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Appendix B
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ALGORITHM AND DATA USER MANUAL FOR THE SPECIAL SENSOR MICROWAVE IMAGER/ SOUNDER (SSMIS)

Appendix B: SSMIS LOWER AIR TEMPERATURE AND THICKNESS RETRIEVAL ALGORITHM

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TECHNICAL REPORT

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SSMIS LOWER AIR TEMPERATURE AND THICKNESS RETRIEVAL ALGORITHMS

1 INTRODUCTION AND SUMMARY

The SSMIS system is required to determine air temperatures at a fixed set of pressure levels from 1000mb to 0.03mb and the thicknesses of the atmosphere between specified levels. The lower air portion of the retrievals concerns the soundings up to 10Mb (corresponding to a height of approximately 30 km) and is separated from retrievals substantially above this level because the rafter requires a consideration of physical phenomena arising from the Zeeman splitting of the oxygen molecule absorption lines due to the earth's magnetic field and demands specialized treatment.

For the atmosphere up to 10mb, the SSMIS must determine the air temperature at 15 mandatory pressure levels: 1000,850,700,500, 400,300,250,200,150,100,70,50,30,20, and 10mb. In addition, the 14 thicknesses between each pair of adjacent levels is to be determined. Estimates of the tropopause pressure and temperature are also required. This note describes the algorithms developed to accomplish this task.

A regression matrix approach is used. In order to meet accuracy requirements, a number of matrices are required. However, in contrast to the earlier SSM/T-1, which used a fixed stratification based on four seasons of the year and three geographical zones, the SSMIS employs a dynamical stratification method where the choice of the inversion matrix to be used is determined by an initial estimate of the tropopause pressure, Ptrop , obtained from an analysis of the microwave data. Three regimes are distinguished: (1) Ptrop <120mb which corresponds to high tropopause heights and typically to warm or hot mean tropospheric air temperatures, (2) a middle range 120< Ptrop<250mb, and (3) Ptrop> 250mb which corresponds to low tropopause heights and typically to cool or cold mean tropospheric air temperatures. After the proper matrix is selected, the air temperatures are retrieved together with the tropopause temperature and a final estimate of the tropopause pressure.

A separate calculation of the atmospheric thicknesses between the specified pressure levels is made using the derived air temperatures and a knowledge of the specific humidity (which is obtained from humidity retrieval algorithms contained in the SSMIS software package). The dependence of the thicknesses upon humidity data requires that, in the ordinary running of the SSMIS software, the humidity algorithms be exercised before the thickness algorithms. The air temperature retrieval is independent of the humidity algorithms and may be run either before or after the humidity algorithms. If, for any reason, the humidity algorithms are not run, atmospheric thicknesses may still be obtained by setting the specific humidity equal to zero at each of the levels where it is required in the thickness algorithms. In this case, the accuracy of the derived thicknesses is decreased in the lowest portion of the atmosphere. However, the retrieval results are still quite satisfactory. The thickness algorithms should not be exercised without air temperature data.

In order to apply the regression technique mentioned above, some accounting for earth surface effects must be made because the emissivity and reflectivity of the earth can vary over a wide range and because the earth's surface is not always at sea level but can vary over a height of several thousand meters. To accommodate these effects without introducing a host of regression matrices representing different backgrounds, a technique, which was pioneered in the SSM/T-1 program, is used where a component of the data vector is not simply the measured brightness temperature but consists of that part of the brightness temperature which depends only on the atmospheric state and is independent of the background. The data vector components for those channels which receive energy only from higher levels of the atmosphere and do not "see" the surface reduce to the brightness temperatures. For the SSMIS, significant refinements in the SSM/T-1 background correction algorithms have been made so that greater accuracy is achieved.

It is shown that the algorithms retrieve air temperatures with the required RMS accuracy at all pressure levels (8K at 1000mb, 6Kat 850mb, and 2K from 700 to 10mb). In most instances, the retrieval accuracy is significantly better than the stated requirement. For the tropopause temperature, the required 5K accuracy is met with wide margin. However, the goal of 1 K accuracy is not achieved. Nor is the goal of a tropopause pressure accuracy of $\pm$20mb (RMS) achieved. The fact that these very stringent goals for the tropopause were not reached is not surprising in view of the wide variability of the tropopause height and the width of the weighting functions. However, the accuracy achieved by the SSMIS in this area is significantly better than that reached by its predecessor, the SSM/T-1. The mean calculated error in the retrieved air temperature at each of the levels from 1000 to 10mb showed that the temperature bias requirement of less than 1 K is fully satisfied.

2 PHYSICAL CONSIDERATIONS

The SSMIS is a 24 channel radiometer system which uses a conical scan and the satellite motion to cover the earth's surface and atmosphere. For a nominal orbital altitude of 833 km, the angle of incidence with the earth's surface of the radiometer beam is 53.1deg. Only the channels within the oxygen absorption complex in the 50-70 GHz region are particularly significant for air temperature retrievals and only these will be considered here. Table I lists the characteristics of these channels.

The usefulness of a channel for sounding the atmosphere at a particular height is determined by its weighting function behavior. The weighting function is defined as follows. For-a given frequency, the radiative transfer equation may be solved for the brightness temperature, T_B, at satellite altitude to yield the expression

$$T_B = L\left[\in T_g + (1-\in)\, T_{sky}\right] + T_{atm}$$

Eq. 1

where

$$L = \exp\left[-\sec\theta \int_0^{\infty} K dz\right]$$

Eq. 2

$$T_{sky} = \sec\theta \int_0^{\infty} K_{air} \exp\left[-\sec\theta \int_0^{Z} K dz\right] dz + LT_c$$

Eq. 3

$$T_{atm} = \sec\theta \int_0^{\infty} KT_{air} \exp\left[-\sec\theta \int_Z^{\infty} K dz\right] dz$$

Eq. 4

Here θ is the angle of incidence on the earth's surface, K the height dependent absorption coefficient at the specified frequency, T_{air} the height dependent temperature of the atmosphere being observed, T_c the cosmic background temperature, T_g. the temperature of the ground, and ε: the emissivity of the ground. The integrals in equations (Eq. 2)-(Eq. 4) are integrations over the height of the atmosphere. Physically, L represents the effect of attenuation in propagating through the atmosphere, T_{sky} represents the downward flowing radiation emitted by the atmosphere and incident on the surface, and T_{atm} represents the upward flowing radiation emitted by the atmosphere and reaching the radiometer. Thus, the total signal at a frequency consists of the sum of the reflected sky brightness temperature and temperature emitted by the ground, both attenuated by the intervening atmosphere when propagating toward the satellite, and the direct contribution of the atmosphere. The brightness temperature detected by a particular channel is simply the average of T_B over the pass band of the channel. Eq. 1 to Eq. 4 may be rearranged as

Eq. 5

where

$$W(z) = L \sec\theta\, K \left\{(1-\in)\exp\left[-\sec\theta\int_0^Z \mathrm{K dz}\right] + \exp\left[\sec\theta\int_0^Z \mathrm{K dz}\right]\right\}$$

Eq. 6

The function W(z), averaged over the channel pass band, is a measure of the amount of energy emitted by the atmosphere in the height interval dz at the height z and is called the weighting function of the channel.

$$T_B = L \in T_g + \int_0^\infty W(z)\, T_{air}(z)dz$$

Figure 1 is a plot of the weighting functions over a calm sea background for the channels listed in

Table I. It is seen that channels 19 to 23 receive large amounts of energy only from altitudes substantially above 30 km and hence are not too sensitive to atmospheric conditions below the 10mb level. For this reason, they are not too significant for lower air temperature retrievals and will be ignored here. An additional reason for ignoring channels 19 to 23 for studies below 10Mb is the complication introduced by the fact that the weighting functions for these channels depend on the strength, B_e, of the earth's magnetic field and the angle, θB, between the earth's magnetic field vector and the propagation direction. Thus, there remain only the eight channels 1 to 7 and 24 to consider for the lower air temperature retrievals.

Among these eight channels, it is obvious from Figure I that channel I receives a large part of its energy from the earth's surface. In fact, it is so sensitive to the highly variable surface contribution (and humidity near the surface) that it is not particularly useful for air temperature sounding per so. However, its sensitivity to surface conditions implies that it would be useful in estimating surface contributions to channels affected by the surface but responding principally to the atmosphere. These are channels 2 and 3 and, over highly elevated terrain, channel 4. These surface effects should be removed if the atmosphere is the object of study. To see what is required, rearrange Eq. 1 as.

$$\mathrm{T_B} = \in \mathrm{T_g}\ (\mathrm{L} - \mathrm{LT_{sky}T_g}) + \ \mathrm{T_{atm}} + \mathrm{LT_{sky}}$$

Eq. 7

Eq. 7 shows that surface effects (emissivity, ground temperature) are isolated in the first term while the term $T_{atm} + LT_{sky}$ depends only on the atmospheric state. It will be shown how to estimate the background corrections to T_B for channels 2 to 4 in

Section 4. For the present, assume that this can be done so that the quantity $(T_{atm} + LT_{sky})_o$ many considered as known when T_B is measured (the subscript o denotes that $T_{atm} + TL_{sky}$ is to be evaluated for a reference surface at sea level since background corrections must also incorporate the effects of elevated terrain). Thus, the measured data to be used in lower air temperature retrievals may be arranged as a seven component vector, d, called the data vector, which is defined as

Eq. 8

The last equation follows from the fact that $(T_{atm} + LT_{sky})_o$ is, for all practical purposes, the same as T_B for

$$d = \begin{pmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \\ d_6 \\ d_7 \end{pmatrix} + \begin{pmatrix} (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan2 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan3 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan4 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan5 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan6 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan7 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan24 \end{pmatrix} + \begin{pmatrix} (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan2 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan3 \\ (\mathrm{T_{atm}} + \mathrm{LT_{sky}})_0\, chan4 \\ T_B chan5 \\ T_B chan6 \\ T_B chan7 \\ T_B chan24 \end{pmatrix}$$

channels 5,6,7, and 24 because of the insignificance of surface effects for these channels.

3 LOWER AIR TEMPERATURE RETRIEVALS

The SSMIS is required to retrieve air temperatures (K) at 15 mandatory pressure levels. Using the pressure level (mb) as an argument, these are $T_{air}(1000)$, T_{air} (850), T_{air} (700), T_{air} (500),.T_{air} (400), T_{air} (300), T_{air} (250), T_{air} (200), T_{air} (150), T_{air} (100), T_{air} (70), T_{air} (50), T_{air} (30), T_{air} (20),and T_{air} (10). In addition, the tropopause pressure P_{trop} (mb) and tropopause temperature (K) are required. These 17 retrieved parameters may be arranged as a column vector, p, which will be referred to as the parameter vector with components pj (i=l,...,17). Specifically, p_1, = T_{air} (1000), $p_2 = T_{air}$ (850),…, $p_{15} = T_{air}$ (10), $p_{16} = P_{trop}$, and $p_{17} = T_{trop}$.

If a linear multiple regression technique is used to retrieve p in conjunction with a set of measurements arranged in a data vector (for the lower air temperature sounding problem, this is given by Eq. 8), a well known equation expresses p as

$$p - \langle p \rangle = D\,(d - \langle d \rangle)$$

Eq. 9

where D is a matrix (the regression matrix or simply the D matrix) with as many rows as p has components and as many columns as d has components. The angular brackets <... > in eq (9) denote expected value. The expected values and D many be computed from historical data (RAOBS and ROCOBS) together with integration (see eq.'s (Eq. 2)-(Eq. 4)) and averaging over channel bandwidths. Specifically

$$D = C(p - \langle p \rangle, d - \langle d \rangle)[C(d \langle d \rangle, d - \langle d \rangle) + C(\delta,\delta)]^{-1}$$

Eq. 10

where C(.......) denotes a covariance matrix. The term C(δ,δ) in Eq. 10 represents the noise covariance matrix and is required in order to account for noise in the measurements. It is useful to write Eq. 9 as

$$p = Dd + \text{const}$$

Eq. 11

$$\text{const} = \langle p \rangle - D \langle d \rangle$$

Eq. 12

for numerical work.

Because of the wide range of atmospheric conditions that will be encountered over the earth, it is useful to stratify the retrievals into classes, each of which requires a different D matrix. In this way, each matrix will have to incorporate a smaller range of conditions and thus change a problem which, in principal, is non-linear to smaller parts, each of which is more nearly linear. For the SSMIS, a dynamical stratification procedure is used where an initial estimate, P'_{trop} of the tropopause pressure is made. One of three different D matrices and constant vectors, each D with 17 rows and 17 columns and each constant with 17 components, (Eq. 11 and Eq. 12) are chosen according to whether P'_{trop} <120mb, 120≤ P'_{trop} ≤ 250mb, or P'_{trop} > 250mb. This initial estimate of the tropopause pressure may be made by using a global regression formulation (a 1X7 matrix and a 1 dimensional constant vector for the SSMIS):

Eq. 13

4 BACKGROUND CORRECTIONS

As discussed in Section 2, it desirable to work with a data vector that is independent of background

$$P'_{trop} = D_{trop}\ d + cons_{trop}$$

conditions. The estimation of the quantity $(T_{atm} + LT_{sky})_O$ for channels 2,3, and 4 will be considered here.

If the earth's surface is at a height h above sea level, then the obvious equality, obtained by using Eq. 7 with the height explicitly indicated,

$$\left(T_{atm} + LT_{sky}\right)_0 = \left(T_{atm} + LT_{sky}\right)_0 + T_B(h) - \in T_g \left\lfloor L - LT_{sky} / T_g \right\rfloor_h - \left(T_{atm} + LT_{sky}\right)_h = T_B(h) + \Delta h$$

Eq. 14

where

$$\Delta h = \left(T_{atm} + LT_{sky}\right)_0 - \left(T_{atm} + LT_{sky}\right)_h - \in T_g \left\lfloor L - LT_{sky} / T_g \right\rfloor_h$$

Eq. 15

is found. A specification of Δh will then yield the desired components of the data vector when a measurement of T_B over a surface at height h is made.

One may estimate Δh_k, for a fixed height h_k, using a regression approach. It has been found that good results may be obtained by using a 2 component data vector consisting of the measured brightness temperatures T_B chan 1 (h_k) and T_B chan 3 (h_k). Thus, defining a 3 component parameter vector PΔ where PΔ i (h_k)= h_k chan (i+1) (i=1,2,3), the equations

$$P\Delta i(h_k) = DT(h_k)_{i1}\ T_{Bchan\ 1} + DT(h_k)_{i2}\ T_{Bchan\ 3} C0_i(h_k)\ (i = 1,2,3)$$

Eq. 16

are found where DT is the regression matrix and CO is the constant vector. Of course, since any height between 0 and 6200 meters (the largest height in the AFGWC RFIX64 field) may arise in practice, Eq. 16's must be extended to allow a continuous dependence upon the height h. The coefficients in Eq. 16's become continuous functions of h. A satisfactory approximation to these continuous functions is obtained by using a piecewise linear approximation, where the transition to diff aren't linear pieces are made at-

$$p\Delta i(h) = C_{i1}(h)\, T_B chan1(h) + C_{i2}(h)\, T_B chan3(h) + C_{i0}(h)\ (i = 1,2,3)$$

nodes h_k (k=l,...,K). Plots of the behavior of the coefficients showed that a suitable set of nodes consists of the eight heights 0,500,1000,2000,3000,4000, 5000,6200 meters. With this approach, the background correction parameter vector may be expressed as

Eq. 17

where, for example, if $h_{k-1} \leq h \leq h_{k,}$ then

$$C_{i1} = \frac{DT_{i1}(h_k) - DT_{i1}(h_{k-1})}{h_k - h_{k-1}}\left(h_k - h_{k-1}\right) + \left(DT_{i1}(h_{k-1})\right)$$

Eq. 18

Linear equations analogous to Eq. 18 apply to coefficients $C_{i2}(h)$ and $C_{io}(h)$.

Numerical studies indicate that Eq. 17 lead to significant improvements over an earlier algorithm developed for the SSM/T-1 for surface heights above a few hundred meters. They also lead to some improvement at sea level. However, a further refinement may be made by distinguishing the ocean from all other backgrounds since the ocean, even at high sea states, will generally not lead to εT_g products (see Eq. 1) exceeding 151K at the frequency, polarization, and angle of incidence of channel 1. This is generally much less than found for other backgrounds. A regression based inequality for -ET, of the form

$$T_{G1}\ T_{Bchan1} + \in TG_2\ T_{Bchan3} + + \in TG_0 < 151$$

Eq. 19

together with the condition h=O is used to identify ocean backgrounds. If the inequality Eq. 19 is satisfied and h=O, the background is identified as Ocean and the regression equations

Eq. 20

$$p_{\Delta i} = ODT_{i1}\ T_{B\,chan\,1} + ODT_{i2} T_{B\,chan\,3} + OCO_i \qquad (i = 1,2,3)$$

are used to estimate the background correction instead of Eq. 17, which are used for all other cases. The coefficients in Eq. 20 are derived by calculations using conditions pertinent only to the ocean.

5 THICKNESS RETRIEVALS

The SSMIS is required to retrieve the thickness of the atmosphere between the pressure levels at which the air temperature is retrieved up to 10mb. Specifically, the thickness is required for the 14 pressure intervals 1000-850,850-700,700-500,500- 400,400-300,300-250,250-150,150-100,100-70,70-50,50-30,30-20, and 20-10mb.

A direct, physically based retrieval of these thicknesses is performed. It is assumed that the air temperatures have already been obtained and that the specific humidity up to 300mb has been retrieved by use of the humidity sounding channels. If the specific humidity is not available, setting it equal to zero in the equations below will provide slightly reduced accuracy in the thickness calculations.

The basis for the algorithm is the set of equations

$$P = \rho R T_V$$

Eq. 21

$$dP = -\rho g dz$$

Eq. 22

Eq. 21 expresses the ideal gas law for air (P = pressure, ρ = density, R = gas constant for dry air, and T_v virtual temperature) and Eq. 22 is the differential equation for- static equilibrium (g = acceleration due to gravity, z = height). Eliminating ρ and solving for P yields the equation

Eq. 23

$$\ln(P / P_1) = -\frac{g}{R} \int_{z_1}^{z} \frac{dz}{t_v}$$

$$T_v = T_1 + \frac{T_2 - T_1}{Z_2 - Z_1}(Z - Z_1)$$

where z_1 and P_1 are the height and pressure of a base level. In order to obtain an explicit expression, the height dependence of T_v must be specified. This is assumed to be linear in z between z_1 and some height z_2:

Eq. 24

Using eq (24) in eq (23) results in

$$\ln(P/P_1) = \begin{cases} -(g/R)\dfrac{z - z_1}{T_1} & \text{if} T_1 = T_2 \\ -(g/R)\dfrac{z_2 - z_1}{T_2 - T_1} \quad \ln\left[\dfrac{T_1 + \dfrac{T_2 - T_1}{z_2 - z_1}(z - z_1)}{T_1}\right] & \end{cases}$$

$\text{if} T_1 \neq T_2$

Eq. 25

In particular, Eq. 25 may be solved for the thickness $z_2 - z_1$ to yield

Eq. 26

$$z_2 - z_1 = \begin{cases} -(RT_1/g)\ln(P_2/P_1) & \text{if} T_1 = T_2 \\ -(R/g)(T_2 - T_1)\dfrac{\ln(P_2/P_1)}{\ln(T_2 - T_1)} & \text{if} T_1 \neq T_2 \end{cases}$$

If P_1 and P_2 are chosen to be adjacent pairs of mandatory pressure levels, Eq. 26 is the general solution for the required thickness calculations. However, a simple approximation to Eq. 26 may be obtained if these mandatory levels are used. The terms involving the temperature in the second line of Eq. 26 may be

$$z_2 - z_1 = -(R/2g)\ln(P_2/P_1)\left[T_1 + T_2 - \frac{(T_2 - T_1)^2}{6T_1} + \ldots\right]$$

expanded in powers of $(T_2\text{-}T_1)/T_1$, to yield the uniform expression

Eq. 27

valid whether or not $T_1=T_2$. Since the adjacent mandatory pressure levels are close enough so that $(T_2\text{-}T_1)^2/6\,T_1$, is very small compared to T_1+T_2 , it is usually neglected. Thus, the equation for thickness is

Eq. 28

$$z_2 - z_1 = -(R/2g)\ln(P_2/P_1)[T_1 + T_2]$$

$$T_V = T\left[1 + .608\text{x}10^{-3}q\right]$$

In Eq. 28, T_1 and T_2 represent virtual temperatures. These are related to the air temperature, T, and specific humidity, q(gm/kg), by

Eq. 29

Eq. 28 and Eq. 29 represent the thickness calculation algorithm. The multiplying factor $-(R/2g)\ln(P_2/P_1)$ is a constant. Table 11 is a tabulation of this constant for the required thickness levels. It is obtained from the values R=287.04XI0^6 erg/(gm K) and g=9.8m/sec^2 that are used at AFGWC (in the AFGWC system, the value of g does not vary with height up to 10mb). Thus R/2g m 14.645m/K.

6 RETRIEVAL ACCURACY

The lower air temperature retrieval algorithms were derived using a developmental set of 1187 atmospheric soundings representing all seasons of the year in the polar, mid- altitude, and tropical zones, A second, independent set of 1174 atmospheric soundings covering all seasons and climate zones was used to derive the performance statistics to be discussed below.

In addition to the atmospheric soundings, care was taken to develop a representative set of earth surface conditions for the tests. In fact, each of the 1174 test soundings were combined with 15 randomly selected backgrounds to produce 17610 simulated brightness temperature measurements. These backgrounds were chosen according to a number of considerations.

First, the AFGWC PFIX64 data bass was analyzed at the 1/8 mesh density. It was found that 69.5% of the backgrounds were water (primarily ocean, of course but some large lakes are included), 25.2% land, 1.72% sea ice, and 3.54% coastal regions in June 1990. The sea ice-water percentage varies during the course of the year because of shifting ice boundaries but the sum of the water and sea ice percentages is fixed. In generating the surface backgrounds, a choice between these four backgrounds was made with a probability corresponding to the percentage occurrence (with a slight variability in the water and sea ice fractions to allow for the temperature constraints discussed below). In the case of land and coastal backgrounds, the terrain height was randomly generated with a probability density following the percentage occurrence in the RFIX64 data bass. The highest land surface in this base is 6200 meters. Coastal surface heights follow a different distribution law than land with more than 99.99% of the height less than 2200 meters (the extreme height is 4500m).

A second consideration was the surface temperature. This, of course, may differ considerably from the air temperature at the surface. A uniformly distributed random surface temperature was generated satisfying the condition $| T_g - T_{stc\ air} | \leq 20K$ where T_g is the surface temperature and $T_{stc\ air}$ is the air temperature at the surface. Some constraints were placed on the surface temperature. If the background corresponded to water, a minimum of 271K and a maximum of 303K was allowed. For sea ice, the maximum allowed temperature was 272K.

Third, the emissivities for the backgrounds used in the inversion tests were also allowed to vary considerably. For ocean backgrounds, the emissivity as chosen uniformly in the interval (.32, .55). The lower end of this range corresponds to calm, warm seas for channel 1 while the upper and corresponds to rough, cold seas with a wind speed of 25m/sec. The choice a uniform distribution emphasizes high wind condition somewhat more than the naturally occurring distribution over the ocean, but leads to a more stringent test of the algorithm performance. For land, emissivities were allowed to range from .6 to 1. The lower value corresponds to moist conditions (or perhaps mixed backgrounds with, say, a river or small lake partially in the field of view) while the upper limit to drier, jungle type environments. Sea ice emissivities for channel 1 were chosen uniformly within the interval bounded b .737 (old sea ice) and .97 (new sea ice). Finally, coastal emissivities ranged from .36 to .96 corresponding to backgrounds consisting of mostly water to mostly high emissivity land.

FORTRAN subroutines were written to implement the inversion algorithms. Brightness temperatures were calculated using the independent atmospheric data bass and background conditions described above. In all cases, random Gaussian noise with zero mean and standard deviation given by the NEΔT's listed in Table I was added to the computed brightness temperatures.

Figure 2 is a plot of the RMS errors in the retrieved air temperatures and the mean error in the retrievals. Table III presents the results in numerical format together with the required not to be exceeded RMS errors and, where applicable, accuracy goals. Mean retrieval errors are also shown. The mean errors are well below the maximum allowed I K. It's seen that all requirements for RMS accuracy are met and, in many cases, exceeded by a substantial margin. It will be noted that the largest RMS retrieval errors are found near the surface. This is expected from the nature of the physical phenomena involved. Highly variable surface effects (emissivity, thermal temperature, terrain height) produce the equivalent of noise in the radiometer outputs as far as air temperature retrievals are concerned. The fact that requirements are met shows that the background correction algorithm removes most of the surface generated noise.

Another point of interest with respect to Table III is the increase in the retrieval error in the 400 to 150mb range. This is due to the fact that the tropopause very often lies within this interval. If a preliminary typing of the sounding were not done prior to the selection of the regression matrix, retrieval errors could easily exceed the maximum allowed 2K in this region. For example, even artificially restricting oneself to looking at only surfaces at sea level, a calculation using a single global regression matrix showed RMS retrieval errors of 2.08 and 2.17K at the 250 and 200mb levels respectively. The RMS error in the retrieved tropopause temperature of 4.37K is also considerably worse than shown in Table 111.

Atmospheric thickness retrieval errors using the same data bass and range of background conditions as above are shown in Table IV. Two cases are considered. The first assumes that the specific humidity at each level up to 300mb is measured with an error uniformly distributed in the range -30 to +300%. The second assumes that the specific humidity is not measured and is set equal to zero in the algorithm. No requirements have been specified for the accuracy of the thickness retrievals. Although not required, Table IV also shows the accuracy of the retrieval of the thicknesses of the 1000-500,500-300, and 300-100mb pressure intervals. These thicknesses were obtained by summing the retrieved thicknesses of the constituent partial layers. It is seen that the errors are considerably less than the sum of the RMS errors for the constituents. This is due to the fact that the retrievals for adjacent layer thicknesses are highly correlated with excess thickness estimates in one layer usually corresponding to diminished values in an adjacent layer.

Table I TEMPERATURE SOUNDING CHANNELS OF THE SSMIS

CHANNEL	CENTER FREQUENCY (MHz)	NOMINAL PRE-DETECTION BANDWIDTH (MHz)	POLARIZATION	NE∆T (K)	SPATIAL RESOLUTION (KM)
1	50300	400	H	.26	38
2	52800	400	H	.26	38
3	53596	400	H	.26	38
4	54400	400	H	.26	38
5	55500	400	H	.26	38
6	57290	350	H+V	.30	38
7	59400	250	H+V	.35	38
19	$f_2 \pm f_3$	1.5	H+V	1.57	75
20	$f_0 \pm f_1$	1.5	H+V	1.57	75
21	$f_0 \pm f_1 \pm 2.0$	3.0	H+V	1.20	75
22	$f_0 \pm f_1 \pm 5.5$	6.	H+V	.85	75
23	$f_0 \pm f_1 \pm 6.0$	16.0	H+V	.51	75
24	$f_0 \pm f_1 \pm 50$	60.0	H+V	.55	38

f_0=60792.668 MHz
f_1=357.892 MHz
f_2=63283.248 MHz
f_4=285.271 MHz

Table II COEFFICIENTS R/2g ln P_2/P_1 USED FOR LOWER AIR THICKNESS CALCULATIONS

Pressure Interval (mb)	R/2g ln P_2/P_1 (meters/K)
1000 - 850	2.3802
850 – 700	2.8435
700 – 500	4.9278
500 – 400	3.2680
400 – 300	4.2132
300 – 250	2.6702
250 – 200	33.2680
200 – 150	4.2132
150 – 100	5.9382
100 – 70	5.2237
70 – 50	4.9278
50 – 30	7.4813
30 – 20	5.9382
20 – 10	10.151

Table III SSMIS RETRIVAL STATISTICS AND REQUIREMENTS FOR AIR TEMPERATURE BELOW 10mb

PARAMETER VECTOR COMPONENT	DESCRIPTION	A-PRIORI DATA		RMS RETRIVAL ERROR		BIAS IN RETRIVAL	
		MEAN	STANDARD DEVIATION	SSMIS	REQUIRED	SSMIS	REQUIRED
1	$T_{air}(1000)(K)$	28W.0	16.7	5.20	8.0	-.54	1.
2	$T_{air}(850)(K)$	276.8	13.9	3.14	6.0	-.15	1.
3	$T_{air}(700)(K)$	269.1	13.1	1.99	2.0	.62	1.
4	$T_{air}(500)(K)$	254.2	12.5	1.59	2.0	.25	1.
5	$T_{air}(400)(K)$	243.4	12.2	1.61	2.0	-.07	1.
6	$T_{air}(300)(K)$	230.1	10.3	1.83	2.0	-.12	1.
7	$T_{air}(250)(K)$	223.9	7.85	1.83	2.0	-.16	1.
8	$T_{air}(200)(K)$	218.2	6.37	1.67	2.0	-.09	1.
9	$T_{air}(150)(K)$	212.7	8.71	1.64	2.0	.39	1.
10	$T_{air}(100)(K)$	208.5	12.2	1.34	2.0	-.04	1.
11	$T_{air}(70)(K)$	210.3	11.0	1.33	2.0	-.24	1.
12	$T_{air}(50)(K)$	213.7	9.44	1.27	2.0	.16	1.
13	$T_{air}(30)(K)$	218.9	9.32	1.24	2.0	-.01	1.
14	$T_{air}(20)(K)$	223.2	10.2	1.60	2.0	-.02	1.
15	$T_{air}(10)(K)$	231.9	11.5	1.56	2.0	.20	1.
16	$P_{trop}(mb)$	195.8	90.0	31.0	20.0 (GOAL)	6.40	-
17	$T_{trop}(K)$	208.1	11.3	3.16	5.0 (REQ) 1.0 (GOAL)	.41	-

Table IV SSMIS RETRIEVAL STATISTICS FOR LAYER THICKNESSES

PRESSURE INTERVAL (Mb)	A-PRIORI DATA (METERS)		RMS RETRIVAL ERROR (METERS)	
	MEAN THICKNESS	STANDARD DEVIATION	± 30% ERROR IN q	Q=0
1000 - 850	1338	75.7	16.6	19.6
850 – 700	1556	78.7	12.4	13.6
700 – 500	2582	127.7	14.5	14.3
500 – 400	1627	81.3	9.3	9.3
400 – 300	1995	95.3	11.5	11.6
300 – 250	1212	47.4	8.4	8.4
250 – 200	1445	51.6	9.7	9.7
200 – 150	1815	58.3	10.5	10.5
150 – 100	2498	127.2	21.9	21.9
100 – 70	2186	122.3	10.8	10.8
70 – 50	2089	99.2	10.3	10.3
50 – 30	3236	135.3	12.1	12.1
30 – 20	2625	115.3	14.9	14.9
20 – 10	4618	219.1	26.2	26.2
1000 – 500	5476	280.1	31.4	35.4
500 – 300	3621	176.0	17.6	17.9
300 - 100	6970	199.7	28.2	28.2

[End of Appendix B]