Sea” is stored in a common block made available to the driver, which inspects “Sea” before and after each of its calls to “GEO”. A change from false to true indicates that the ocean has been hit during that call. A hit induces a geometry calculation by a call to subroutine “Foot” (if IEMSCT = 1) or subroutine “SunFoot” (if IEMSCT = 2). This is followed in each case by a call to subroutine “Card”.

The purpose of “Card” is to supply sources for the Cox-Munk routines “Sky” and “Sun”. As shown in figure 7, geometry cards are issued here to file “Tape5.Sea” to obtain spectral radiance along paths to the sky at three separate zenith angles. These three cards, one for each zenith angle, are called “Sky Cards” in the flowchart. Later these data will be used by subroutine “Fit” to establish a two-parameter least squares fit at each wave number providing “Sky” with the sky dome radiance. If the sun is involved, “Card” will issue a fourth and final Card 3, called a “Sun Card” in the flowchart, which provides solar irradiance for later use as a source by subroutine “Sun”.

The modifications described to this point have, in effect, inserted three sky cards (followed by a sun card if necessary) into the user’s input file without the user’s knowledge. The insertion is made only if the user has chosen a Card 3 whose path terminates on the surface of the earth. Such a Card 3 is called a “Path Card” in figure C-1. Within the wave number integration loop in “TRANS”, spectral values of transmission, incident sky radiance, and incident solar irradiance are stored in arrays Tau(V), Nsky(V), and Ho(V), respectively. Outside the wave number integration loop these values are recalled for the sea radiance calculation by subroutine “Sky” (or subroutine “Sun” if IEMSCT = 2).

The modified version of “DRIVER” is contained in Appendix B along with a detailed flowchart of its modifications. Appendix C contains the source code and a flow-chart for the modified version of “TRANS”, and Appendix D contains new code for the sea radiance calculation.

Figure 5. Flow chart for modifications to MODTRAN2 subroutine “DRIVER”.

Figure 6. Flow chart for modifications to MODTRAN2 subroutine “DPFNMN”.

Figure 7. Flow chart for SeaRad subroutine “Card”.

11. Conclusion.

SeaRad, a modification of MODTRAN2, computes sea radiance between 52.63 cm^{-1} and 25000 cm^{-1}. Preliminary comparisons with data show that *SeaRad* has an accuracy approximately several °C in the infrared.

SeaRad is currently designed for a single pixel and takes approximately 10 s to execute. Each time a new geometry is chosen by the user, *SeaRad* recalculates the source radiance and the path radiance and transmission. However, only the path properties change significantly from one pixel to the next in an ocean image. If *SeaRad* were redesigned to apply to sea images, the speed per pixel could be reduced, up to a factor of almost four, by calculating values of source radiance values just once for the entire image.

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Appendix A.

SeaRad INPUT and OUTPUT FILES

“Tape5Rad.Std” Input File

“Out” File

“Tape5.Sea” File

Appendix B.

MODIFIED SUBROUTINE “DRIVER”.

Appendix C.

MODIFIED SUBROUTINE "TRANS"

APPENDIX D.

SOURCE CODE for NEW SeaRad SUBROUTINES and FUNCTIONS:
SKY, SUN, FIT, FOOT, CARD, SIDE, ANGLE, RHO