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METHODS FOR CORRECTING MICROWAVE SCATTERING AND EMISSION MEASUREMENTS FOR ATMOSPHERIC EFFECTS

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REMOTE SENSING LABORATORY

Methods for Correcting Microwave Scattering and Emission Measurements for Atmospheric Effects

by Mark Komen

ABSTRACT

Algorithms have been developed to permit correction of scattering coefficient and brightness temperature for the Skylab S-193 Radscat for the effects of cloud attenuation. These algorithms depend upon a measurement of the vertically polarized excess brightness temperature at 50° incidence angle. This excess temperature is converted to an equivalent 50° attenuation, which may then be used to estimate the horizontally polarized excess brightness temperature and reduced scattering coefficient at 50°. For angles other than 50° the correction also requires use of the variation of emissivity with salinity and water temperature. When theoretical values are used for this, the effect may be translated to an equivalent 50° case and the attenuation estimated.

Use of 50° estimates should be quite satisfactory for the in-track modes of the S-193, but the more complex (and less reliable) methods based on using theory to obtain an equivalent 50° number must be used in the cross-track modes because the same spot is not viewed at both 50° and another angle in these modes.

1.0 INTRODUCTION

The removal of atmospheric effects from radiometer and scatterometer measurements has been the focus of this part of the technical study on the RADSCAT. Two main areas, correction of scattering coefficient for atmospheric effects and brightness temperature for atmospheric, angle, and surface effects are discussed in this memorandum.

It has been shown (Hollinger, 1971) that vertically polarized brightness temperature at 50° incidence angle is insensitive to surface roughness and correspondingly to windspeed while still being sensitive to changes in the atmosphere. Brightness temperature at the surface is related to apparent temperature at the satellite altitude, the difference bein ed as excess temperature. If the excess temperature at 50° incidence angle is known, the theory covering the 50° incident angle case can be extended to all incidence angles.

Also to be considered is translating the brightness temperature to a reference brightness temperature at some standard water temperature and standard incidence angle so that the radiometric measurements after the removal of the temperature and incident angle effects reflect only atmospheric and roughness effects. The final result of correcting for atmospheric effects is presented in the form of two user-oriented subroutines, one which removes the atmospheric effects based on the 50° incident angle brightness temperature insensitivities, and the other which performs the reference temperature/incidence angle translation.

The purpose of this memorandum is twofold, the first being to remove the effects of the atmosphere from the radiometer and scatterometer measurements.

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Also to be considered is translating the brightness temperature to a reference brightness temperature at some standard water temperature and standard incident angle so that the radiometric measurements reflect the removal of the temperature and incident angle effects. The final result of correcting for atmospheric effects is presented in the form of two user-oriented subroutines, one which removes the atmospheric effects based on the 50° incident angle brightness temperature insensitivities, and the other which performs the reference temperature/incident angle translation.

2.0 Removing the Effects of the Atmosphere-Derivation of Excess Temperature and Attenuation

The estimation of the atmospheric effect begins with the calculation of vertical excess temperature near 50° incidence angle. This excess temperature is calculated by taking the difference in the apparent temperature measured by Skylab and the surface brightness temperature as calculated from Fresnel theory. Although Fresnel theory is only valid for smooth surface conditions at 50° incidence angle and vertical polarization, the result is independent of windspeed. Given the incident angle, salinity, frequency, and the surface water temperature, the reflection coefficients for an electromagnetic wave incident on a smooth sea (zero wind case) can be calculated. The polarized reflection coefficient $R_p(\theta, Tw)$, where θ is the incident angle, Tw is the water temperature, and p represents the polarization, is expressed as:

$$R_V(\theta, T_W) = \frac{\epsilon_r(T_W)\cos\theta - \sqrt{\epsilon_r(T_W) - \sin^2\theta}}{\epsilon_r(T_W)\cos\theta + \sqrt{\epsilon_r(T_W) - \sin^2\theta}}$$

$$R_H(\theta, T_W) = \frac{\cos\theta - \sqrt{\epsilon_r(T_W) - \sin^2\theta}}{\cos\theta + \sqrt{\epsilon_r(T_W) - \sin^2\theta}}$$

where ϵ_r (Tw) is the complex relative dielectric constant of sea water at temperature Tw. Emissivity ϵp (θ, Tw) is related to the Fresnel coefficient by

$$\epsilon_p(\theta, T_W) = 1 - |R_p(\theta, T_W)|^2$$

The vertical brightness temperature is expressed as:

$$T_{BV} = \epsilon_V (50^\circ, T_W) \cdot T_W \quad (1)$$

Where T_w is the water temperature at the surface. By definition, the excess temperature is the difference between the apparent temperature and the brightness temperature.

$$T_{ex} = T_{app} - T_B \quad (2)$$

where T_{app} is the radiometric temperature at the satellite altitude in the antenna pointing direction and T_B is the surface brightness temperature.

An empirical relation between vertical excess temperature and attenuation at 50° incidence angle was derived from soundings taken by a NIMBUS satellite. Further analysis by the ATRAD* atmospheric radiation package yielded a graph of attenuation vs. vertical excess temperature (Figure 1). Regression analysis shows the two quantities related by the equation

$$\alpha (50^\circ) = 0.0179X - 0.0000556X^2 + 0.00000433X^3$$

where X represents the vertical excess temperature in degrees Kelvin and $\alpha(50^\circ)$ the attenuation in decibels.

ATRAD also yielded a relation between horizontal and vertical excess temperatures at 50° incidence angle which (Figure 2) by using a regression analysis, is described by

$$T_{ex_H} = 1.531 V + 0.00447 V^2 - 0.00008 V^3$$

where V is the vertical excess temperature and T_{exH} is the horizontal excess temperature at 50° incident an le, all in degrees Kelvin.

Since the a ation by the atmosphere is now known, the scatterometer measurement is correcte

$$\sigma \quad (dB) = \sigma^\circ (dB) + \alpha (dB)$$

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* Reference

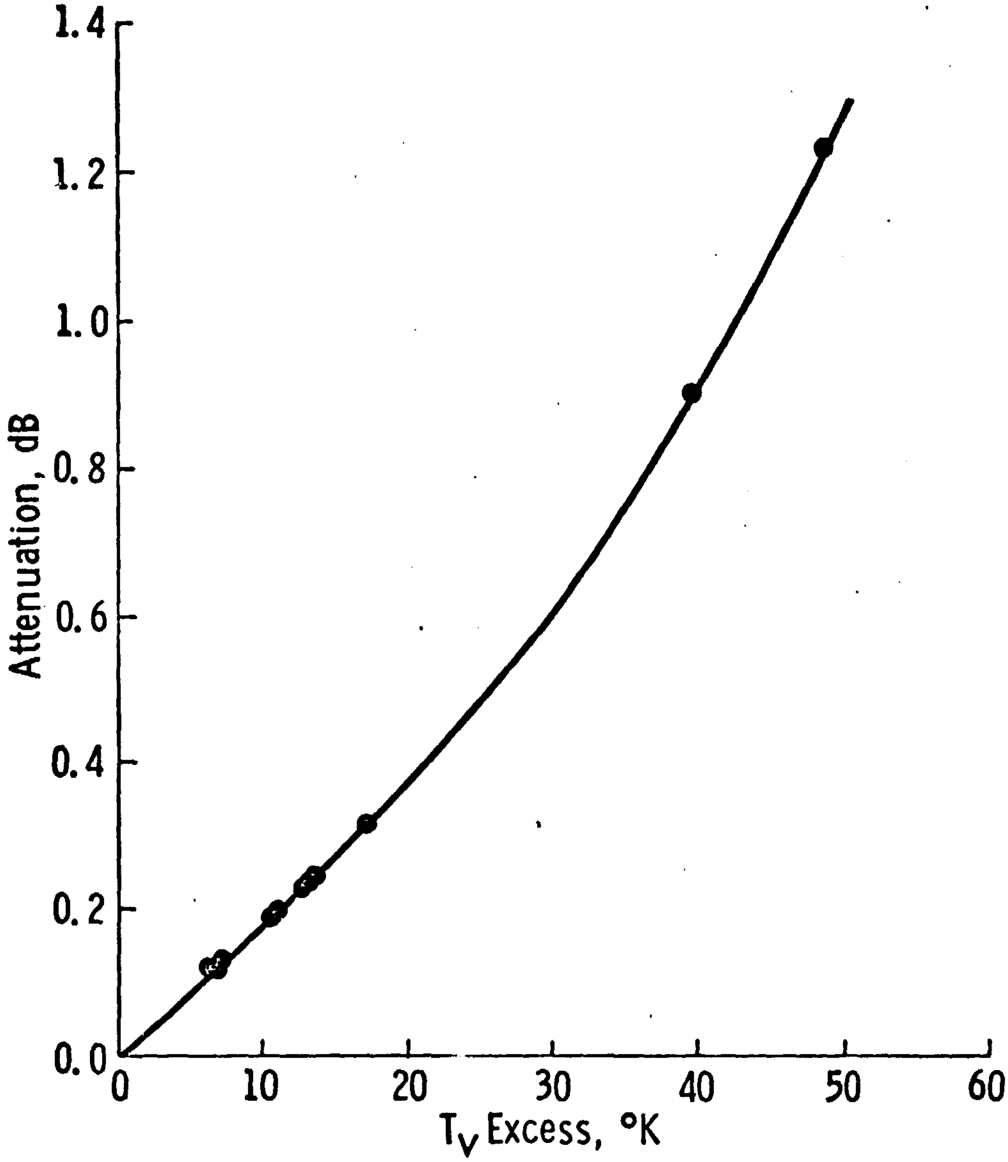


Figure 1. Attenuation vs. vertical excess temperature (50° incidence angle).

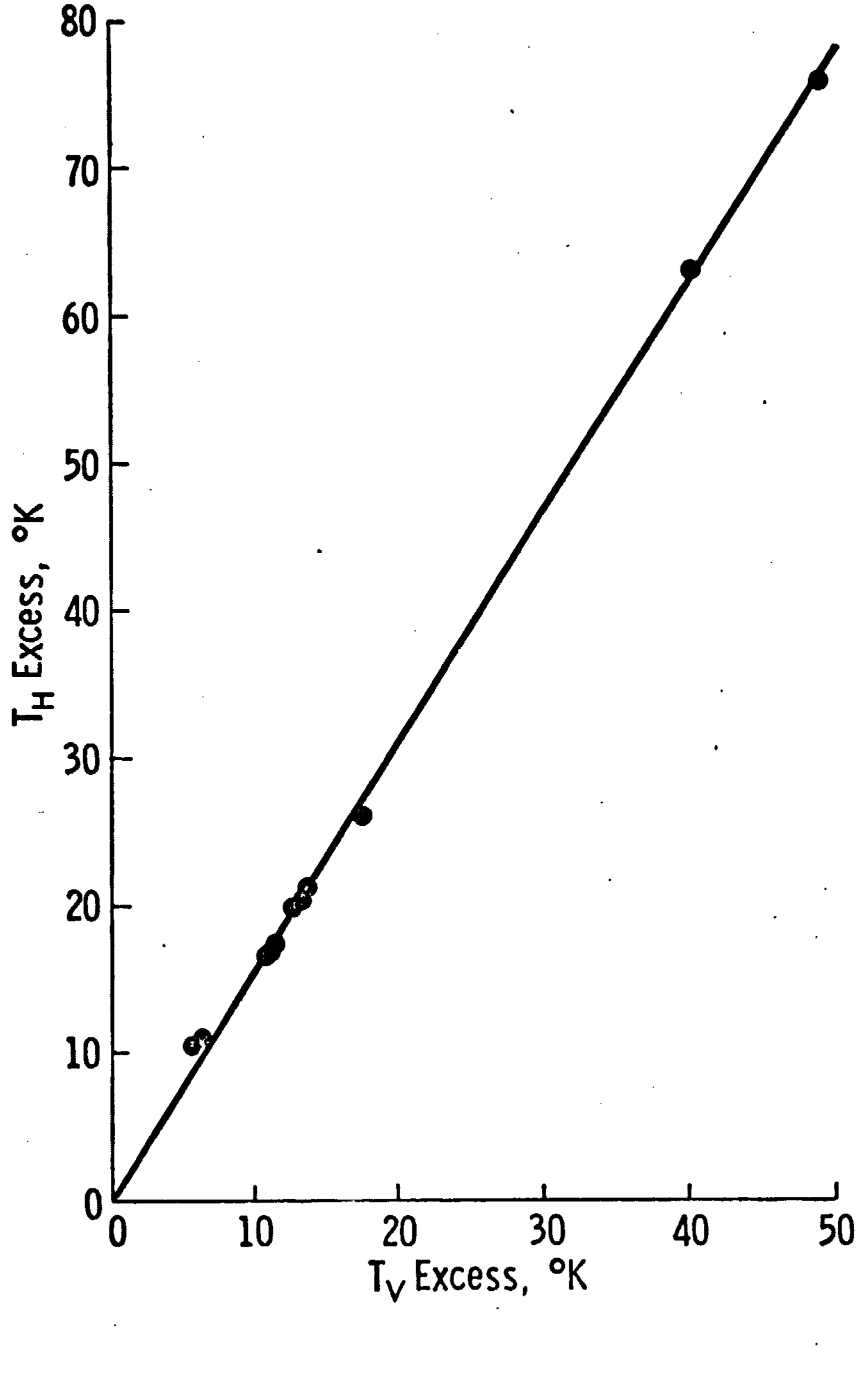


Figure 2. Horizontal excess temperature vs. vertical excess temperature (50° incidence angle).

where σ^o is the scatterometer cross section, α the attenuation, and σ^o_c the corrected scatterometer measurement, all in decibels.

At this point, all the 50^o incidence angle data can be corrected for atmospheric effects. Knowing the horizontal excess temperature, the horizontal brightness temperature at 50^o incidence angle can be obtained from equation (2). The horizontal emissivity at 50^o can be obtained by solving equation (1) for $\epsilon_p(\theta, T_W)$ for horizontal polarization.

The next step is to calculate certain parameters to be used at other incidence angles.

Attenuation and transmittance are related by the expression

$$\Gamma(\theta) = 10^{-\alpha/10}$$

where $\Gamma(\theta)$ is the transmittance at some incidence angle and α is the attenuation in decibels. Transmittance is also a function of incidence angle (θ) and atmospheric opacity (τ_o).

$$\Gamma(\theta) = e^{-\tau_o \sec\theta} \qquad (4)$$

Solving for τ_o, which is independent of incidence angle:

$$\tau_o = \frac{-\ln \Gamma(50^\circ)}{\sec 50^\circ}$$

It is important to examine the actual components of the apparent temperature. Figure 3 shows an electromagnetic wave incident on some surface having some brightness temperature T_B. T_B represents the amount of energy the antenna will see transmitted through the atmosphere. T_{up} is the atmospheric contribution T_{sky} (looking up) plus that part of the cosmic background T_c (2.7° Kelvin) transmitted through the atmosphere. There will be some reflectivity ρ at the surface, so $\Gamma\rho T_{up}$ represents that part of T_{up} which is reflected and transmitted. Finally, there is some contribution T_{ATM} from just the atmosphere itself. Summing these components, it is seen that

$$T_{app} = T_{ATM} + \Gamma(T_B + \rho T_{up}) \qquad (6)$$

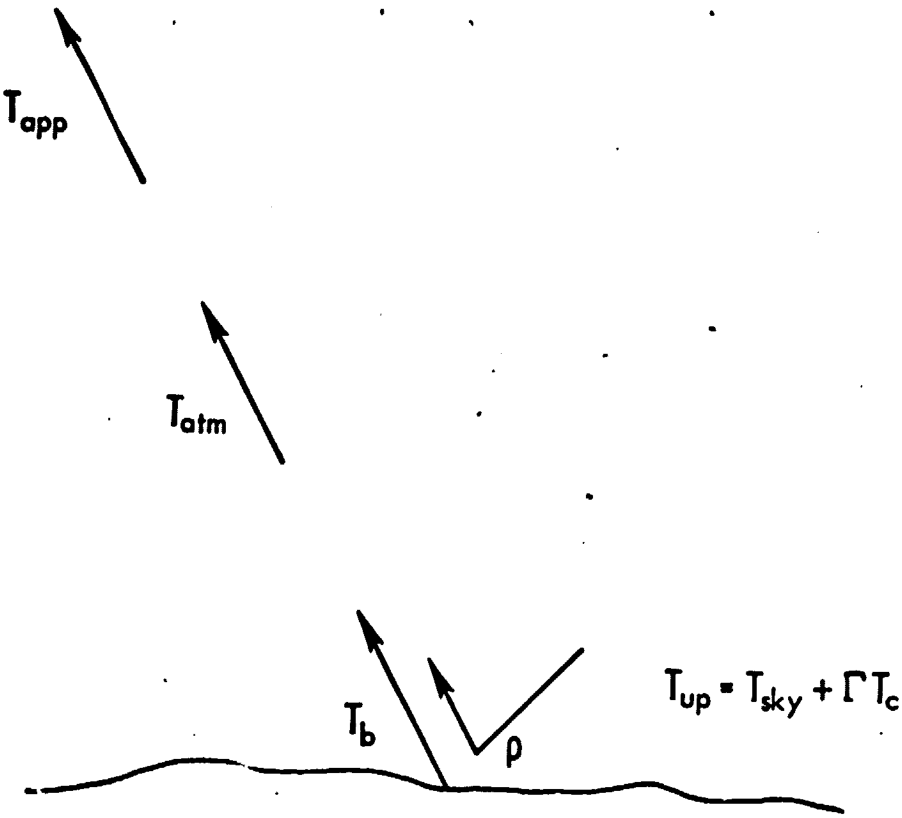


Figure 3. Components of apparent temperature (T_{app})

Substituting ϵT_w for T_B, $(1-\epsilon)$ for ρ and $(T_{sky} + \Gamma T_c)$ for T_{up}, where $T_{sky} \cong T_{ATM}$, equation (6) becomes

$$T_{app}(\theta) = \Gamma(\theta)\left\{\epsilon_p(\theta, T_w)T_w + \left[1-\epsilon_p(\theta,T_w)\right]\left[T_{ATM}(\theta) + \Gamma(\theta)T_c\right]\right\} + T_{ATM}(\theta) \qquad (7)$$

showing the angular dependence, or

$$T_{exp}(\theta) = \left[\Gamma(\theta)-1\right]\epsilon_p(\theta, T_w)T_w - \Gamma(\theta)\left[1-\epsilon_p(\theta,T_w)\right]\left[T_{ATM}(\theta) + \Gamma(\theta)T_c\right] + T_{ATM}(\theta)$$

Solving for $T_{ATM}(50^\circ)$

$$T_{ATM}(50^\circ) = \frac{T_{exv}(50^\circ) - \left[\Gamma(50^\circ)-1\right]\epsilon_v(50^\circ, T_w) - 2.7\left[\Gamma^2(50^\circ)\left\{1-\epsilon_v(50^\circ, T \ldots\right.\right.}{\Gamma(50^\circ)\left[1-\epsilon_v(50^\circ, T_w)\right]+1} \qquad (8)$$

$\bar{T}_A$ or the mean atmospheric temperature is a weighted average of the physical temperature of the atmosphere as it varies with altitude and is related to the atmospheric temperature (T_{ATM}) and the transmittance (Γ) by the following expression (see Appendix A-2 for a detailed development of $\bar{T}_A$):

$$\bar{T}_A = \frac{T_{ATM}(50^\circ)}{1-\Gamma(50^\circ)}$$

$\bar{T}_A$ is independent of incident angle for a given scan.

As was shown in equation (4) and (5), given the opacity at 50° and the incident angle, the transmittance at any angle can be calculated. Hence, the attenuation at any angle is given by

$$\alpha(\theta) = -10\log_{10}\Gamma(\theta) \quad dB.$$

Now, the scatterometer can be corrected as per equation (3).

Solving for T_{ATM} (θ) in equation (9) for any incidence angle, and with T_A constant for a given scan,

$$T_{ATM}(\theta) = \bar{T}_A\left[1 - \Gamma(\theta)\right]$$

Solving for the emissivity at any angle ϵ_p (θ, T_W) in equation (7) knowing the transmittance, apparent temperature, water temperature, and the atmospheric temperature at any incidence angle,

$$\epsilon_p(\theta, T_W) = \frac{T_{APP}(\theta) - T_{ATM}(\theta)\left[1 - \Gamma(\theta)\right] - 2.7\,\Gamma^2(\theta)}{\Gamma(\theta)\left[T_W - T_{ATM}(\theta) - 2.7\,\Gamma(\theta)\right] - T_{ATM}(\theta)}$$

Since equations for the brightness temperature and excess temperature have been defined in equations (1) & (2), the data for incidence angles other than 50° can be corrected for atmospheric effects.

3.0 Removing the Effects of Water Temperature and Incident Angle Variations

To illustrate variation of brightness temperature with windspeed, and, indeed, to provide a suitable reference for attenuation determination, effects of other parameters must be accounted for. Skylab data were taken at many water temperatures and incidence angles; variations in these parameters affect the measured radiometric brightness temperature. The incidence angles varied by two or three degrees at each command angle while the sea water temperatures varied by 10 or 15 degrees Kelvin. A nominal sea water temperature of 290°K and nominal incidence angles (50.0°, 40.0°, 30.0°, 15.0°, and 0.0°) for each command angle were chosen and the brightness temperature which would have been measured at these nominal conditions was estimated. The estimated brightness temperature for these conditions is referred to as the reference brightness temperature.

Emissivities for rough surfaces are larger than those for smooth surfaces, but Fung and Claassen [1] showed that for a given windspeed and frequency, the emissivities for smooth surfaces and rough surfaces differed by a value which was independent of water temperature. Therefore, the change in emissivity in translating from the surface water temperature to the standard water temperature for a smooth sea will be identical with that for a roughened sea.

Fresnel theory was used to obtain the polarized emissivities for a smooth sea as was done previously, fiven frequency, salinity, incidence angle, and surface water temperature (denoted by the point ϵ_o, T_w on the W_o=0 curve in Figure 4). The polarized emissivities are then calculated at the given salinity and frequency but at the standard water temperature of 290° Kelvin (denoted by the point (ϵ_{os}, T_s) on the W_o=0 curve in Figure 4). The polarized emissivities corrected for atmospheric effects (section I) are represented by the point (ϵ_2, T_w) on the W_1 curve in Figure 4, where W_1 is the windspeed at the surface cell. Translating to point (ϵ_{1s}, T_s) is done by noting

$$\Delta \epsilon_{T_w} = \epsilon_{os} - \epsilon_o = \epsilon_{1s} - \epsilon_1 .$$

Figure 5 shows the emissivity varying with incidence angle for a given windspeed. It is not known at this time exactly what the incidence angle dependence is for all windspeeds due to a lack of experimental data. At some points, the variation in windspeed caused by variations in incidence angle are significant and therefore the W_o curve was used to estimate some first order correction for the data. This correction for incidence angle variation is obtained by translating along the W_o curve and assuming that this is comparable to translating along the W_1 curve.

The total change in emissivity is then,

$$\Delta \epsilon = \Delta \epsilon_{T_w} + \Delta \epsilon_\theta$$

Hence,

$$\epsilon_{1s} = \epsilon_1 + \Delta \epsilon .$$

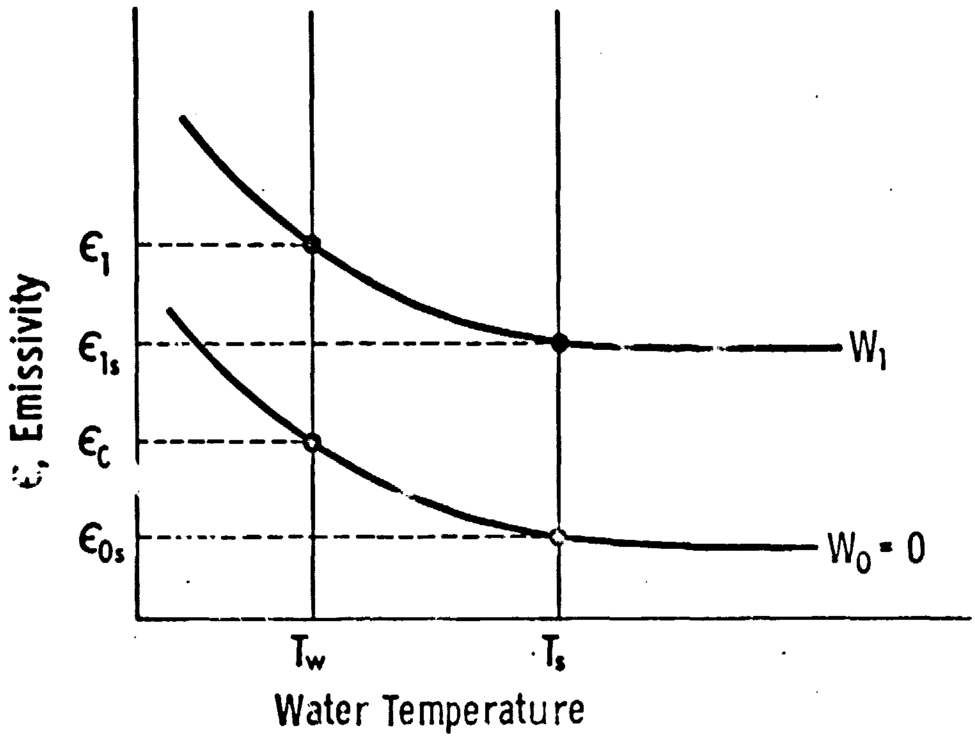


Figure 4. Emissivity vs. water temperatu[illegible] a wind roughened (W_1) or a dead calm (W_0) sea at a [illegible]ant incidence angle.

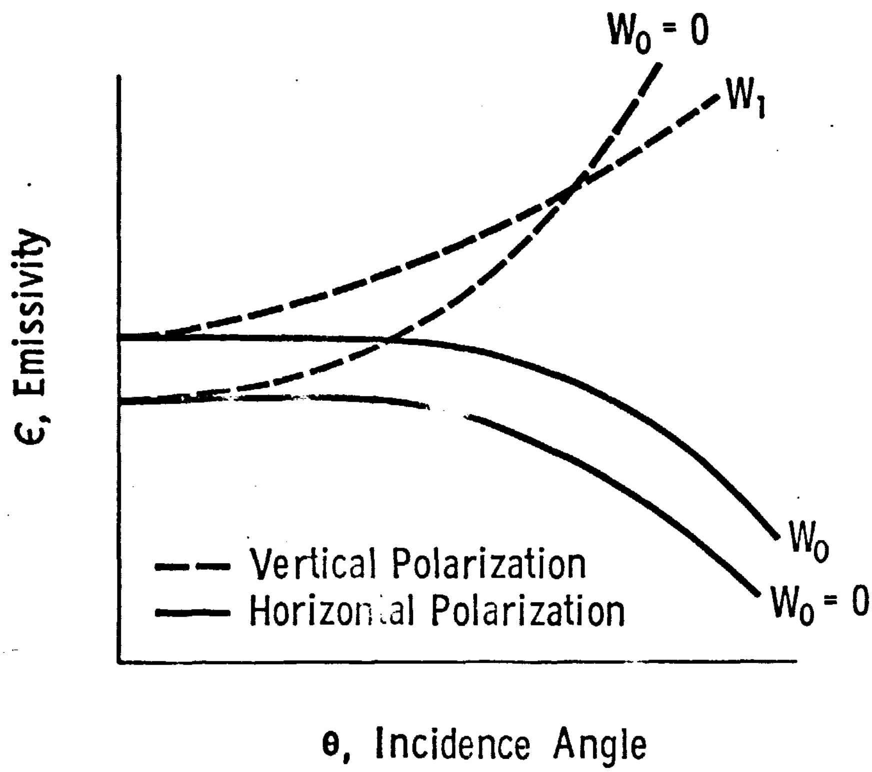


Figure 5. Emissivity vs. incidence angle for a wind roughened (W_1) or a dead calm (W_0) sea.

Knowing the emissivity at the standard water temperature and the standard incidence angle, the reference brightness temperature is calculated and the radiometer is corrected for variations in water temperature and incidence angle.

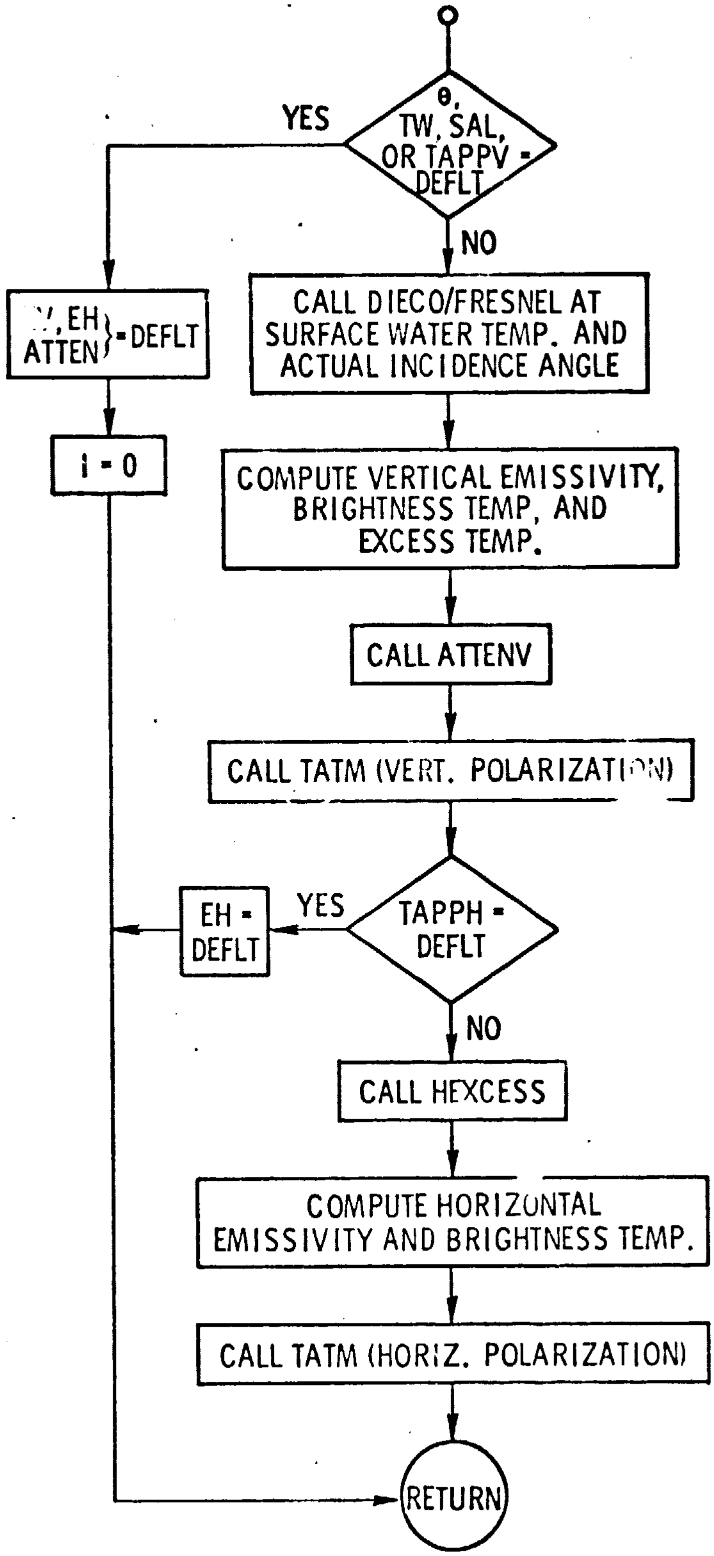
$$T_{B_{REF}} = \epsilon_p (\theta_s, T_{ws}) T_{ws}$$

where T_{BREF} is the reference brightness temperature and ϵ_p (Θ_s, T_{ws}) the polarized emissivity at the standard incidence angle (Θ_s) and the standard water temperature (T_{ws}).

4.0 Algorithms

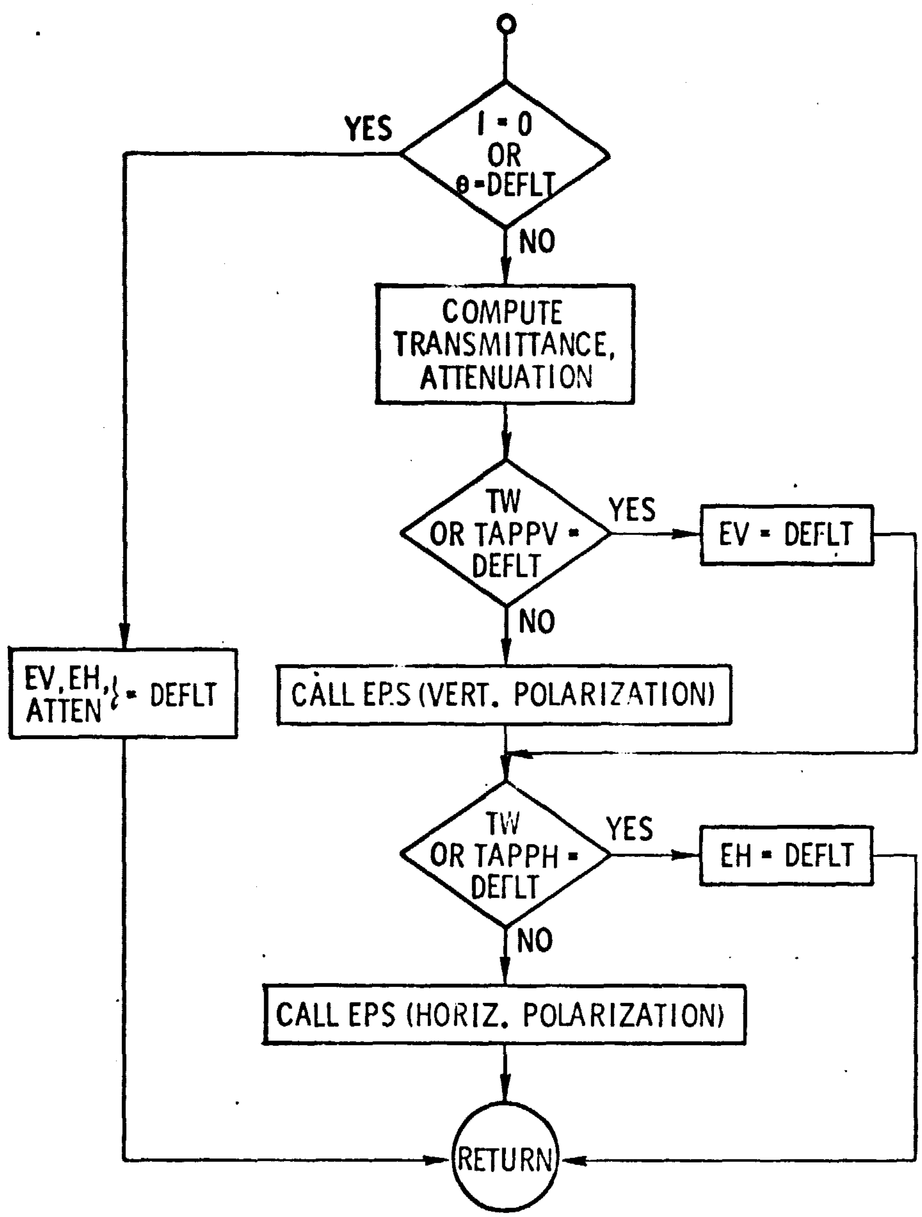
This section outlines in flow chart form the algorithms for computing the attenuation and emissivities at 50° incident angle (subroutine ATM50), those at any other incidence angle (entry point ATM), and the brightness temperature translations (subroutine TRANSREF). These major routines, and others called internally, are described and listed in Appendix A-1.

SUBROUTINE ATM50



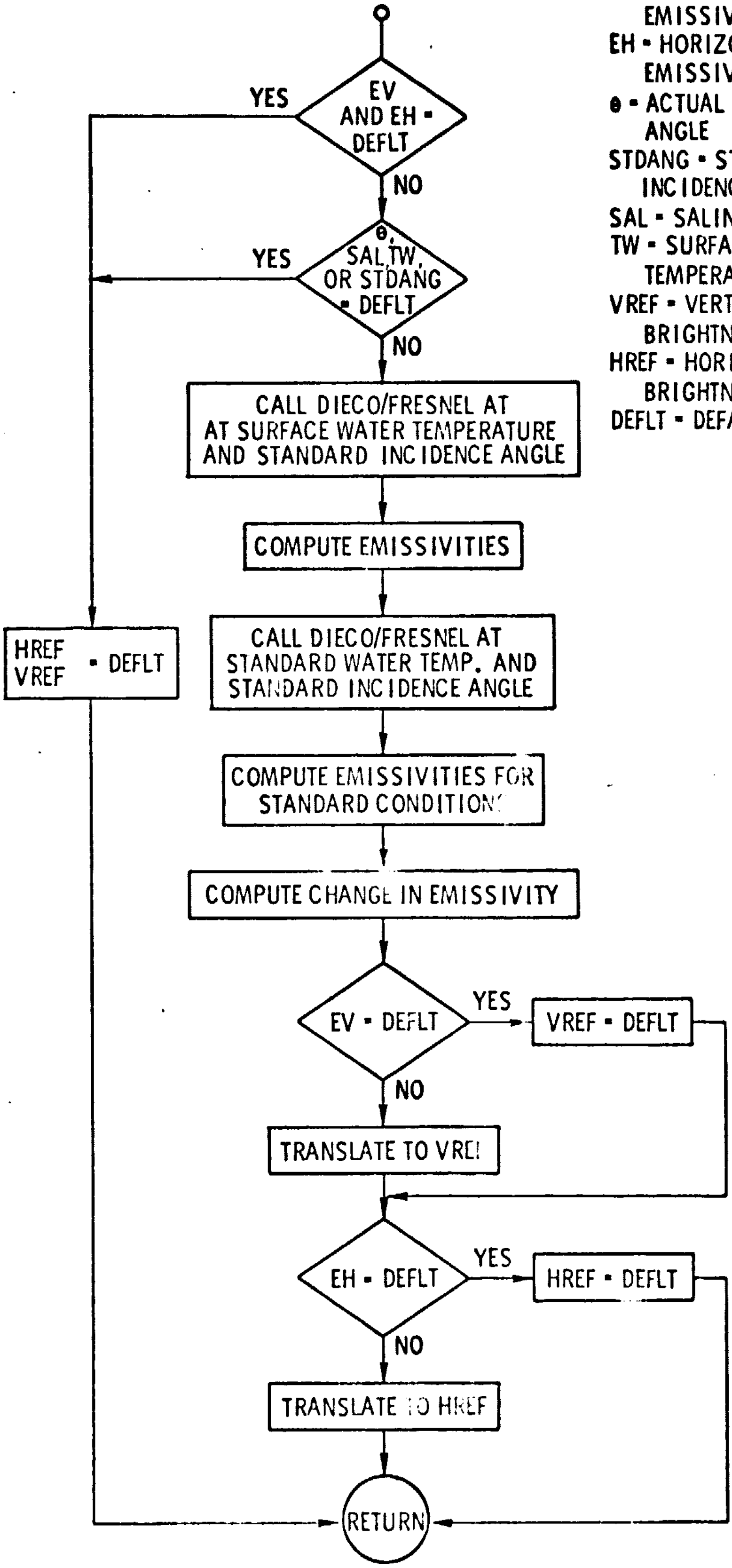
EV = VERTICAL EMISSIVITY
EH = HORIZONTAL EMISSIVITY
ATTEN = ATTENUATION
θ = ACTUAL INCIDENCE ANGLE
TW = SURFACE WATER TEMPERATURE
SAL = SALINITY
TAPPV = VERTICAL APPARENT TEMPERATURE
TAPPH = HORIZONTAL APPARENT TEMPERATURE
DEFLT = DEFAULT VALUE

ENTRY POINT ATM



EV = VERTICAL EMISSIVITY
EH = HORIZONTAL EMISSIVITY
ATTEN = ATTENUATION
θ = ACTUAL INCIDENCE ANGLE
TW = SURFACE WATER TEMPERATURE
TAPPV = VERTICAL APPARENT TEMPERATURE
TAPPH = HORIZONTAL APPARENT TEMPERATURE
DEFLT = DEFAULT VALUE

SUBROUTINE TRANSREF



EV = VERTICAL EMISSIVITY
EH = HORIZONTAL EMISSIVITY
θ = ACTUAL INCIDENCE ANGLE
STDANG = STANDARD INCIDENCE ANGLE
SAL = SALINITY
TW = SURFACE WATER TEMPERATURE
VREF = VERTICAL REFERENCE BRIGHTNESS TEMPERATURE
HREF = HORIZONTAL REFERENCE BRIGHTNESS TEMPERATURE
DEFLT = DEFAULT VALUE

APPENDIX A-1

Description and Listing of Subroutines

Fortran IV subroutines and a brief description of how to use them are listed in this appendix. Each routine is documented internally for more detailed user information. The equations and formulas shown in the programs are based on derivations given in the text, with some modifications as to variable names.

MAJOR SUBROUTINES

Subroutine ATM50 A-1.1

This routine computes the polarized emissivities and attenuation for the 50° incidence angle case. Should input variables of incidence angle, water temperature, salinity, or vertical apparent temperature be default, the output variable will likewise be defaulted since all of these input quantities are necessary to compute emissivity and attenuation. Vertical emissivity and attenuation are computed independently of horizontal apparent temperature, so should horizontal apparent temperature be default, a default value only for horizontal emissivity will be returned along with computed values for vertical emissivity and attenuation.

Entry point ATM A-1.2

This entry point in subroutine ATM computes the polarized emissivities and attenuation for incidence angles other than 50°. The input and output arguments are identical with those in subroutine ATM50. The mean atmospheric temperature and the opacity, which are constant at all incidence angles, are determined in ATM50 and are used here to determine the polarized emissivities and the attenuation.

Subroutine TRANSREF A-1.3

This routine performs the reference brightness temperature translations discussed in section II. Input quantities of water temperature, salinity, incidence angle, and standard incidence angle are required to calculate the Fresnel reflection coefficients and, likewise the emissivities, for a smooth sea. The values for frequency and salinity are specified in a DATA statement. The change in emissivity in translating from the surface water temperature at the actual incidence angle to the standard water temperature at the standard incidence angle is computed. Then, by knowing the emissivities for a roughened sea, the standard emissivities and the reference brightness temperature can be computed.

```
      SUBROUTINE ATM50(THETA,TW,TAPV,TAPH,SAL,EV,EH,ATTEN)
C
C              THIS ROUTINE COMPUTES THE POLARIZED EMISSIVITIES AND
C              ATTENUATION AT 50 DEGREES INCIDENT ANGLE. THE INCIDENT
C              ANGLE (THETA) AND WATER TEMPERATURE (TW) ARE CONVERTED
C              FROM DEGREES TO RADIANS AND FROM DEGREES CENTIGRADE
C              TO DEGREES KELVIN INTERNALLY. THE ROUTINE ALSO CHECKS
C              THE INPUT ARGUMENTS FOR DEFAULT VALUES. SHOULD THERE
C              EXIST ANY DEFAULTED INPUT PARAMETERS, THE ROUTINE
C              WILL RETURN DEFAULT VALUES FOR THE CORRESPONDING
C              OUTPUT PARAMETERS.
C
C     INPUT PARAMETERS
C                  THETA = INCIDENT ANGLE (DEG)
C                  TW = WATER TEMPERATURE (DEG C)
C                  TAPV = VERTICAL APPARENT TEMPERATURE (DEG K)
C                  TAPH = HORIZONTAL APPARENT TEMPERATURE (DEG K)
C                  SAL = SALINITY IN PPM
C     OUTPUT PARAMETERS
C                  EV = VERTICAL EMISSIVITY
C                  EH = HORIZONTAL EMISSIVITY
C                  ATTEN = ATTENUATION (DB)
C      INTERNAL PARAMETERS
C                  I = A FLAG WHICH IS SET TO DETERMINE WHETHER OR NOT
C                      ALL THE OUTPUT PARAMETERS ARE DEFAULTED FOR THE
C                      50 DEGREE CASE. WHEN I=0, ALL THE 50 DEGREE CASE
C                      PARAMETERS ARE DEFAULTED AND THERE IS NO NEED TO
C                      PERFORM THE CALCULATIONS AT THE ENTRY POINT ATM.
C                      WHEN I=1, ALL THE OUTPUT PARAMETER VALUES FOR THE
C                      50 DEGREE CASE ARE NOT DEFAULT. I IS RESET TO 1
C                      FOR EACH NEW SCAN.
C                 RV,RH = POLARIZED FRESNEL COEFFICIENTS
C                  GAMMA = TRANSMITTANCE AT 50 DEGREES INCIDENT ANGLE
C                  GAMANG = TRANSMITTANCE AT OTHER INCIDENCE ANGLES
C                  TABARV,TABARH = POLARIZED MEAN ATMOSPHERIC TEMP.
C                  TVAT,THAT = POLARIZED ATMOSPHERIC TEMPERATURES
C                  T = ATMOSPHERIC OPACITY
C
      COMPLEX RV,RH
      DATA DEFLT/0377777777777/
      DATA FREQ,I/13.9,1/
      IF(THETA.EQ.DEFLT.OR.TW.EQ.DEFLT.OR.TAPV.EQ.DEFLT.OR.SAL.EQ.DEFLT)
     1GO TO 20
C                          CONVERT INCIDENT ANGLE IN DEG TO RADIANS
      ANGRAD=THETA/57.3
C                          CONVERT WATER TEMPERATURE IN DEG C TO DEG K
      TWK=TW+273.18
C                          CALCULATE THE VERTICAL EMISSIVITY FOR
C                          THE ZERO WIND CASE
      CALL DIECO(FREQ,TWK,SAL)
      CALL FRESNEL(ANGRAD,RV,RH)
      RVM2=RV*CONJG(RV)
```

```
      EV=1.-RVM2
C                                   CALCULATE VERTICAL BRIGHTNESS TEMPERATURE
      TBV=EV*TWK
C                                   CALCULATE VERTICAL EXCESS TEMPERATURE
      TVEX=TAPV-TBV
      CALL ATTENV(TVEX,THETA,GAMMA,ATTEN,T)
      CALL TATM (TVEX,GAMMA,TWK,TAPV,TVAT,TABARV)
      IF(TAPH.EQ.DEFLT) GO TO 10
      CALL HEXCESS(TVEX,THEX)
C                                   CALCULATE HORIZONTAL BRIGHTNESS TEMPERATURE
      TBH=TAPH-THEX
C                                   CALCULATE HORIZONTAL EMMISIVITY
      EH=TBH/TWK
      CALL TATM (THEX,GAMMA,TWK,TAPH,THAT,TABARH)
      GO TO 30
   10 EH=DEFLT
      GO TO 30
   20 EV=DEFLT
      EH=DEFLT
      ATTEN=DEFLT
      I=0
   30 RETURN
      ENTRY ATM(THETA,TW,TAPV,TAPH,EV,EH,ATTEN)
C                    THIS ENTRY POINT CALCULATES THE POLARIZED
C                    EMISSIVITIES AND THE ATTENUATION FOR INCIDENT
C                    ANGLES OTHER THAN 50 DEGREES.  THE MAIN ROUTINE
C                    IS CALLED ONCE TO DETERMINE THE POLARIZED MEAN
C                    ATMOSPHERIC TEMPERATURES (TABARV AND TABARH) AND THE
C                    ATMOSPHERIC OPACITY (T) FOR THE 50 DEGREE CASE AND
C                    SINCE THESE ARGUMENTS ARE CONSTANT AT ALL OTHER
C                    INCIDENCE ANGLES, THE EMISSIVITIES AND ATTENUATION
C                    MAY BE DETERMINED FOR ANY INCIDENT ANGLE.
C
      IF(I.EQ.0.OR.THETA.EQ.DEFLT) GO TO 70
      ANGRAD=THETA/57.3
      SECANG=1./COS(ANGRAD)
C                                   CALCULATE THE TRANSMITTANCE AND ATTENUATION
      GAMANG=EXP(-SECANG*T)
      ATTEN=-10.*ALOG10(GAMANG)
      IF(TAPV.EQ.DEFLT.OR.TW.EQ.DEFLT) GO TO 40
      TWK=TW+273.18
      CALL EPS (TABARV,TAPV,GAMANG,TWK,EV)
      GO TO 50
   40 EV=DEFLT
   50 IF(TAPH.EQ.DEFLT.OR.TW.EQ.DEFLT) GO TO 60
      TWK=TW+273.18
      CALL EPS (TABARH,TAPH,GAMANG,TWK,EH)
      GO TO 80
   60 EH=DEFLT
      GO TO 80
   70 EV=DEFLT
      EH=DEFLT
```

```
   105             ATTEN=DEFLT
   106          80 RETURN
   107             END
*****W  1470 EQUALITY OR NON-EQUALITY COMPARISON MAY NOT BE MEANINGFUL IN LOGICAL IF EXPRESSIONS
```

```
      SUBROUTINE TRANSREF(TW,SAL,THETA,STDANG,EV,EH,TBVREF,TBHREF)
C
C                 THIS ROUTINE CORRECTS THE RADIOMETER MEASUREMENTS
C                 BY TRANSLATING THE BRIGHTNESS TEMPERATURE TO A
C                 REFERENCE BRIGHTNESS TEMPERATURE BASED ON 290 DEGREE
C                 KELVIN WATER TEMPERATURE AND THE STANDARD ANGLE
C                 SPECIFIED.
C
C     INPUT PARAMETERS
C                      TW = WATER TEMPERATURE (DEG C)
C                      SAL = SALINITY IN PPM
C                      THETA = INCIDENT ANGLE (DEG)
C                      STDANG = STANDARD ANGLE (DEG)
C                      EV = VERTICAL EMISSIVITY
C                      EH = HORIZONTAL EMISSIVITY
C     OUTPUT PARAMETERS
C                      TBVREF = VERTICAL REFERENCE TEMPERATURE (DEG K)
C                      TBHREF = HORIZONTAL REFERENCE TEMPERATURE (DEG K)
C
      DATA FREQ,TS/13.9,290./
      DATA DEFLT/03777777777777/
      COMPLEX RV,RH
      IF(EV.EQ.DEFLT.AND.EH.EQ.DEFLT) GO TO 100
      IF(TH.EQ.DEFLT.OR.SAL.EQ.DEFLT.OR.THETA.EQ.DEFLT.OR.STDANG.EQ.DEFL
     1T) GO TO 100
C                                    CONVERT INCIDENT ANGLE IN DEG TO RADIANS
      ANGRAD=THETA/57.3
C                                    CONVERT STANDARD INCIDENT ANGLE
C                                    IN DEGREES TO RADIANS
      SAR=STDANG/57.3
C                                    CONVERT WATER TEMPERATURE IN DEG C TO DEG K
      TWK=TW+273.18
C                                    CALCULATE THE FRESNEL COEFFICIENTS AND
C                                    THE EMISSIVITIES AT THE CELL WATER
C                                    TEMPERATURE AND THE ACTUAL INCIDENT ANGLE
      CALL DIECO(FREQ,TWK,SAL)
      CALL FRESNEL(ANGRAD,RV,RH)
      RVM2=RV*CONJG(RV)
      RHM2=RH*CONJG(RH)
      EPSLV=1.-RVM2
      EPSLH=1.-RHM2
C                                    CALCULATE THE FRESNEL COEFFICIENTS AND
C                                    THE EMISSIVITIES AT THE STANDARD WATER
C                                    TEMPERATURE (290 DEG KELVIN) AND THE
C                                    STANDARD INCIDENT ANGLE
      CALL DIECO(FREQ,TS,SAL)
      CALL FRESNEL(SAR,RV,RH)
      RVMG2=RV*CONJG(RV)
      RHMG2=RH*CONJG(RH)
      EPSLNV=1.-RVMG2
      EPSLNH=1.-RHMG2
C                                    CALCULATE THE CHANGE IN EMISSIVITY BETWEEN
```

```
      C                              THE STANDARD AND CELL WATER TEMPERATURES
            DELEV=EPSLNV-EPSLV
            DELEH=EPSLNH-EPSLH
      C                              TRANSLATE TO THE REFERENCE WATER TEMP.
            IF(EV.EQ.DEFLT) GO TO 50
            ESV=EV+DELEV
            TBVREF=TS*ESV
            GO TO 60
         50 TBVREF=DEFLT
         60 IF(EH.EQ.DEFLT) GO TO 80
            ESH=EH+DELEH
            TBHREF=TS*ESH
            GO TO 200
         80 TBHREF=DEFLT
            GO TO 200
        100 TBVREF=DEFLT
            TBHREF=DEFLT
        200 RETURN
            END
*****W  1470 EQUALITY OR NON-EQUALITY COMPARISON MAY NOT BE MEANINGFUL IN LOGICAL IF EXPRESSIONS
```

ROUTINES CALLED BY THE MAJOR ROUTINES

Subroutine ATTENV A-1.4

This routine which is called by ATM50 takes the 50° vertical excess temperature and returns the attenuation and the transmittance. The incidence angle is then used in conjunction with the transmittance to obtain the atmospheric opacity.

Subroutine HEXCESS A-1.5

This routine, which is called at the entry point ATM, takes the 50° vertical excess temperature and returns the horizontal excess temperature.

Subroutine TATM A-1.6

This routine, which is called at the entry point ATM, takes the input quantities excess temperature, transmittance, water temperature, and apparent temperature, calculates the emissivity and atmospheric temperature and returns a value for the mean atmospheric temperature for any incidence angle.

Subroutine EPS A-1.7

This routine, which is called at the entry point ATM, calculates the emissivity at any incidence angle given the mean atmospheric temperature, the apparent temperature, the transmittance, and the surface water temperature.

Subroutine FRESNEL A-1.8

This routine, called by both ATM50 and TRANSREF, computes the Fresnel reflection coefficients for sea water given the incidence angle. This routine must be initialized by calling entry point DIECO which computes the dielectric constant for sea water, given the frequency, water temperature, and salinity.

```
      SUBROUTINE ATTENV (TVEX50,THETA,GAM50,ATTN50,T)
C             THIS ROUTINE CALCULATES THE ATTENUATION,TRANSMITTANCE,
C             AND OPACITY AT 50 DEGREES INCIDENT ANGLE.
C
C     INPUT PARAMETERS
C                     TVEX50 = VERTICAL EXCESS TEMPERATURE
C                              AT 50 DEGREES INCIDENT ANGLE (DEG K)
C                     THETA = INCIDENT ANGLE (DEG)
C     OUTPUT PARAMETERS
C                     GAM50 = TRANSMITTANCE AT 50 DEGREES
C                     ATTN50 = ATTENUATION AT 50 DEGREES (DB)
C                     T = ATMOSPHERIC OPACITY
C
      X=TVEX50
      ATTN50=0.017950335*X-0.00005559*X**2+0.000004331*X**3
      GAM50=10.**(-ATTN50/10.)
      RAD=THETA/57.3
      SEC=1./COS(RAD)
      T=-(ALOG(GAM50))/SEC
      RETURN
      END
```

```
      SUBROUTINE HEXCESS(V,H)
C              THIS ROUTINE CALCULATES THE HORIZONTAL EXCESS TEMPERATURE
C              AS A FUNCTION OF VERTICAL EXCESS TEMPERATURE.
C
C     INPUT PARAMETER
C                   V = VERTICAL EXCESS TEMPERATURE (DEG K)
C     OUTPUT PARAMETER
C                   H = HORIZONTAL EXCESS TEMPERATURE (DEG K)
C
      H=1.53102*V+.00447*V**2-.00008*V**3
      RETURN
      END
```

```
      SUBROUTINE TATM(TEX50,GAMMA,TWK,TAPP,TATM50,TK)
C           THIS ROUTINE CALCULATES THE POLARIZED ATMOSPHERIC
C           TEMPERATURE AT 50 DEGREES AND MEAN ATMOSPHERIC TEMP.
C
C     INPUT PARAMETERS
C              TEX50 = EXCESS TEMPERATURE FOR 50
C                      DEGREES INCIDENT ANGLE (DEG K)
C              GAMMA = TRANSMITTANCE AT 50 DEGREES INCIDENT ANGLE
C              TWK = WATER TEMPERATURE (DEG K)
C              TAPP = POLARIZED APPARENT TEMPERATURE (DEG K)
C     OUTPUT PARAMETERS
C              TATM50 = POLARIZED ATMOSPHERIC TEMPERATURE (DEG K)
C              TK = POLARIZED MEAN ATMOSPHERIC TEMPERATURE
C
      E50=(TAPP-TEX50)/TWK
      A=TEX50
      B=GAMMA
      C=E50
      D=TWK
      TATM50=(A-(B-1.)*C*D-2.7*B*B*(1.-C))/(B*(1.-C)+1.)
      TK=TATM50/(1.-GAMMA)
      RETURN
      END
```

```
      SUBROUTINE EPS(TK,TAPP,GAMANG,TWK,E)
C             THIS ROUTINE CALCULATES THE POLARIZED EMISSIVITY AT A
C             GIVEN INCIDENT ANGLE OTHER THAN 50 DEGREES.
C
C     INPUT PARAMETERS
C                   TK = POLARIZED MEAN ATMOSPHERIC TEMPERATURE
C                   TAPP = POLARIZED APPARENT TEMPERATURE (DEG K)
C                   GAMANG = TRANSMITTANCE
C                   TWK = WATER TEMPERATURE (DEG K)
C     OUTPUT PARAMETER
C                   E = POLARIZED EMISSIVITY
C
      TATM=TK*(1.-GAMANG)
      A=TAPP
      B=GAMANG
      C=TATM
      D=TWK
      E=(A-C*(B+1.)-2.7*B*B)/(B*(D-C-2.7*B)-C)
      RETURN
      END
```

```
      SUBROUTINE FRESNEL(THETA,RV,RH)                                   350
C            THIS ROUTINE COMPUTES THE CLASSICAL                        360
C            FRESNEL REFLECTION COEFFICIENTS FOR SEA WATER.             370
C            THIS SUBROUTINE MUST BE INITIALIZED BY                     380
C            CALLING THE SECONDARY ENTRY ROUTINE DIECO.                 390
C            THE COMPLEX PERMITTIVITY IS COMPUTED BY DIECO.             400
C            ONCE HAVING COMPUTED THE PERMITTIVITY FOR A PARTICULAR     410
C            FREQUENCY(FREQ), WATER TEMPERATURE(TEMP), AND              420
C            SALINITY(SAL), FRESNEL MAY BE CALLED REPEATEDLY            430
C            FOR DIFFERENT ANGLES(THETA).                               440
C                                                                       450
C     INPUT PARAMETERS                                                  460
C                  FREQ = FREQUENCY IN GHZ                              470
C                  TEMP = TEMPERATURE(DEG K)                            480
C                  SAL = SALINITY IN PPM                                490
C                  THETA = INCIDENT ANGLE (RADIANS)                     500
C     OUTPUT PARAMETERS                                                 510
C                  RV = VERT. POL. FRESNEL COEFF. (COMPLEX)             520
C                  RH = HORT. POL. FRESNEL COEFF. (COMPLEX)             530
      DIMENSION E(2)                                                    540
      EQUIVALENCE (E(1),ESP)                                            550
      COMPLEX ESP,COST,SQ,RV,RH                                         560
      DATA PID/0.0314159265/                                            570
      COST=CMPLX(COS(THETA),0.0)                                        580
      SQ=CSQRT(ESP-CMPLX(SIN(THETA)**2,0.0))                            590
      RV=(ESP*COST-SQ)/(ESP*COST+SQ)                                    600
      RH=(COST-SQ)/(COST+SQ)                                            610
      RETURN                                                            620
      ENTRY DIECO(FREQ,TEMP,SAL)                                        630
C            THIS ENTRY POINT COMPUTES THE DIELECTRIC CONSTANT          640
C            FOR SEA WATER.  ALGO BASED ON PORTER'S WORK (1971).        650
C            (SEE S.T. WU AND A.K. FUNG'S REPORT NASA CR 2329).         660
C                                                                       670
C            CONVERT SALINITY TO NORMALITY (SEE STOGRYN IEEE            680
C            MTT AUG. 1971)                                             690
      S = SAL                                                           700
      S=((4.058E-09*S+1.205E-05)*S+1.707E-02)*S                         710
      T=TEMP-273.18                                                     720
C            NORMALIZED WAVELENGTH                                      730
      R1=((0.00147*T-0.11)*T+3.38+(0.0173*T-0.52)*S)*FREQ/30.0          740
C                                                                       750
      R2=(R1)**1.96                                                     760
      R1=R1**.98                                                        770
      E(2)=83.0-15.3*S-0.363*T                                          780
      D=1.0+2.0*R1*PID+R2                                               790
      E(1)=4.8+E(2)*(1.0+R1*PID)/D                                      800
      SIG=(0.12*T+5.0)*S+0.04*T                                         810
      E(2)=18.0*SIG/FREQ+E(2)*R1/D                                      820
      RETURN                                                            850
      END                                                               860
```

APPENDIX A-2

Derivation of the Mean Atmospheric Temperature

T_{SKY} is defined as the atmospheric contribution to apparent temperature looking up through the atmosphere. T_{SKY} can be represented as the integral if the physical temperatures,

$$T_{SKY} = \sec\theta \int_0^{\infty} T(z)\,\alpha(z)\, e^{-\sec\theta \int_0^{z} \alpha(z')\,dz'}$$

T (z) is the physical temperature at altitude z the attenuation and $e^{-\sec\theta \int_0^z \alpha(z')dz'}$ the transmittance with $\tau = \int_0^z \alpha(z')\,dz'$ being the atmospheric opacity. Then,

$$d\tau = \alpha(z)\,dz$$

Now, T_{SKY} is expressed as

$$T_{SKY} = \sec\theta \int_0^{\tau_0} T(z)\, e^{-\tau\sec\theta}\, d\tau$$

Define $\bar{T}_A(\theta)$ as

$$\bar{T}_A(\theta) = \frac{\int_0^{\tau_0} T(z)\, e^{-\tau\sec\theta}\, d}{\int_0^{\tau_0} e^{-\tau\sec\theta}\, d}$$

Using this value with the equation for T_{SKY}

$$T_{SKY} = \bar{T}_A(\theta)\,\sec\theta \int_0^{\tau_0} e^{-\tau\sec\theta_0}\, d\tau$$

Integrating,

$$T_{SKY} = \bar{T}_A(\theta)\left(1 - e^{-\tau_0\sec\theta}\right) = \bar{T}_A(\theta)\left[1 - \Gamma(\theta)\right]$$

Sample calculations from ATRAD show $\tilde{T}_A$ to be virtually independent of θ.

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2. Hollinger, J. P., "Passive Microwave Measurements of Sea Surface Roughness", IEEE Transactions, vol. GE-9, no. 3, pp. 165-169, July 1971.

3. Wu, S. T., and A. K. Fung, "A Theory of Microwave Apparent Temperature Over the Ocean", NASA Contractor Report, NASA CR-2359, November, 1973.

4. Computer program prepared by John Claassen, Remote Sensing Laboratory, University of Kansas.