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DATA PROCESSING FOR THE DMSP MICROWAVE RADIOMETER SYSTEM

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ABSTRACT

A software program has been developed and tested to process microwave radiometry data to be acquired by the microwave sensor (SSM/T) on the Defense Meteorological Satellite Program (DMSP) spacecraft. The SSM/T 7-channel microwave radiometer and systems data will be data-linked to Air Force Global Weather Central (AFGWC) where they will be merged with ephemeris data prior to product processing for use in the AFGWC Upper Air Data Base (UADB). The overall system utilizes an integrated design to provide atmospheric temperature soundings for global applications. The fully automated processing at AFGWC is accomplished by four related computer processor programs to produce compatible UADB soundings, evaluate system performance, and update the a priori developed inversion matrices. Tests with simulated data produced results significantly better than climatology.

1. INTRODUCTION

With the SSM/T temperature sounder, the United States Air Force Space and Missile Systems Organization (SAMSO) and AFGWC are continuing efforts to improve the accuracy of global atmospheric temperature soundings. The objective is to overcome the limitations of infrared radiometers by providing a better capability to recover such soundings under cloudy conditions. This is expected to contribute significantly to AFGWC weather forecasting capability.

The SSM/T software is designed to satisfy the specific requirements of AFGWC. They include requirements for the operating environment, inputs, data location, operator interaction, calibration data correction, inversion algorithm, and output products. In the operational software, the brightness temperatures are processed to yield atmospheric temperatures for mandatory pressure levels of 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 mb; 14 thicknesses between the mandatory levels; and the temperature and pressure of the tropopause. These comprise the parameter vector defined in Section 3. The heights of the mandatory levels are computed by stacking the thicknesses on to the forecast 1000-mb height which is retrieved from the AFGWC system. These parameter data are stored in catalogued disk files prior to data transfer and archiving for diagnostic analysis and updating purposes.

To obtain these parameters, the SSM/T sounder system, developed at Aerojet ElectroSystems Company, operates in the oxygen absorption band at frequencies of 50.5, 53.2, 54.35, 54.9, 58.4, 58.825 and 59.4 GHz. The sensor is a crosstrack scanning radiometer which acquires data at 32-second intervals at 7 angular positions separated by 12 degrees. A multiple regression technique, applied after the radiation temperatures are adjusted for antenna pattern and terrain height effects, is used to invert the microwave data. The inversion matrices (one for each season, geographic zone and scan position) have been calculated from carefully selected a priori ensembles of atmospheric soundings and preflight-calibrated radiometer characteristics. Provisions are made to update and correct the inversion matrices after launch using coincident microwave and composite radiosonde/rocketsonde observations.

The SSM/T sensor system is expected to be operational in 1978. In the meantime, the software system has been developed, tested and implemented into the AFGWC system at Offutt Air Force Base, Nebraska. The tests, involving the use of simulated data, indicated that soundings will be obtained with an accuracy considerably better than estimates based on climatology.

2. SYSTEM DESCRIPTION

The SSM/T sensor system is designed to acquire microwave data simultaneously in the seven channels shown in Table I. Design specifications for these channels are also given in this table. Channel 1 is a window channel responding strongly to the earth's surface characteristics, dense clouds, and rain. It is centered at a frequency of 50. 5 GHz and is used to correct the other channels for these background effects. Since the polarization dependent surface effects are removed from the brightness temperature measurements, only the atmospheric effects, which are the same for all polarizations, remain. Thus, a priori polarization corrections are avoided. To achieve this result, Channels 1-4 are required to receive the same, but arbitrary, polarization. Since Channels 5-7 are not affected by the surface, their polarization may be arbitrary. The choice of an orthogonal mode was made solely for the sensor frequency separation design requirements. Frequency stabilization, stepped automatic gain control (SAGC), and instrumentation to provide critical component temperature data are further refinements of the sensor design that have a bearing on the software.

Microwave data are acquired by means of a mechanically scanning, shrouded-reflector antenna system. The calibration and data acquisition scanning geometry are illustrated in Figure 1 and the scan parameters in Table II. A planar scan is generated by mechanically rotating the shrouded reflector perpendicular to the flight path. As shown in Figure 1, microwave data are acquired for all frequencies at seven scan positions at 12-degree angular intervals. On each scan the radiometer is calibrated; first by a 300 K warm reference load and then by sensing the cold space cosmic background (2. 7 K). The scan period is 32 seconds when synchronized and 29. 4 seconds when in automatic mode. Synchronization, control, clock reference, system time and source power are furnished by the DMSP spacecraft.

For each frequency, the antenna temperature, T_A, is determined in the software by the fundamental relationship

$$T_A = T_H + \frac{T_C - T_H}{V_C - V_H} (V - V_H) \tag{1}$$

where

T_H = warm calibration reference load input temperature
T_C = cold space calibration input temperature
V_H = output voltage during warm load calibration
V_C = output voltage during cold space calibration
V = output voltage corresponding to T_A

3. RETRIEVAL TECHNIQUE

The SSM/T retrieval method is based on a linear multiple regression technique. This method, developed specifically for the DMSP SSM/T application, is described briefly below. It is assumed that the deviation of the parameter vector from the climatological mean may be expressed as a linear combination of the deviations of the measured data from its mean. Thus,

$$\hat{p} - \langle p \rangle = D\left(d - \langle d \rangle\right) \tag{2}$$

where

p = atmospheric parameter vector, d = data vector
$\hat{p}$ = predicted value of p, $\langle p \rangle$ = expected value of p
$\langle d \rangle$ = expected value of the data vector, and D is a matrix.

Equation (2) requires the matrix D to have as many rows as p has components and as many columns as d has components. The matrix D is determined by the condition that the expected value of the square of the difference between the true value of the parameter vector p and $\hat{p}$ be a minimum. This leads to the equation

$$D = C\left(p - \langle p \rangle, \, d - \langle d \rangle\right) C^{-1}\left(d - \langle d \rangle, \, d - \langle d \rangle\right) \tag{3}$$

where $C(\cdot\,,\,\cdot)$ denotes the covariance matrix of its two arguments.

By collecting terms, Equation (2) may be rewritten in the form

$$\hat{p} = Dd + A \tag{4}$$

where

$$A = \langle p \rangle - D\langle d \rangle \tag{5}$$

so that the predicted parameter vector is expressed as a constant A and a linear combination of the data.

To determine the covariance matrices required in Equation (3), either real time data gathered during sensor operation or a priori data may be used. Since a large number of upper air soundings, representing a wide range of meteorological conditions, have been archived over the years and the microwave response to a given atmosphere may be calculated, the latter method was considered to be more practical for implementation.

Since microwave radiometers possess inherent instrumental noise characteristics, the noise must be accounted for in the computations. This is accomplished by writing the data vector d as

$$d = d_o + \delta \tag{6}$$

where d_o is the exact value and δ a random error representing system noise with an expected value of zero. By replacing d on the right side of Equation (3) by Equation (6), the covariance matrices are found to be

$$C\left(p - \langle p \rangle, d - \langle d \rangle\right) = C\left(p - \langle p \rangle, d_o - \langle d_o \rangle\right) \tag{7}$$

$$C\left(d - \langle d \rangle, d - \langle d \rangle\right) = C\left(d_o - \langle d_o \rangle, d_o - \langle d_o \rangle\right) + C(\delta, \delta) \tag{8}$$

Equation (8) incorporates the expected instrumental noise characteristics in the computations through the noise covariance matrix $C(\delta, \delta)$.

As indicated above, the data vector d required for use in the multiple regression method is constructed from brightness temperatures. Frequencies at which the brightness temperatures are measured are chosen to respond to different atmospheric layers ranging from sea level to the 10 mb level. The resulting vertical coverage is determined by weighting functions which indicate the amount of microwave radiation arising from specific altitude regimes.

The weighting functions are defined by the following procedure. The radiative transfer equation shows that the brightness temperature may be expressed as

$$T = L\left[\epsilon T_g + (1 - \epsilon)\, T_{sky}\right] + T_{atm} \tag{9}$$

where

$$L = \exp\left[-\sec\theta \int_0^\infty \kappa \, dZ\right] \tag{10}$$

$$T_{sky} = \sec\theta \int_0^\infty \kappa\, T_{air} \exp\left[-\sec\theta \int_0^Z \kappa \, dZ\right] dZ \tag{11}$$

$$T_{atm} = \sec\theta \int_0^\infty \kappa\, T_{air} \exp\left[-\sec\theta \int_Z^\infty \kappa \, dZ\right] dZ \tag{12}$$

θ = angle with respect to earth's surface

T_{air} = air temperature at height Z

κ = absorption per unit length in the atmosphere

ϵ = emissivity of the ground

T_g = ground thermal temperature

Equations (10)-(12) are the transmission factor, the downward flowing component of the brightness temperature at the surface, and the upwelling component emitted between the earth and the microwave sensor. The contribution of the radiation emitted by the atmosphere to the temperature T is isolated from the ground component term by writing Equation (9) as

$$T = L\,\epsilon T_g + \int_0^\infty W(Z)\,T_{air}\,dZ \tag{13}$$

where W(Z) is the weighting function given by

$$W(Z) = L\sec\theta\,\kappa\left\{(1-\epsilon)\exp\left[-\sec\theta\int_0^Z \kappa\,dZ\right] + \exp\left[\sec\theta\int_0^Z \kappa\,dZ\right]\right\} \tag{14}$$

The function W specifies the contribution of the atmosphere in a thickness dZ at an altitude Z to the total signal energy received. Weighting functions corresponding to the 7 SSM/T frequencies are shown in Figure 2. These are computed for an ARDC model atmosphere and a calm sea background corresponding to an incident angle of 0° using a nominal spacecraft orbit altitude of 450 nmi.

For the DMSP application a data vector was chosen to depend only on the atmospheric state. This data vector is derived from a rearrangement of Equation (9) as

$$LT_{sky} + T_{atm} = T - \epsilon T_g\,L\left(1 - \frac{T_{sky}}{T_g}\right) \tag{15}$$

and

$$d_i = (L\,T_{sky} + T_{atm})_{\nu_i} \tag{16}$$

where ν_i = radiometer frequencies.

Since the right-hand side of Equation (16) is not directly measurable, it must be computed from the measurements. This is made possible by the proper employment of the 50.5 GHz channel to determine ϵT_g and the lower troposphere contributions from dense clouds and rain. Thus the data vector defined in Equation (16) is a 6-component vector where ν_i are the 6 highest frequencies previously specified.

To fully understand the ramifications of the SSM/T data vector concept, Equation (9) is rewritten as

$$(\epsilon T_g)_{50.5} = \left[T - L\,T_{sky} - T_{atm}\right]_{50.5} \Big/ \left[L\left(1 - \frac{T_{sky}}{T_g}\right)\right]_{50.5} \tag{17}$$

specialized to 50.5 GHz. Since the same portion of the earth is viewed by all radiometer channels and with the same polarization, Equation (17) is substituted in Equation (15) to provide a measured data vector defined as

$$d_i = T_{\nu_i} - (T_{50.5} - s_{50.5})\,a_{\nu_i} \qquad (i = 1, 2, \ldots, 6) \tag{18}$$

where

$$s_{50.5} = \left\langle L\,T_{sky} + T_{atm}\right\rangle_{50.5}$$

and

$$a_{\nu_i} = \left\langle L\left(1 - \frac{T_{sky}}{T_g}\right)\right\rangle_{\nu_i} \Big/ \left\langle L\left(1 - \frac{T_{sky}}{T_g}\right)\right\rangle_{50.5} \qquad (i = 1, 2, \ldots, 6)$$

These expected values are computed from the same a priori data used to determine the covariance matrices.

When these equations are applied to the form of the multiple regression method described by Equations (4) and (5), the estimate of the parameter vector p is given by

$$\hat{p} = S\,T_B + A' \tag{19}$$

where $S = (-Da \,\vdots\, D)$ is a matrix whose first column is $-Da$ and whose remaining columns are the columns of D,

$$T_B = \begin{pmatrix} T_{50.5} \\ \vdots \\ T_{59.4} \end{pmatrix}$$

and

$$A' = \langle p \rangle - D \langle d \rangle + s_{50.5} \, Da$$

In summary this retrieval technique contains elements which depend mainly on the atmosphere not on the background. It is equally valid over land, water or mixed surface conditions. In contrast to the ground, the atmosphere emits unpolarized radiation so that the received polarization is no longer a factor in the data processing. The data processing does provide, however, corrections for antenna pattern and terrain height effects. These are described below.

Antenna pattern corrections are applied to the antenna temperatures directly after calibration to yield brightness temperatures. The method consists of scaling the antenna temperature $T_A(\nu_i, \theta_j)$ by a factor g_e which is the fraction of the total gain of the antenna intercepting the earth, to produce the brightness temperature.

$$T_B(\nu_i, \theta_j) = T_A(\nu_i, \theta_j)/g_e(\nu_i, \theta_j) \tag{20}$$

A total of 49 factors are used, one for each frequency and scan angle.

Since the inversion matrices are computed only for sea level surface conditions, adjustments to the brightness temperatures determined above must be made for measurements taken over elevated terrain. This adjustment is necessary because the brightness temperatures measured by the lower microwave frequency channels may differ significantly from temperatures which would arise were the same surface at sea level. The effect caused by the missing portion of the atmosphere requires an adjustment to the brightness temperatures prior to inverting. The adjustment is derived from Equations (9) and (17) as

$$T_o(\nu) = T_1(\nu) + \Delta_a - \epsilon T_g \, \Delta_b \tag{21}$$

where

$$\Delta_a(\nu) = \langle T_{atm} + L \, T_{sky} \rangle_o - \langle T_{atm} + L \, T_{sky} \rangle_1 \tag{22}$$

$$\Delta_b(\nu) = \left\langle L\left(1 - \frac{T_{sky}}{T_g}\right)\right\rangle_1 - \left\langle L\left(1 - \frac{T_{sky}}{T_g}\right)\right\rangle_o \tag{23}$$

and

$$\epsilon T_g = \left[T_{1,\nu=50.5} - s_{50.5} + \Delta_a(50.5)\right] \Big/ \left[\left\langle L\left(1 - \frac{T_{sky}}{T_g}\right)\right\rangle_{o,\nu=50.5} + \Delta_b(50.5)\right] \tag{24}$$

In these equations, the subscript 1 represents the true atmosphere and surface at height h while o represents the true atmosphere above h and an intervening atmosphere which is determined statistically between sea level and h . The quantities $s_{50.5}$ and the first term in the denominator of Equation (24) have been defined in Equations (18) and (17) respectively. The factors $\Delta_a(\nu)$ and $\Delta_b(\nu)$ are computed only for Channel 1 to 4 frequencies since the three highest frequency channels are unaffected by the terrain. These factors are determined by the characteristics of the atmosphere comprising the statistical data ensembles. Quadratic functions were found to fit the data satisfactorily. Specifically, for each of the low channels

$$\Delta_a = A_a \, h + A_b \, h^2 \tag{25}$$

and

$$\Delta_b = B_a \, h + B_b \, h^2$$

where h is the terrain height and the constants A_a , A_b , B_a , B_b are regression values determined from the data base ensembles.

The SSM/T software contains provisions to correct the a priori D-matrices during the operational phase to optimize the retrieved data when necessary. The procedure consists of comparing SSM/T derived soundings with coincident radiosonde soundings. The implemented update procedure corrects for sensor and atmospheric modeling bias errors. A linear regression is performed between the measured data vector and a data vector calculated from coincident composite radiosonde and rocketsonde observations. Regression coefficients α_i and β_i are computed for the ith frequency by

$$d_m = \alpha d_c + \beta \tag{27}$$

where d_m is the measured data vector and d_c the calculated data vector. These coefficients are used to update the a priori correlation matrices (indicated by the subscript a) and the expected data vector $\langle d_a \rangle$ to yield updated quantities (indicated by the subscript u) as shown in Equations (28)-(31)

$$\alpha = \begin{pmatrix} \alpha_1 & 0 & 0 \\ 0 & \alpha_2 & 0 \\ 0 & & \ddots \end{pmatrix} \qquad \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \cdot \\ \cdot \\ \cdot \end{pmatrix} \tag{28}$$

$$C\left(p-\langle p\rangle, d_u-\langle d_u\rangle\right) = C\left(p-\langle p\rangle, d_a-\langle d_a\rangle\right)\alpha \tag{29}$$

$$C\left(d_u-\langle d_u\rangle, d_u-\langle d_u\rangle\right) = \alpha C\left(d_a-\langle d_a\rangle, d_a-\langle d_a\rangle\right)\alpha \tag{30}$$

$$\langle d_u\rangle = \alpha\langle d_a\rangle + \beta \tag{31}$$

These updated matrices are combined with an operationally determined error covariance matrix, $C(\delta,\delta)$, to yield new matrices defined by

$$D = C\left(p-\langle p\rangle, d_u-\langle d_u\rangle\right)\left[C\left(d_u-\langle d_u\rangle, d_u-\langle d_u\rangle\right) + C(\delta,\delta)\right]^{-1} \tag{32}$$

4. DATA PROCESSING

4.1 GENERAL DESCRIPTION

Ephemeris data are merged with the raw microwave sensor data and DMSP system data at AFGWC to form the required input files for processing. The SSM/T data processing consists of four main computer program components labeled PROCESSOR-A, PROCESSOR-B, MICRO-CHECK, and D-UPDATE. Only PROCESSOR-A and PROCESSOR-B are designed to operate in real time. PROCESSOR-A is fundamentally a preprocessor for PROCESSOR-B, the inversion processor. MICRO-CHECK is an on-line program, operating once each day as a preprocessor for the update program, D-UPDATE. Both MICRO-CHECK and D-UPDATE are designed to evaluate and correct the a priori D-matrices. Each of these processing programs consists of a driver routine and numerous subroutines. They are described in the following section in reference to the top level flow diagram shown in Figure 3.

4.2 PROCESSOR-A

PROCESSOR-A is designed to process data contained in the input file PROD*AEROJET-MDATA while retrieving required information from various AFGWC data base components. The processing is initiated at the UNIVAC 1110 system console by operator keyboard input. Data are read in convenient groups from the input file to minimize input/output operations. Raw data, in digital counts, are processed to produce the SSMT*BRTEMP file, SSMT*-CALGAIN file, and various page print diagnostics. SSMT*BRTEMP file serves as the main input to PROCESSOR-B whereas SSMT*CALGAIN is generated for off-line operational analysis and system evaluation. The diagnostics are produced for error analysis purposes to aid in the recovery of possible program failures. As depicted in Figure 3, valid sensor data are stripped from the input file and identified for each spacecraft. These data are calibrated, corrected for antenna patterns, timed, and earth-located. Gross error checks are made to the corrected brightness temperatures against fixed upper and lower limits. Corresponding terrain heights and 1000-mb heights are retrieved from appropriate elements in the AFGWC data base. The corrected brightness temperatures and associated view data are stored in the SSMT*BRTEMP file while validated raw data are stored in the SSMT*CALGAIN file. Page-print diagnostics may be generated for this processor by the operator. PROCESSOR-A executes automatically processing one or more orbits of data from the input file which may contain a maximum of 24 hours of data. After PROCESSOR-A executes, further real-time processing is continued in PROCESSOR-B

4.3 PROCESSOR-B

PROCESSOR-B runs sequentially to PROCESSOR-A in an automatic mode with the processing mode and area limits keyed in by the operator. Processing involves reading data from the SSMT*BRTEMP file, selecting data for appropriate views (scan position), testing for the likelihood of dense clouds or rain (over oceans only), adjusting for terrain height and inverting to obtain atmospheric temperature soundings. The inversion process is described in Section 3. All a priori D-matrices are stored in the SSMT*D-MATRICES file. There are 48 D-matrices in all, including one each for three geographic zones (tropics, mid-latitudes and arctic/antarctic), four seasons, and four scan positions. The recovered soundings are stored in the SSMT*SOUNDINGS file and SSMT*VERIFICATION file. The corresponding brightness temperatures are also stored in the SSMT*VERIFICATION file. In addition PROCESSOR-B produces page-print diagnostics of files as well as the location of views having dense clouds or rain. After processing the last view of the SSMT*BRTEMP file, PROCESSOR-B provides a listing of the number of soundings processed prior to termination.

4.4 MICRO-CHECK

The MICRO-CHECK program is designed to run once each day. Inputs to MICRO-CHECK are derived from the SSMT*VERIFICATION and AFGWC UADB. MICRO-CHECK searches the UADB for radiosonde observations coincident with the inverted SSM/T soundings. It computes the residual errors between the SSM/T soundings and the coincident radiosonde observation. The residual error data are used to evaluate the overall performance of the retrieved profiles. Coincident rocketsonde soundings are also found. When rocketsonde and radiosonde observations are found to be coincident with an SSM/T sounding, they are quality tested and combined to produce a single sounding extending from sea level to the 0.5-mb level. This composite sounding is then used to calculate the data vector. The measured data vector is also determined. These data vectors are finally stored in the SSMT*SSMTSTATFILE file with the residual error data and the number of coincident data vector pairs. The SSMT*SSMTSTATFILE file is used also as an input to MICRO-CHECK and successively updated each day with new data. MICRO-CHECK also contains provisions for print-plotting coincident SSM/T and radiosonde soundings and listing the statistical data. MICRO-CHECK runs to completion when all soundings in the UADB are processed.

4.5 D-UPDATE

Periodically, depending on the number of coincident measurements found in MICRO-CHECK, the D-UPDATE program is executed. It runs automatically with input data from SSMT*SSMTSTATFILE. Using the data input from this file, D-UPDATE tests the data for sample-size representativeness and distribution in temperature. If these tests are satisfactorily passed, an OPTION 1 update may be executed. New D-matrices are generated, tested in PROCESSOR-B and used operationally if warranted. After five successive OPTION 1 updates, tests of OPTION 2 may be performed to determine if the sensor bias and random errors exceed the threshold values. When they exceed threshold values, an OPTION 2 update is executed by modifying the correlation matrices, testing them in PROCESSOR-B, and replacing operational D-matrices with the newly developed ones.

5. RESULTS

The SSM/T software has been implemented, tested and verified in the AFGWC UNIVAC 1110 system using simulated data in the input file PROD*AEROJETMDATA. These data were computed from an independent set of soundings selected from the World Data Center A and Eastern Meridional high-altitude meteorological soundings. Data were selected for all stations in these networks and stratified by latitude and season to complete a nominal DMSP orbit. A total of 192 soundings were used in the simulation with 1344 views. Each view was assigned latitude and longitude coordinates, surface height, surface temperature and emissivity value (over land) or salinity value (in parts per thousand) for views located over the ocean. Antenna temperatures were computed for each channel frequency and input to a simulator program with sensor and system data to generate the input file for test and verification purposes. Several versions of this file were generated by the simulation program to test and verify various system mode characteristics. The inverted soundings produced in the normal processing mode were compared to original source reference data by a separate subroutine for 2 seasons and 6 geographic zones. These included the arctic, mid-latitude, and tropic spring in the Northern Hemisphere, and the antarctic, mid-latitude, and tropic fall in the Southern Hemisphere.

The results, obtained from comparing 224 inverted soundings with the source reference soundings in each geographic zone, are shown in Figure 4. The standard deviation of the 224 soundings in each zone-season are also shown in this figure. As shown in Table I, the SSM/T sensor can measure brightness temperatures averaged over the weighting functions shown in Figure 2 with an rms accuracy of 0.4 to 0.6 K for integration time of 2.7 seconds. The results shown in Figure 4 indicate the SSM/T rms uncertainty averaged over the 15 mandatory levels is of the order of 2 K. Larger uncertainties occur at the 1000-mb heights since the inferred soundings are biased to the 1000-mb forecast height. A qualitative comparison of the rms uncertainty in the inferred soundings with the standard deviation of the source soundings reveals that soundings will be obtained from the SSM/T measurements with an accuracy considerably better than estimates based on climatology.

TABLE I. CHANNEL PARAMETER DESIGN SPECIFICATIONS

Channel	Polarization	Frequency (GHz)	Bandwidth (MHz)	NETD ($^{\circ}$K)
1	Principally Horizontal	50.5	400	0.6
2		53.2	400	0.4
3		54.35	400	0.4
4		54.9	400	0.4
5	Orthogonal to Channels 1-4	58.4	115	0.5
6		58.825	400	0.4
7		59.4	250	0.4

TABLE II. SCAN PARAMETERS

Scan Type	Cross-Track Nadir
Cross-Track Positions	7
Calibration Positions	2-Cold Space and 300°K
Instantaneous Field of View	14°
Total Cross-Track Scan	36°
Total Scan Period	32 Seconds
Integration Time (Cross-Track and Calibration Positions)	2.7 Seconds
Sync Mode	Auto Mode or On-Sync

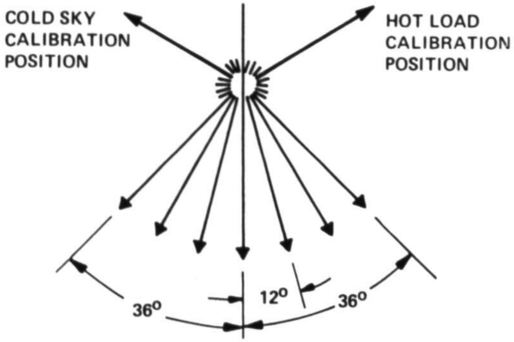


FIGURE 1. Scan Geometry

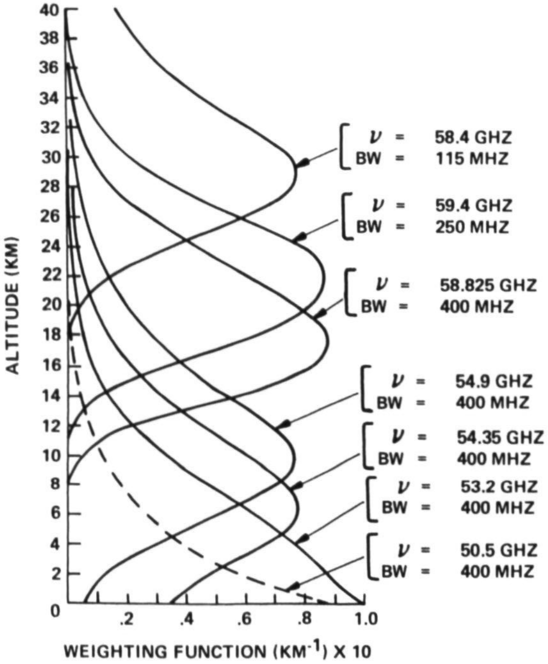


FIGURE 2. Weighting Function, $\theta = 0^{\circ}$, Calm Sea Background

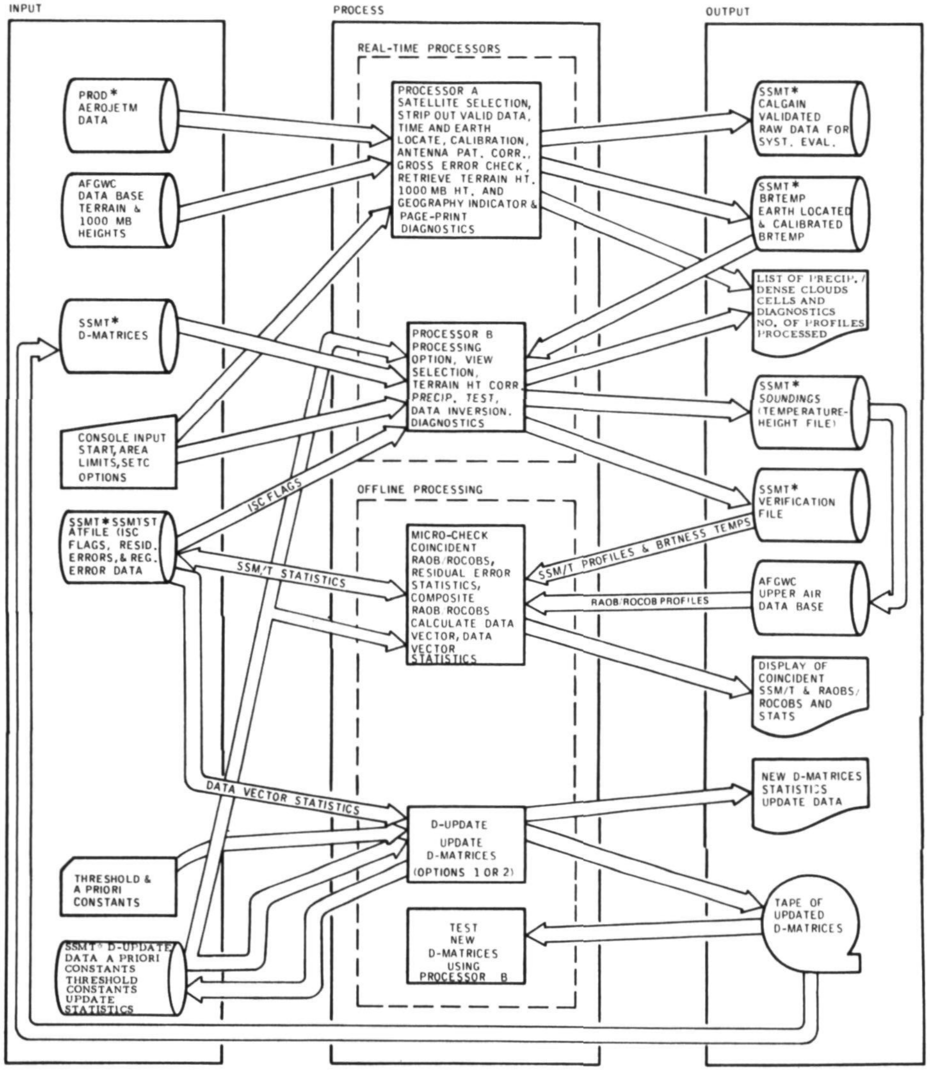
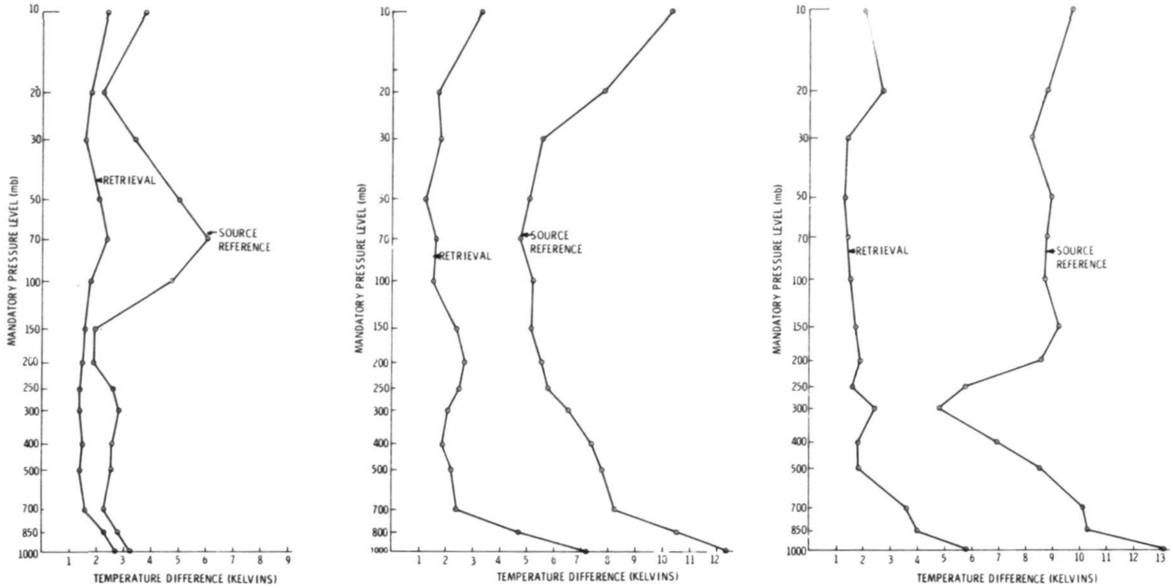


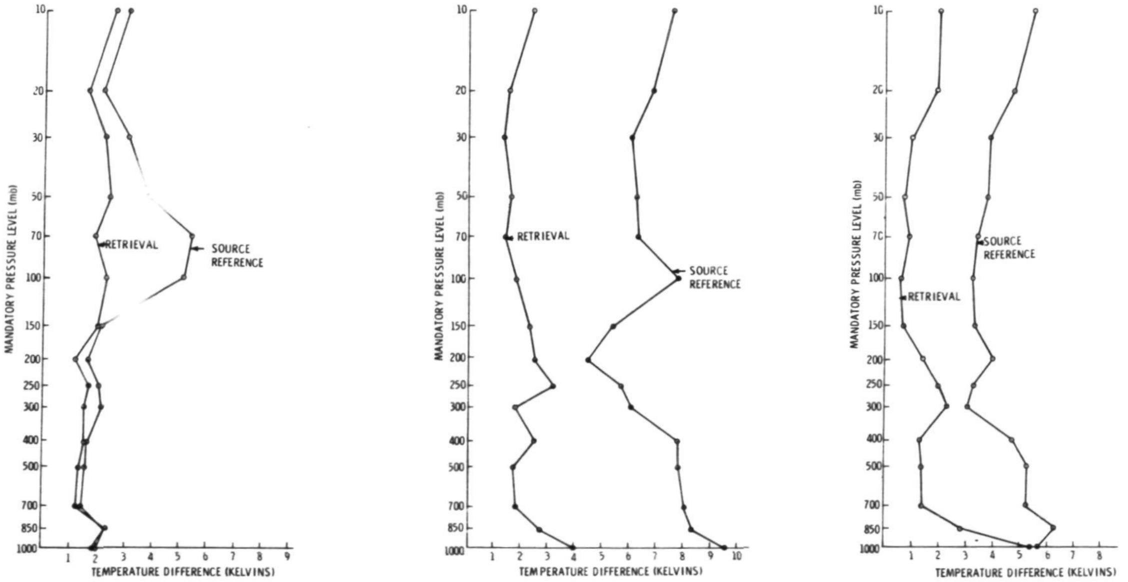
FIGURE 3. SSM/T Software Diagram



A. Tropic Spring
Northern Hemisphere

B. Mid-Latitude Spring
Northern Hemisphere

C. Arctic Spring
Northern Hemisphere



D. Tropic Fall
Southern Hemisphere

E. Mid-Latitude Fall
Southern Hemisphere

F. Antarctic Fall
Southern Hemisphere

FIGURE 4. RMS Errors in SSM/T Retrievals and Variations in Source Reference