



## TOTAL REFLECTANCE OF WIND-ROUGHENED SEA SURFACES: DIRECTIONAL PROPERTIES

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**Abstract**—Development of global algorithms for remote sensing of oceans in the optical channels requires quantitative estimates on directional properties of sea-surface reflectance to isolate the surface reflected light from the ocean color and the atmospheric haze. Experimental data on directional sea-surface reflectance for different sea states are scarce to nonexistent because no such measurements are made at sea whereas theoretical computations on surface reflectance are rendered difficult because of uncertainties regarding the contribution because of foam. In this paper, we present a unified model to compute directional sea-surface reflectance which is based on the first principles of Fresnel's reflection laws for a semitransparent medium as applied to a nonflat continuously moving boundary such as a wind-roughened sea surface. We have incorporated the contribution resulting from foam by separately computing the reflection from a Lambertian surface for that fraction of sea surface which is covered by foam.

Sample results obtained from the model are in agreement with the theoretical estimates established by other authors. The model computes the sea-surface reflectance for any given sea state and for any look angle of a satellite sensor. Source code listing of a FORTRAN computer program for the model proposed in the paper also is presented to allow users to compute the surface reflectance for user-defined inputs.

*Key Words:* Sea-surface reflectance, Remote sensing, Foam cover, FORTRAN.

### INTRODUCTION

Visible light reflected from a wind-roughened sea surface towards the direction of a satellite sensor is a major parameter of interest in remote sensing of the ocean in the optical channels. Seawater being a semitransparent medium, part of the light incident on the sea surface penetrates into the seawater and part is reflected upwards in accordance with Fresnel's reflection laws. The light that penetrates into the sea interacts with the seawater and its various constituents and as a result, undergoes changes in its spectral character. Some of this underwater light gets back-scattered upwards and eventually escapes the sea to join the surface reflected light towards the direction of a satellite sensor. These two types of light are treated differently in ocean remote sensing. The former is known as 'ocean color', the latter as 'surface reflectance'. Ocean color is sensed remotely by optical sensors and is used to study the distribution of chlorophyll, suspended sediments, and yellow organic dissolved matter in the sea. In such studies, the surface reflectance is treated as noise and its elimination from the signal forms a major exercise in algorithms that decode the ocean color.

In a diametrically opposite context, the surface reflectance itself is shown to be a useful signal for remote sensing of oceans in several works. Through an extensive study of aerial photographs of sun-glitter

pattern on the sea surface, Cox (1974) showed that the specularly reflected light from the sea can be related directly to the sea state. Takashima and Masuda (1985) have computed the polarization status of diffuse reflected light from the sea surface and shown it to be related to the atmospheric conditions whereas Sathe and Sathyendranath (1986) have derived exact expressions to compute the wind speed prevailing over the sea surface from the polarization status of surface reflected light for various look angles of a satellite sensor. In these studies, the ocean color serves as noise whereas the surface reflectance is the signal.

Unfortunately, the basic information on directional properties of sea-surface reflectance is considerably less because no adequate instruments are used at sea. The radiometers used to collect optical data at sea are designed to measure the scalar irradiance below the sea surface and the incoming solar radiation incident on the sea. When such radiometers are used to measure the light reflected upward by the sea surface, they do not distinguish between the sea surface reflected light and the light emerging upwards from within the sea. Efforts to estimate the surface reflected light from satellite data in optical channels are constrained by the available instrumentation which measures the total radiation received from a given footprint on the sea surface rather than the reflected one. The total radiation received by a satellite sensor consists of the ocean color and the

atmospheric back-scattered light (haze) besides the surface reflected light from the sea (Robinson, 1985).

Presently, there is no reliable estimate on how much reflected radiation from the sea surface enters the field of view of an ocean-looking satellite sensor whether as noise or as a signal under different oceanic conditions. This is the result partly because of difficulties encountered in computing the contribution by the foam to the overall sea-surface reflection. This is one of the reasons why in algorithms that retrieve the ocean color from satellite data, the sea-surface reflectance is not distinguished from the atmospheric back-scattered light.

In this paper, we present a theoretical model which computes the fraction of light that seawater reflects towards a satellite sensor under given physical conditions. The physical conditions include the wind speed prevailing over the sea surface and its effect on the sea-surface roughness, the foam cover and its reflectivity, and the look angle of the satellite sensor. Complete source code of a computer program in FORTRAN 77 also is presented in the Appendix to allow the user to compute the sea-surface reflectance under the user-defined input parameters. No attempt is made here to simulate the sun-glint because the viewing geometry of ocean-looking sensors in the visible spectrum is such that reception of direct specularly reflected sunlight from the sea always is avoided (Gordon, 1987). As a consequence, all incident light on the sea surface is considered diffuse so that our model gives realistic results for remote-sensing purposes. The foam cover on the sea surface is computed by the model from the value of the wind speed supplied by the user. The model also has a provision to (optionally) accept the value for the foam cover directly from the user without relating it to the wind speed. The average waveslope of the sea surface is computed from the wind speed using the Cox and Munk (1954) law and assuming the waveslope distribution (around its mean) to be Gaussian, the wind-roughened sea surface simulated. The total reflectance of light from the sea surface is computed by taking into account the individual contribution from each probable waveslope within the context of the Gaussian probability distribution. Foam is considered a Lambertian reflector and its reflectance is computed in accordance with the method suggested by Sturm (1981). The reflectance of foam-free areas and foam-covered areas are computed separately and then added. The model computes the sea-surface reflectance for any given look angle of the ocean-looking sensor.

#### BASIC CONCEPTS AND ASSUMPTIONS

The algorithm for the simulation procedure is based on the following fundamental concepts in marine optics:

- (1) The average waveslope of a wind-roughened sea surface is related to the wind speed by the

well-known Cox and Munk (1954) law, which is used widely (see also Takashima and Masuda, 1985; Preisendorfer and Mobley, 1986; Sathe and Sathyendranath, 1986, 1992).

- (2) The probability distribution of waveslopes on the sea surface around their mean is Gaussian (Preisendorfer, 1976).
- (3) Total reflectance of the sea surface (for a given look angle) can be expressed as the sum of reflectance for parallel and perpendicular components of polarization in accordance with Fresnel's reflection laws (Jerlov, 1976).
- (4) Foam cover on the sea surface can be related to wind speed (Ross and Cardone, 1974; Monahan, 1982).
- (5) Foam can be considered as a Lambertian reflector, that is foam reflectivity can be assumed to be independent of direction of reflected light (Sturm, 1981).

#### METHOD

##### *Foam-free sea surface*

For a given wind speed, the model computes the mean square waveslope of the sea surface using the Cox and Munk (1954) relation as follows.

$$\tan^2(\theta) = 0.003 + 0.00512 * w \quad (1)$$

where  $\tan(\theta)$  is mean waveslope and  $w$  is wind speed in meters per second. The first term (0.003) in Equation (1) is the result of swell, that is average waveslope generated resulting from winds blowing elsewhere. Assuming further that the distribution of waveslopes around their mean is Gaussian (Preisendorfer, 1976), following expression is used to compute the probability function  $P(\phi)$  of the occurrence of waveslope  $\tan(\phi)$  when the mean waveslope is  $\tan(\theta)$ .

$$P(\phi) = \exp(-0.5 * \tan^2(\phi) / \tan^2(\theta)). \quad (2)$$

We have considered 90 possibilities of waveslope angles ranging between 0 and 90° spread around each computed value of the mean waveslope. The slopes and their probabilities are addressed by the variables TILT (90) and QTILT (90) respectively (see COMMENT CARDS in the source code listing of the program REFLEC given in the Appendix for explanation). The two extreme possibilities of waveslope angles being 0 and 90° refer to sea surface being flat and vertical respectively. Each possible waveslope on the sea surface encounters the incident light with a unique orientation thus giving rise to a variety of directions in which the reflected light may leave the sea surface. Under diffuse illumination, there exists incoming light with an appropriate angle of incidence for each waveslope which will be reflected in the direction of the satellite sensor. Thus, all 90 possible waveslopes under a given windspeed have 90 possible angles of incidence which reflect light towards the

sensor. For a given look angle of an ocean-looking sensor, our model computes the required angles of incidence for all possible waveslopes and then uses Fresnel's reflection laws to compute their individual contributions to the sea-surface reflectance as follows.

The reflected light from the sea surface has two orthogonal components of polarization. One component is parallel ( $C_{\parallel}$ ) and the other is perpendicular ( $C_{\perp}$ ) to the plane of incidence. They are computed as follows:

$$C_{\parallel} = \tan^2(I - J)/\tan^2(I + J) \quad (3)$$

$$C_{\perp} = \sin^2(I - J)/\sin^2(I + J) \quad (4)$$

and the reflectance is expressed as

$$\text{Ref} = 0.5*(C_{\parallel} + C_{\perp}) \quad (5)$$

where  $I$  and  $J$  are angles of incidence and refraction respectively. The angle of refraction is computed from the refractive index of seawater (with respect to air) which is taken to be 1.3333 for the present study. For a given look angle, the total reflectance of the sea surface is arrived at by integration of the individual reflectance from each waveslope weighted by its probability of occurrence.

#### Foam-covered sea

Foam consists of a layer of fine, small particles of water which scatter light in a myriad of directions leading to diffuse reflection. Further, a ray of light incident on foam gets multiplied and reflected because of its successive encounters with countless small spheres of water and air bubbles. This renders the reflection process stochastic. Because the particles of foam have dimensions larger than wavelengths of visible light, the resultant diffuse reflection is non-selective, that is the same in all directions. Hence, we treat foam as a Lambertian reflector (Jerlov, 1976) for the purpose of this model and consider its coverage and reflectivity as the only parameters of interest in this connection as earlier derived by Sturm (1981) and discussed by Sathe and Sathyendranath (1986) for computing polarization status of surface reflected light from the sea.

Foam cover on the sea surface is computed by the expression developed by Monahan (1982) for wind-speeds up to 9 m/sec. For higher winds, we use a similar expression given by Ross and Cordone (1974). The expressions are as follows:

$$F = (1.2*10^{**(-5)})*(w**3.3) \text{ Monahan} \quad (6)$$

$$F = (1.2*10^{**(-5)})*(w**3.3)*(0.225*w - 0.99) \text{ Ross and Cordone} \quad (7)$$

where  $F$  is the fraction of sea surface covered by foam and  $w$  is the wind speed prevailing over the sea surface in meters per second. If the user supplies the foam cover directly as input, our program skips the given computation.

The values for reflectivity of foam suggested in the literature differ. Experimental data on reflection from foam are sparse because such measurements normally are not carried out at sea. The estimates of foam reflectivity range from as high as 0.90 (Gordon and Jacobs, 1977) to as low as 0.45 (Quenzel and Kastner, 1980). These estimates merely are assumptions made by authors in calculations of the upwelling light from the sea. The present authors have made some measurements of light present immediately below the foam under a variety of foam conditions in the central Arabian sea with a view to arriving at a realistic value for foam reflectivity. We have determined that 38–45% of ambient light at the sea surface was present below the foam. Even if one assumes that the foam absorbs a small fraction of incident light that falls onto it and that the underwater (under-foam) light-field will include some extraneous light which has undergone the total internal reflection at the air-sea interface within the sea, one may place the value of foam reflectivity within a range of 0.55–0.62 as a first approximation.

The wide range of suggested values for foam reflectivity by various authors indicates the variety in foam structures arising out of the different sizes of water particles and air bubbles that constitute it at different foam temperatures. We recommend that only a measured value of foam reflectivity (for the water body of the user's interest) be supplied to our model as input instead of selecting a certain value from the literature which may be assumed by the authors under specific conditions. We have used a value of 0.585 (being the central value in the range from 0.55 to 0.62 observed by us) for foam reflectivity in the sample results shown in this paper.

#### Total sea-surface reflectance

Total reflectance of the sea surface in a given look angle is arrived at by adding the reflectance computed for foam-free and foam covered areas in proportion to the fraction of the sea surface covered by them. The expression used is as follows:

$$R = (1 - F)*0.5*(C_{\parallel} + C_{\perp}) + F*R_f/\pi \quad (8)$$

where  $F$  is the fraction of the sea surface covered by foam and  $R_f$  is foam reflectivity.  $F$  is computed by using Equations (6) and (7), and ( $C_{\parallel}$ ) and ( $C_{\perp}$ ) have their usual meanings as explained in Equations (3) and (4) respectively. The appearance of  $\pi$  in the second term of Equation (8) is meant to restrict the foam reflectivity in a given look angle (Sturm, 1981).

## RESULTS

Figures 1 and 2 show some sample results on reflectance curves for a wind-roughened sea surface for various look angles obtained from the model proposed in this paper. Figure 1 shows the results obtained by ignoring the effect of foam whereas Figure 2 shows the same obtained by considering the

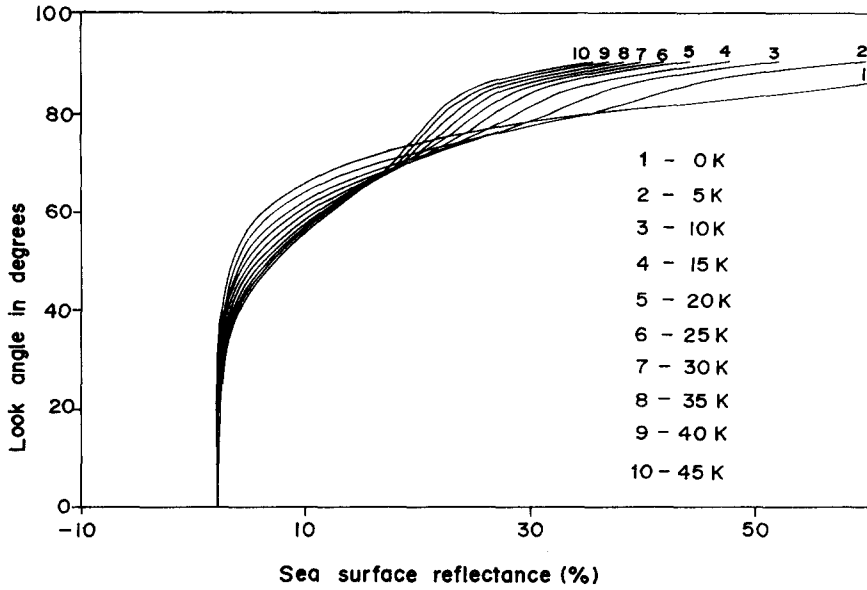


Figure 1. Reflectance curves for different wind speeds from 0 to 45 knots for wind-roughened sea surface against different look angles. Effect resulting from foam is not considered in these results.

contribution of foam. The look angles considered are from zero (nadir-looking) to 90°. The results for wide-look angles in the neighborhood of 90° serve only academic interests because ocean remote sensing does not involve the study of radiation traveling horizontally across the sea surface to be received by a satellite in the horizon.

Figure 1 shows that if the effect resulting from foam is ignored, reflectance of sea surface has little variation with wind speed for look angles up to 30°; its value is between 2.04 and 2.09% (of incident light). However for large-look angles, the sea-surface reflectance

markedly increases from a mere 2% to more than 40% for all wind speeds. The notable feature in these results is that calm seas reflect less than rough seas for small-look angles but as look angle increases, calm seas reflect more than rough seas. The inversion takes place between look angles of 60 and 70°. The reason behind this is that the light incident vertically down on a calm sea surface tends to enter (penetrate) into the water whereas that at grazing incidence tends to get reflected out of it. If the sea surface is roughened, light incident at grazing incidence encounters many wavelets facing the light at different

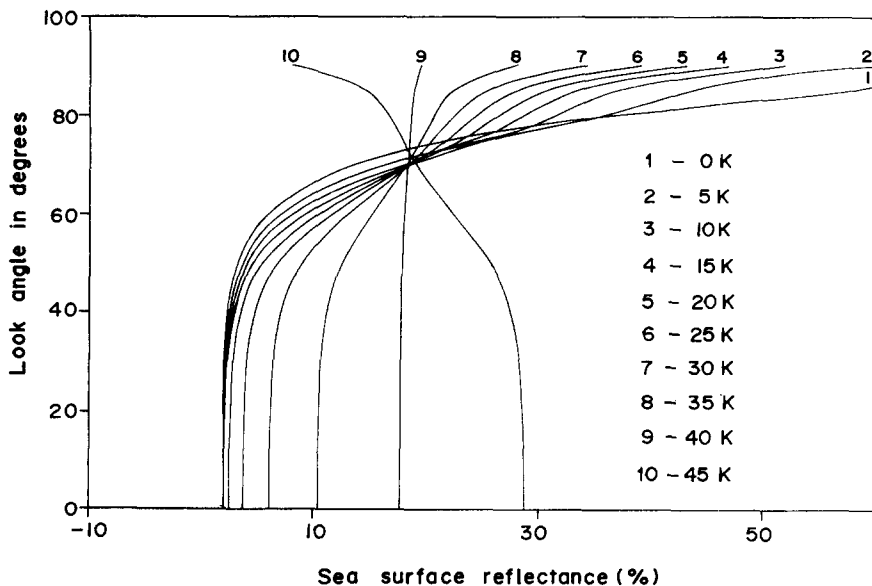


Figure 2. Reflectance curves for different wind speeds from 0 to 45 knots for wind-roughened sea surface against different look angles. These curves are obtained by incorporating contribution resulting from foam which usually is present at higher wind speeds.

orientations (other than the horizontal) which enable it to penetrate into the sea.

These results, although theoretically interesting, have little practical applications because in real situations the effect of foam on sea surface reflectance cannot be ignored at higher wind speeds. Results in Figure 2 are more suited to practical applications since they take into account these effects. It is seen in Figure 2 that for lower wind speeds, viz. up to 10 knots, sea-surface reflectance for all look angles is similar to what is shown in Figure 1. This is so because foam covers a negligible area on the sea surface for low winds and hence does not contribute to reflectance. However, with increasing wind speeds, the foam completely alters the reflectance curves. The overall effect of foam is to increase the sea-surface reflectance for look angles up to  $70^\circ$  and thereafter, foam tends to decrease the reflectance. This feature is more pronounced for higher wind speeds.

The main reason for the significant departure of reflectance curves for foam covered sea from foam-free sea is the Lambertian nature of foam reflectivity. The reflectivity of foam is assumed to be independent of direction whereas that of foam-free seawater is highly direction dependent. The calm seawater uncovered by foam reflects little towards the zenith (small-look angles) because light incident vertically downwards on calm sea tends to penetrate the water. As the look angles increase, reflectance sharply increases as light incident at grazing incidence on calm waters tends to get reflected outwards towards the horizon. This is not true of foam whose reflectivity in all directions is exactly the same. Thus, as more and more sea surface gets covered by foam at higher wind speeds, the directionality of sea surface reflectance is largely offset by the Lambertian nature of foam reflectance.

#### LIMITATIONS OF THE MODEL

It is difficult to validate the results obtained by the model because the present-generation instruments that measure the radiation at sea do not distinguish between the sea-surface reflectance and the upwelling radiation emerging from within the sea, as discussed in the Introduction. This leaves us to compare our results only with the theoretical estimates obtained by earlier authors under simplifying assumptions such as Jerlov (1976), Sturm (1981), and Sathe and Sathyendranath (1986). None of these authors have incorporated the contribution from foam in their results and their estimates for foam-free sea surface are obtained for a few limited situations. Although our results compare with these limited estimates fairly well, they need to be validated fully either with experimental data or with another suitable theoretical model.

In this situation, our model may be viewed only as the first unified attempt to compute the sea-surface reflectance under a variety of sea states and for any given look angle that incorporates the contribution by the foam.

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## APPENDIX

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C*****
C
C THIS PROGRAM COMPUTES THE FRACTION OF REFLECTED LIGHT FROM THE
C WIND-ROUGHENED SEA SURFACE THAT ENTERS A SATELLITE'S FIELD OF
C VIEW IN A GIVEN LOOK ANGLE UNDER GIVEN OPTICAL AND PHYSICAL
C CONDITIONS.
C
C WIND = WIND SPEED PREVAILING OVER THE SEA SURFACE IN
C KNOTS
C FOAM = FRACTION OF SEA SURFACE COVERED BY FOAM
C TILT(90) = SURFACE WAVE SLOPES OF THE WATER BODY CAUSED
C DUE TO WINDS, 90 VALUES, CENTERED AROUND 0.5
C DEG, 1.5 DEG, ETC UPTO 89.5 DEG
C QTILT(90) = PROBABILITY OF OCCURENCE OF WAVESLOPE TILT(N),
C UNDER A GAUSSIAN WAVE SLOPK DISTRIBUTION
C QSLOPE = MEAN SQUARE WAVE SLOPE OF THE SEA SURFACE
C GENERATED DUE TO WIND
C ANGLE = LOOK ANGLE OF SATELLITE
C INCI = ANGLE AT WHICH DIFFUSE LIGHT IS INCIDENT ON SEA
C SURFACE
C REFR = ANGLE OF REFRACTION
C MEW = REFRACTIVE INDEX OF SEA WATER
C PARA = PARALLEL COMPONENT OF POLARIZATION (FOR
C REFLECTED LIGHT)
C PERP = PERPENDICULAR COMPONENT OF POLARIZATION (FOR
C REFLECTED LIGHT)
C
C*****

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DIMENSION TILT(90), QTILT(90)
CHARACTER ANS*1
REAL INCI MEW

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C***** DEFINITION OF WATER BODY *****

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1 WRITE(6,10)
10 FORMAT(/' ENTER LOOK ANGLE OF SATELLITE IN DEGREES (ZENITH = 0)
1: ', $)
READ(5,*) ANGLE
WRITE(6,20)
20 FORMAT(/' ENTER WIND SPEED AT THE SEA SURFACE IN KNOTS: ', $)
READ(5,*) WIND
WRITE(6,30)
30 FORMAT(/' DO YOU WISH TO SUPPLY THE VALUE FOR FOAM COVER? '/
1' IF NOT, THE PROGRAM WILL ESTIMATE IT FROM THE WIND SPEED
2 SUPPLIED BY YOU'/' ANSWER (Y) FOR YES AND (N) FOR NO: ', $)
READ(5,40) ANS
FORMAT(A1)
IF((ANS.EQ.'N').OR.(ANS.EQ.'n')) THEN
  QWIND = 0.515*WIND
  F = 1.2*(QWIND**3.3)*(10.0**(-5))
  IF(WIND.LT.9.0) THEN
    FOAM = F
  ELSE
    FOAM = F*(0.225*QWIND - 0.99)
  ENDIF
ELSE
  WRITE(6,50)
  READ(5,*) FOAM
ENDIF
50 FORMAT(/, ' ENTER THE FRACTION OF SEA SURFACE COVERED BY FOAM
1 (VALUE BETWEEN 0 AND 1): ', $)
WRITE(6,60)
60 FORMAT(/, ' ENTER THE VALUE FOR REFLECTIVITY OF FOAM: ', $)
READ(5,*) REFM

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C***** SIMULATION OF WIND-ROUGHENED SEA SURFACE *****

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DO 70 I = 1, 90
TILT(I) = I - 0.5
QTILT(I) = (TAN((I-0.5)*1.5708/90.0))**2

```

70 CONTINUE

QSLOPE = 0.003 + 0.00512 \* 0.515 \* WIND

R = 0.0

DO 80 K = 1, 90

QTILT(K) = EXP(-0.5\*QTILT(K)/QSLOPE)

R = R + QTILT(K)

80 CONTINUE

DO 90 L = 1, 90

QTILT(L) = QTILT(L)/R

90 CONTINUE

C\*\*\*\* COMPUTATION OF REFLECTANCE THROUGH POLARIZATION COMPONENTS \*\*\*\*

SUM = 0.0

MEW = 1.3333

DO 100 M = 1, 90

INCI = (1.5708/90.0) \* (ANGLE-TILT(M))

REFR = ASIN(SIN(INCI)/MEW)

PARA = (TAN(INCI-REFR))\*\*2/(TAN(INCI+REFR))\*\*2

PERP = (SIN(INCI-REFR))\*\*2/(SIN(INCI+REFR))\*\*2

RE = 0.5\*(PARA + PERP)

IF((ANGLE+TILT(M)).LT.90.0) THEN

INCI = 1.5708/90.0 \* (ANGLE + TILT(M))

REFR = ASIN(SIN(INCI)/MEW)

PARA = (TAN(INCI-REFR))\*\*2/(TAN(INCI+REFR))\*\*2

PERP = (SIN(INCI-REFR))\*\*2/(SIN(INCI+REFR))\*\*2

RE = (RE + 0.5\*(PARA+PERP))/2.0

ENDIF

SUM = SUM + RE\*QTILT(M)

100 CONTINUE

TOTAL = 100\*((1.0 - FOAM)\*SUM + FOAM\*REFM/3.1416)

WRITE(6,110)

110 FORMAT(////,80('\*')//)

WRITE(6,120) TOTAL

120 FORMAT (5X, 'PERCENTAGE REFLECTANCE OF THE SEA SURFACE IS ' ,  
1F5.2)

WRITE(6,130) WIND

130 FORMAT(/,5X, 'THE WIND SPEED PREVAILING OVER THE SEA SURFACE IS ' ,  
1F5.2, ' KNOTS')

WRITE(6,140) ANGLE

140 FORMAT(/,5X, 'THE LOOK ANGLE OF THE SATELLITE IS ' F5.2, ' DEGREES')

WRITE(6,150)

150 FORMAT(/80('\*')//)

WRITE(6,160)

160 FORMAT('DO YOU WANT TO RUN THE PROGRAM AGAIN? (Y/N) :', \$)

READ(5,40) ANS

IF((ANS.EQ.'N') .OR. (ANS.EQ.'n')) THEN

STOP

ELSE

GOTO 1

ENDIF

END