NOAA Technical Report NESDIS 64

ADJUSTMENT OF TIROS OPERATIONAL VERTICAL SOUNDER DATA TO A VERTICAL VIEW

Washington, D.C.
March 1993

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Office of Research and Applications

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ANGULAR ADJUSTMENTS OF TIROS OPERATION VERTICAL SOUNDER (TOVS) DATA

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ABSTRACT. In an earlier study, observations from the Special Sensor, Meteorological/Temerature (SSM/T) on the Defense Meteorological Satellite Program satellites have been used to calculate limb-adjustment coefficients to transform all SSM/T data to the values they would have in a vertical view. Application of the same methods to the TIROS Operational Vertical Sounder (TOVS) measurements in the infrared regions has been hampered by the irregularities of clouds and their influence on radiance temperatures. To overcome this difficulty, the angular distributions of measurements for each spectral interval have been smoothed by a simple quadratic expression. The much greater number of channels in the TOVS allows a broader range of eligible channels in the algorithm for angle adjustment, although each eligible channel must be related physically rather than only statistically. Selection of channels was performed by computing all possible combinations of channels with one, two, and three associated channels and applying two criteria: minimization of the RMS fit and minimization of noise amplification. Estimated errors of fit to the data are generally less than the electrical noise of the instruments. It is shown that the smoothed latitudinal means represent individual sets of observations over a broad range of meteorological conditions and therefore satisfy the angular and universality of requirements placed on the algorithm.

Satellites of the NOAA series carry a set of three instruments which together comprise the TIROS Operational Vertical Sounder. These are the High-resolution Infra-Red Sounder, Model 2 (HIRS-2), the Microwave Sounding Unit (MSU), and the Stratospheric Sounding Unit (SSU). In addition, a similar instrument, the Special Sensor, Meteorological/ Temperature (SSM/T), has been carried on the Defense Meteorological Satellite Program (DMSP) spacecraft commencing with F7. All of these instruments are devoted to providing vertical profiles of temperature or humidity by transforming spectral radiances into the radiative sources and hence the meteorological parameters.

One thing each instrument has in common is a scan perpendicular to the motion of the satellite, allowing a broad swath of measurements to be taken. An undesirable feature of the cross-track scanning is that radiation arises from somewhat different levels in the atmosphere at each of the indivual viewing angles. This results in different radiance values even in an otherwise horizontally homogeneous atmosphere having a homogeneous surface as a background.

There are several disadvantages to having a variety of views of essentially identical conditions. One of these is the requirement to perform a slightly different inversion of the radiances (that is, transformation of radiances to meteorological parameters) at each viewing angle. Another is that any horizontal smoothing or quality checks of the data is virtally impossible in the cross-track direction.

It is for these and other reasons that adjustment of all data to a common angle of view (the vertical) has been a part of the TOVS data processing beginning with the launch of the TIROS-N satellite in 1978. However, the adjustment parameters have been based on simulated data, computed from the radiative transfer equation using the best available atmospheric transmittances and a set of 120 radiosonde/rocketsonde profiles.

As improvements have been made in the processing of the TOVS data over the years, the quality of numerical weather prediction has made even greater strides. The result is that weaknesses in the TOVS processing which would have been overlooked in former years are now resulting in products that are not completely satisfactory to the users. A part of this is tracable to the angle adjustments which have been employed.

An earlier study [1] subjected the SSM/T data to a statistical process, using observations rather than simulated data. Angular adjustment coefficients were obtained for each of the seven channels at each of the six off-nadir scan positions as a linear combination of two or three closely-associated channels. The impetus for that study was the seven-fold increase in the number of radiosonde measurements which could be matched in time and location with the the satellite data at a single angle of view. The data processing of the SSM/T is based on a statistical regression of the seven satellite satellite spectral radiance temperatures at each of the seven beam positions with atmospheric temperatures at the standard atmospheric pressure levels, rather than the mathematical inversion of the radiative transfer equation as used with the TOVS. Therefore, it was thought, the greater number of matched pairs of data would lead to better coefficients, particularly in latitudes where radiosondes are widely spaced.

The procedure from that earlier study was to average all data over a five-day period for each channel and beam position in narrow latitudinal bands for different surface types (water, land and ice). It was shown that each set of latitudinal means could be matched, at the noise level of the measurements, with a single set of measurements by the seven channels. Therefore the means represented individual sets of measurements, and the averages in the seven beam positions were representations of the same atmospheric conditions at the seven angles of view. Hence they were exact measurements, within noise limitations, of a variety of conditions equivalent to those used to produce simulated (computed) radiances, and they possessed no uncertainties inherent in the latter.

When the same procedures were followed using HIRS-2 data, a special problem arose. When coefficients for angle adjustment were produced, they varied wildly with beam position, in contrast with the orderly progression found with the SSM/T data. The reason for this behavior was immediately apparent. Clouds, which are largely transparent in the microwave portion of the spectrum, are largely opaque at infrared wavelengths and greatly modify the radiances in all but those channels insensitive to the troposphere where clouds form. The more transparent channels are therefore sensitive to the coming and going of clouds during a few days, and a latitudinal mean can differ significantly at one beam position from its neighbors. To overcome this shortfall, a much greater sample would be required, which, with the already large numbers of data, becomes impractical. Other means of treating the data are required.

The reader may not be aware of the magnitudes of the limb adjustments which are to be made. To demonstrate the quantities being dealt with, the average amount of limb-darkening or limb-brightening at the extreme left scan positions are given in Table 1.1, taken from one of the samples described in the next section. For Channels 1-20 (HIRS-2) this corresponds to a local angle of 59.19 degrees for a satellite altitude of 825 km; for Channels 21-24 (MSU) the angle is 56.18 degrees; and for Channels 25-27 (SSU) it is 40.38 degrees. These data are computed from the averages of the smoothed data described in Section 4.

Table 1.1. Mean differences between radiance temperatures at the extreme scan positions and the vertical view for the TOVS channels (degrees K). Data are from the NOAA-11 satellite between 82N and 82S during 6-11 July 1991, with daytime obervations excluded for HIRS-2 only. Positive values indicate limb darkening and negative values limb brightening. Channel 20 measures only reflected sunlight and is omitted.

HIRS-2				MSU		SSU	
Chan.	Diff.	Chan.	Diff.	Chan.	Diff.	Chan.	Diff.
1	-4.04	11	5.44	21	-8.55	25	-1.54
2	-3.52	12	5.09	22	12.33	26	-1.61
3	-1.09	13	6.83	23	9.19	27	-0.88
4	5.70	14	8.91	24	-1.56		
5	7.53	15	8.11				
6	8.21	16	0.89				
7	6.68	17	5.41				
8	4.16	18	3.30				
9	8.29	19	3.05				
10	4.61						

2. The limb adjustment algorithm

Stated simply, the algorithm to adjust the radiances to the nadir is a linear combination of radiance temperatures (temperatures of a black body resulting in the same radiances). Radiance temperatures are used in preference to radiances because they represent a common scale, whereas the radiances can vary over orders of magnitude with wavelength.

$$T_{io} = a_{ij} + \sum_{i'} a_{i'j} T_{i'j}, \qquad (2.1)$$

where T is radiance temperature and the a's are coefficients. The subscript i is the channel, j is the beam position, i' is an "associated" channel, and the subscript o indicates the nadir direction.

An associated channel is one which is used to predict the nadir value of a particular channel. The predictor may include the predictand channel, and, indeed, in the present algorithm, it is required. The selection of associated channels is discussed in a later section.

Coefficients in Eq. (2.1) are found by least squares solution from a large ensemble of radiance temperatures. Since the launch of the TIROS-N satellite in 1978 these radiance temperatures have been computed from a set of radiosonde-rocketsonde measurements using step-wise regression. The results have not been entirely satisfactory, and the present study has striven to substitute actual measurements.

Because there are no simultaneous measurements of the angular variations of radiance temperatures, statistical methods have been employed here. It has been assumed that if a very large sample is used, the mean values in a narrow latitude band at each of the beam positions will represent the angular variation of a single meteorlogical condition of temperature, humidity, ozone, and clouds. A test of this principle [1] using the SSM/T of the DMSP satellites was highly successful and has led to this study.

The method used here differs in one other respect from the current operation. Instead of using step-wise regression for the selection of associated channels, an elaborate preparation is made in advance for the selection of associated channels. Solutions for the coefficients are then made for each viewing angle by simple linear regression, using the same combinations of channels at every beam position. In this way, no discontinuities are induced in the fields of limb-adjusted radiance temperatures.

3. The data

A. The first test period. During the period 18-25 September 1989, all TOVS data from the NOAA-11 satellite were collected. That portion of the entire data set which lay between 82N and 82S and passed quality checks comprised 3,414,411 sets of 20-channel HIRS-2 data, 186,783 sets of four-channel MSU data; and 93,863 sets of three-channel SSU data. The elimination of data poleward of 82 degrees is necessary because the orbital inclination of the satellite does not allow a vertical view of the earth in those regions and the nadir values cannot therefore be known.

The first step was to combine the data, which were transformed to radiance temperatures, into the latitudinal means. The following rules were required:

1. Latitude was divided into 82 two-degree belts. The 164 one-degree belts used for the SSM/T data were found only to increase the cloud "noise" in the HIRS-2 channels while producing no discernible benefits.

2. The data were further divided by surface type, dictated mainly by the MSU Channel 1, into water, land and ice. Coastlines were not used.

3. A third division of the data was by beam position. The HIRS-2 has 56 scan positions, the MSU has 11, and the SSU has eight.

4. The final separation was by channel. The respective instruments have 20, 4, and 3 channels.

5. After examination of the results, it was realized that the HIRS-2, and therefore the MSU and the SSU also, would have to be separated into day and night groups because of the influence of reflected sunlight for Channels 17-20 and the re-emission of sunlight and stratospheric heating and cooling for Channels 15 and 16.

6. It was decided that an additional piece of information that might be used was the average cosine of the zenith angle of the sun, during the daytime only.

7. It has been found prudent to delete redundant data, which frequently occur at the end of one orbital readout and the start of another.

The result is that the 69,316,941 radiance temperatures were reduced to 584,496, about 35 percent of which were zeroes because there are no observations for some surface types at some latitudes. It has been the practice to retain the sums of the radiance temperatures and the numbers of data in separate files in order to eliminate mean values comprised of too few measurements to be statistically significant.

B. The second period. During the time 6-11 July 1991 all the data for the three NOAA-11 TOVS data were saved. In contrast with the first period, these data were subjected to closer scrutiny and were handled in a somewhat different way.

1. Where orbits of data were missed, they were obtained from the archive. This provided all available data, although there were still some missing orbits and some gaps in others.

2. Among the 1B data there were some short portions of orbits which are either repetetive or have other undesirable qualities. These files were deleted.

3. Duplicate data were not used. This was accomplished by processing the data chronologically and omitting those data in a particular orbit with times earlier than the last time in the preceding orbit.

4. The data were divided into two groups: in the the ascending and the descending parts of orbits. The reason for this, in preference to a division into day and night, is that the solar zenith angle is virtually the same for any given latitude throughout the five-day period. The influence on certain channels therefore behaves in a regular way which makes later analysis easier.

C. NOAA-12 data. During January 26-31, 1992 there were 71 orbits of data collected, which included all but a portion of one orbit. In this set it was found that two other precautions were required which eliminated about 0.7% of the otherwise acceptable data.

1. Mislocated data. This comprised only a small number of observations. To eliminate these, the latitudes and longitudes were compared with those in the preceding scan line. If either differed by more than a given amount, the observation was rejected. This led to the elimination of two observations when one was in error, but the effect on latitudinal means was negligible.

2. Bad radiometric data. Because these data were so greatly in error it was easy to eliminate them. If the radiance temperature of any thermal channel (all channels except HIRS-2 Channel 20) lay outside the range 150-350K, the entire set of channels was rejected.

4. The effects of solar radiation

In the spectral region with frequencies greater than about 2000 cm^{-1} the radiation from the sun affects the HIRS-2 channels in two ways: by direct reflection from surfaces or clouds, and by coherent scattering in the upper atmosphere. These two effects occur on the short-wavelength side of the 4.3 μ CO_2 band and within that band, which includes channels 14-19. Channel 17 is in the former region for NOAA-11 and the latter for NOAA-12.

When the NOAA-11 Channels 17-19 were examined, no significant asymmetry in latitudinal means was noted because the cosine of solar zenith angles did not vary greatly in the afternoon orbit. With NOAA-12 having a 7:30 equator crossing, the cosine of solar zenith angles changes from zero to about 0.6, and radiances change by as much as a factor of three from one side of the scan to the other. In addition, during portions of the descending part of the orbits there is very strong specular reflection. These factors lead either to rejection of the obervation or to a condition which requires adjustments for the reflected solar radiation prior to limb adjustments.

It is not the purpose of this study to resolve these problems. After examining the NOAA-12 data in some detail, the author has concluded that a large part of the observations on the sunlit side of the earth cannot be adjusted with reasonable accuracy for reflected sunlight. Any adjustments are the purview of other studies and will not be considered further.

Instead, it will be assumed that any user of the data who wishes to make adjustments will already have performed them and that the solar component does not exist.

Therefore, only the observations on the dark side of the earth are used to compute limb-adjustment coefficients. These are distinguished by accepting only those measurements having Channel 20 reflectances less than 0.5 percent. This effectively reduces the samples and the number of latitudinal means by 50 percent. Thus, out of about 250 latitudinal means, only about 125 are employed.

5. Symmetry and smoothing of the data

When the same limb-adjustment algorithm used with the SSM/T data was applied to the first data set of TOVS measurements, the coefficients were found to fluctuate wildly from one beam position to the next. This behavior is illustrated in Fig. 5.1, which shows coefficients for HIRS-2 Channel 8 using Channels 7, 8 and 11 as predictor channels (see Table 6.3). Table 5.1. lists the coefficients and the standard deviations of fit at every fifth beam position. Channel 8 is subject to strong influence by clouds, and the poor behavior of these coefficients is considerably worse than for many other channels. But it illustrates some of the fundamental problems.

This condition could not be allowed to exist because it did not reflect the true behavior of variations of radiance temperatures with the angle of propagation. The nature of angular variation is smooth, so it seemed that by passing a smooth function through the values at all beam positions a smooth behavior in the limb-adjustment coefficients could be achieved.

Angular variations in radiance are caused mostly by the varying optical path through the atmosphere. For monochromatic radiation the optical path (negative logarithm of the atmospheric transmittance) is proportional to the secant of the zenith angle, $t = am \cdot \sec(z)$, where a is a constant (or nearly so), m is the mass of the gas, and z is the zenith angle. For the broad range of spectral frequencies found in each of the HIRS-2 and SSU measurements, the constant varies greatly, so $\exp(-t)$, the kernel of the radiative transfer equation, does not behave in a simple way with $\sec(z)$. However, it is still a smooth function of zenith angle.

It has been found from earlier studies that HIRS-2 radiances or radiance temperatures can be fit, with great precision, to the quadratic

$$T(z) = d_o + d_1[\sec(z)-1] + d_2[\sec(z)-1]^2. \qquad (5.1)$$

When this was done for the second set of NOAA-11 TOVS latitudinal means, the residuals were studied carefully. Figure 5.2. shows the average residuals from fitting Eq. (5.1) by least squares for all latitude belts and surface types for HIRS-2 Channels 1, 2 and 8, and MSU Channels 1 and 2 (21 and 22).

Several things become evident from examination of this figure. First of all, the residuals for Channels 1 and 2 vary linearly with either scan angle or zenith angle. In addition, there is a cyclic variation over about four beam positions, observable also for Channel 8, which has a different amplitude for each channel. These short-wave cyclic variations are not significant.

Channel 8 demonstrates a broader cyclic variation having a greater amplitude. This is ascribed to the influence of clouds which are sampled in a somewhat different way at the various beam positions during the five-day period. Examination of the Channel 20 (visible) values showed similar deviations when fit with an appropriate function; the result is conclusive because the Channel 8 values were found to behave differently for separate data sets, and the daytime data matched the Channel 20 data.

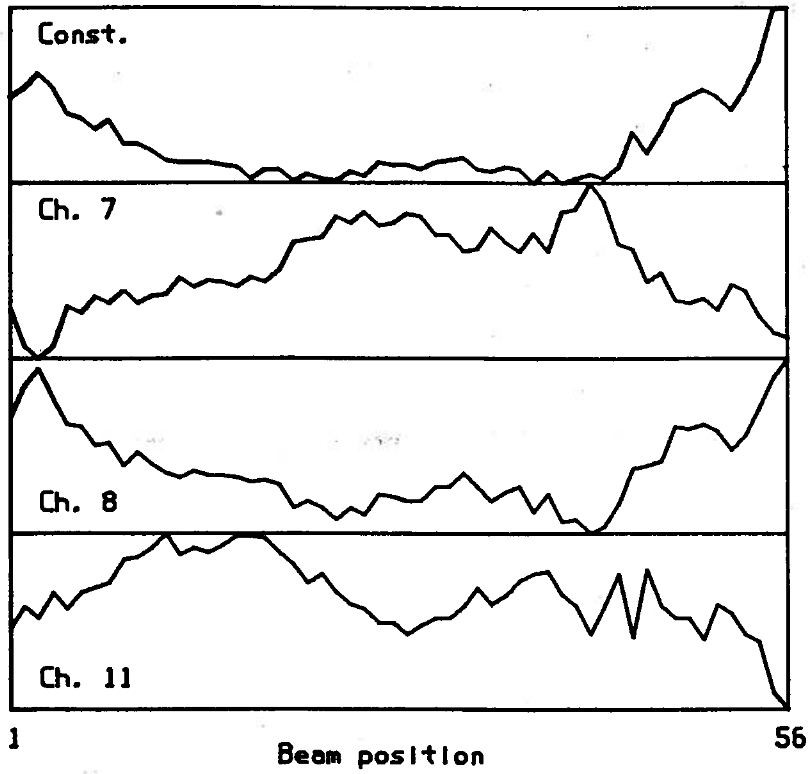

Figure 5.1. Limb-adjustment coefficients for the NOAA-11 HIRS-2 Channel 8, using the SSM/T algorithm. Coefficents are at the 56 beam positions and are normalized to range between their minimum and maximum values.

Table 5.1. Limb-adjustment coefficients for the NOAA-11 HIRS-2 Channel 8, derived from unsmoothed latitudinal mean radiance temperatures. Associated channels are indicated by the subscripts, and the last column gives the standard deviation of fit.

Beam position	Coefficients a_o	a_7	a_8	a_{11}	σ (K)
1	36.4853	-0.4971	1.3395	0.0079	1.6846
6	24.8993	-0.5135	1.2094	0.0714	1.5322
11	7.3141	-0.4215	1.1316	0.2644	1.5444
16	-0.3701	-0.3500	1.0801	0.2741	1.5436
21	-9.6784	-0.1157	0.9476	0.2125	1.3672
26	-6.5788	0.0452	0.9220	0.0632	1.0959
31	1.3060	-0.0764	1.0357	0.0349	1.1395
36	-1.7975	-0.1158	1.0130	0.1120	1.3978
41	-7.5565	0.0690	0.8951	0.0734	1.6271
46	6.1245	-0.3383	1.1193	0.1960	1.5305
51	36.4426	-0.4952	1.2686	0.0784	1.5418
56	84.8045	-0.6645	1.5673	-0.2593	1.6010

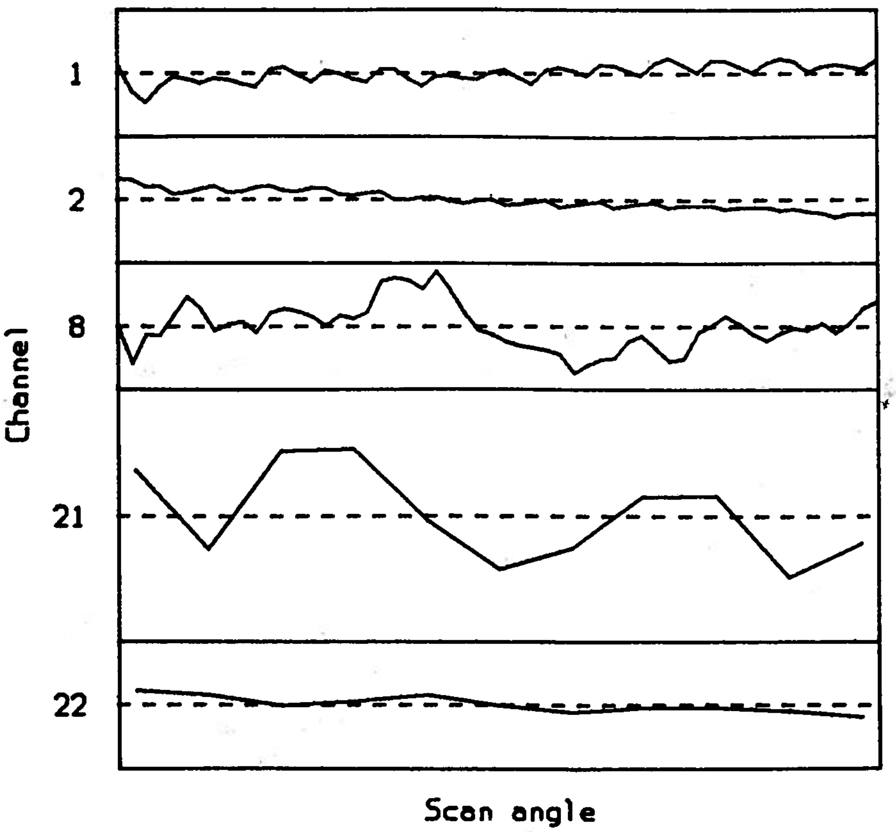

Figure 5.2. Radiance temperature differences, original latitudinal means minus smoothed data, shown as ordinates, and scan angle as the abscissa. The top three figures show the NOAA-11 HIRS-2 Channels 1, 2 and 8; the lower figure shows the MSU Channels 1 and 2. The ordinate scale is ± 0.5 K except for MSU Channel 1 (21), which is ± 1.0 K.

The MSU Channel 1 (Channel 21) also has a two-cycle variation which is bears little resemblence to any other channel. Because the MSU Channel 1 is sensitive to cloud and rain droplets, it might be expected to behave in a way similar to the HIRS-2 Channel 8. Because it does not, the cyclic behavior probably reflects some small surface polarizatiom effects.

Each of the channels for the HIRS-2 and the MSU has an asymmetry which is small but which cannot be neglected. But this very asymmetry may be real, especially for channels sensitive to diurnal variations in cloudiness and in temperatures of the stratosphere or the surface. In an attempt to determine the source of the asymmetry, the latitudinal means for each channel were averaged over all latitudes and surface types, eliminating those data for which not all beam positions were represented. The results were then fit to a quadratic in the nadir angle, a. This representation is poorer than that in Eq. (5.1), but it has the virtue of revealing without artifice any asymmetry which exists in the data. The constant term is the nadir value, and center of symmetry is at $a = c_1/c_2$, where c_1 and c_2 are the coefficients of the first and second order terms.

Table 5.2. Nadir angles of center of symmetry for HIRS-2 Channels 1-12.

Channel	Nadir angle (degrees) Day	Night
1	0.742	0.673
2	-0.693	-0.790
3	-0.316	-0.410
4	0.551	0.448
5	0.270	0.198
6	0.262	0.197
7	0.207	0.153
8	-0.087	0.015
9	-0.060	-0.026
10	0.128	0.126
11	0.209	0.204
12	0.572	0.633

The results for both day and night samples are given in Table 5.2. for the HIRS-2 channels 1-12, which are not contaminated with sunlight. Overall, the results show no significant differences between day and night, and the mean of the 12 channels is +0.134 degrees, with a standard error of estimate of 0.116 degrees. If only the mid-tropspheric channels 4, 5, 6, 7, 11, and 12 are considered, these numbers become +0.326 and 0.074 degrees.

The conclusion from this study is that there may be a displacement of +0.1 to +0.3 degrees in the nadir viewing angle of the HIRS-2 on NOAA-11. However, the appearance of both positive and negative angles renders this conclusion inconclusive and it is probably better to assume that this asymmetry is zero. Because the MSU and the SSU cannot be subjected to the same degree of analysis, and because the mounting of the instruments on the spacecraft was within ±0.1 degrees, the same assumption must be made for all three instruments.

There remains a channel-dependent asymmetry which is quite real. To account for this, Eq. (5.1) can be modified by adding a fourth term which is linear with nadir angle,

$$T(z) = d_o + d_1[\sec(z)-1] + d_2[\sec(z)-1]^2 + d_3 a, \qquad (5.1')$$

where a is the nadir angle. One character of Eqs. (5.1) and (5.1') is that the constant d_o is the nadir value.

The SSU has a characteristic which suggests that the same procedure may not be appropriate. There is a cross-track behavior which cannot be accounted for by a linear term. In addition, there is a "jump" in the radiances between the two beam positions on either side of the nadir, amounting to about 0.1-0.2 degrees Kelvin. It was decided that these behaviors were characteristic of the sample, and the safest alternative was to resort to Eq. (5.1') for the SSU data as well.

By applying Eq. (5.1'), the data set has now been reduced to 106,272 words or 425,088 bytes.

However, the story is not yet complete because of the influence of solar radiation on some channels. Figure 5.3. shows the mean deviations of fit for the 19 thermal channels of the HIRS-2, using Eq. (5.1') (that is, with the linear beam-position term). Channels 1-14 show in varying degrees the characteristics which have already been discussed, as do Channels 17-19 because they are taken from only the nighttime observations. Channels 15 and 16 exhibit the effect of stratospheric heating and cooling. To shed a bit more light on the significance of the shapes of the curves, one should examine the effect of the linear term in beam position of Eq. (5.1'). Table 5.3. gives the value of this term at beam position number one to illustrate its magnitude.

Table 5.3. Average values of the term d_3a in Eq. (5.1') for the 19 channels of the HIRS-2 on NOAA-11 at the left beam position, a = -49.5 degrees. Columns D and A denote descending and ascending parts of the orbit. Data are for NOAA-11 during July 6-11, 1991.

Chan.	Value (K) D	A	Chan.	Value (K) D	A	Chan.	Value (K) D	A	Chan.	Value (K) D	A
1	-.125	-.103	5	.124	.118	10	.294	.110	15	.422	.482
2	.077	.136	6	.172	.136	11	.122	.162	16	.809	.961
3	-.038	.029	7	.216	.120	12	.126	.289	17	.361	.280
4	.106	.149	8	.328	.091	13	.315	.208	18	.524	.504
			9	.167	.068	14	.318	.287	19	.842	.846

Channels 1-14 all have maximum biases which are at or near the noise level of the measurements. Because they are all positive, with the exception of Channels 1 and 3, it would lead one to suspect that there is a true bias. Channel 1, however, would seem to refute this, inasmuch as it is the highest of these channels; however, this could indicate the influence of diurnal heating and cooling of the upper stratosphere.

Channels 15 and 16 show the effects of weighting functions which are higher in the atmosphere, allowing a progressively greater influence of the stratosphere. At the wavelength of these channels there is a coherent scattering of sunlight in the upper stratosphere which enhances the radiances; in addition, there is diurnal heating and cooling of the stratosphere which can have a moderate influence on the results. The two phenomena cannot be separated from the measurements available, but it is quite certain that no interpretation of any kind can be made without separating the data into ascending and descending portions of the orbit.

The shapes of the curves for Channels 17-19 in Fig. 5.3 are the same as that for Channel 8, reinforcing the argument that the cyclic behavior in that channel is dependent only on the sample and is not real.

The conclusion is that the asymmetries found in the data are real in the sense that they indicate diurnal variations in temperature, cloudiness, or coherent scattering of sunlight. The recommended procedure in generating the limb-adjustment coefficients is to use the results from Eq. 5.1 or from Eq. 5.1' without the fourth term on the RHS. This produces identical coefficients on each side of the nadir, but allows the true asymmetries in the observations to remain. Use of all terms in Eq. 5.1' would tend to reduce all data to the local time at the nadir, which would not indicate the true meteorological conditions at the location of the observations.

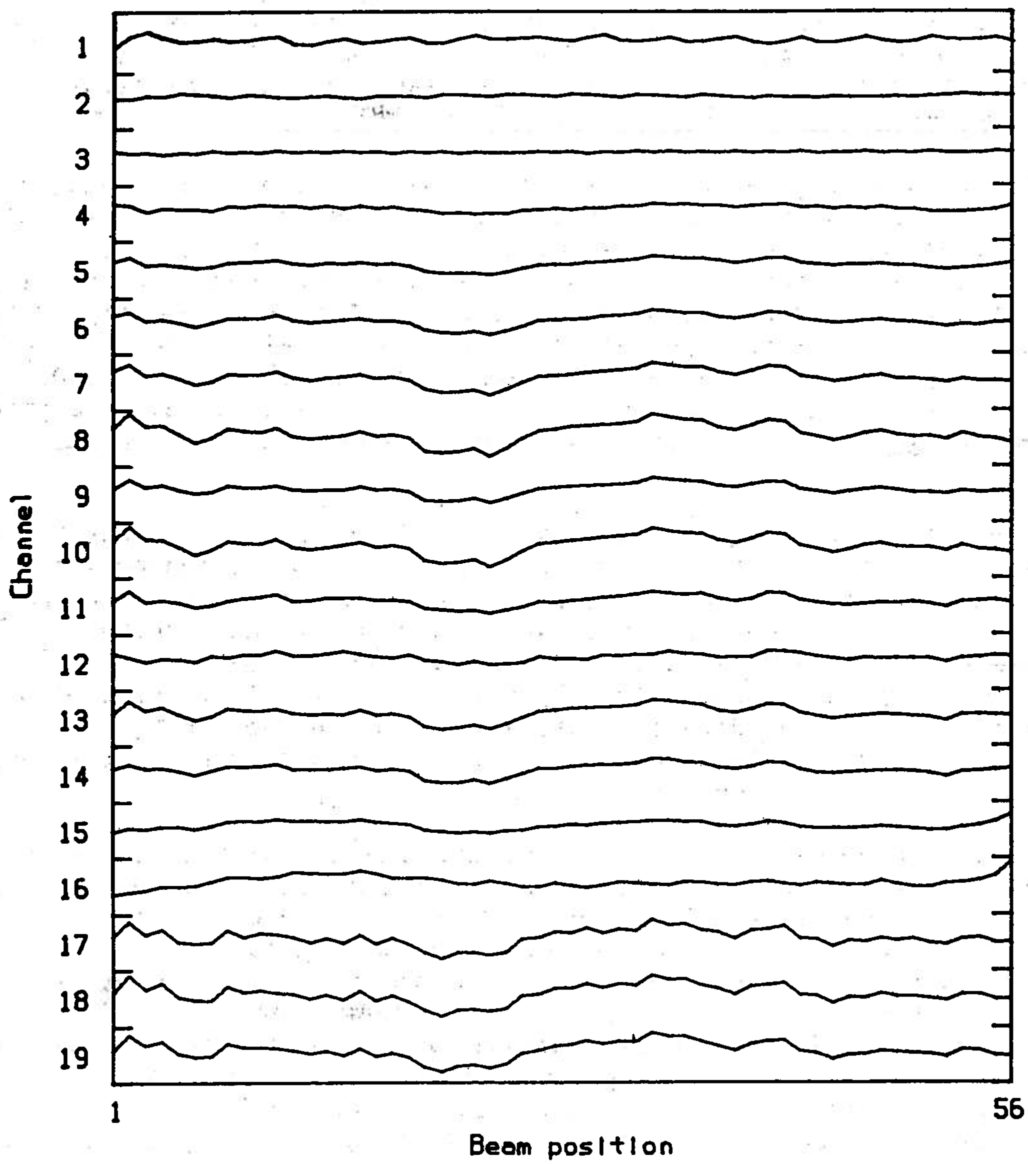

Figure 5.3. Average deviations by beam position for the 19 thermal channels of the HIRS-2 on the NOAA-11 satellite during 6-11 July 1991. The ordinate scale between tic marks is ±0.5 K.

6. Selection of associated channels

If there is no thought given to the physical relation between various channels, inclusion of all channels in the selection process could easily give precedence to channels which have only strong statistical correlations with the channel of interest. However, such correlations are fortuitous, and in another sample would be severely altered. One example of such correlations is that between a channel arising mostly from the lower troposphere and one from the middle stratosphere. In high-latitude early Winter there is a large negative correlation, but as Spring approaches this correlation begins to break down and even changes sign. Use of a stratospheric channel for limb adjustment of a lower tropospheric channel, which would work so well in the dependent sample, would fail in an independent sample. It is therefore necessary to limit the allowable channels.

Before a serious attempt was made to select associated channels, a list of "allowed" channels was compiled. This list was chosen on the basis of the physical relations among the channels as represented by the weighting functions; these weighting functions have been described elsewhere in the literature [2] and will not be repeated here. The orthogonality of two normalized functions is represented by their integral product, yielding a value between 0 and 1. By selecting some cut-off point, such as 0.25, one can delete some combinations from further consideration. By this process as many as 10 or 12 channels were "allowed" for each channel. This list is not presented here.

The next step in the process was the selection of "candidate" channels from among the "allowed" set. This was done by stepwise regression at a limited number of scan positions, using the reduction of variance as the criterion for selection. After careful scrutiny of the results, the "candidate" channels were chosen, using a subjective but liberal approach and eliminating only those which clearly were of little benefit or were detrimental. The candidate channels are listed in Table 6.1. Data used in these tests were the first data set, which was smoothed but not separated into ascending and descending portions.

It is clear that the channels arising from immediately below and immediately above a given channel will be most effective as predictors, given the vertical separation found in the TOVS channels. The addition of other candidates as predictor channels is mostly based on familiarity with the character of the separate channels and the overall system design.

Computation of provisional limb-adjustment coefficients is performed by stepwise regression. In this process, at each beam position a 2 X N matrix is formed from the values of the principal channel at each latitude and surface type represented in the data set (N is about 125), along with a corresponding vector of nadir values for the principal channel. The two coefficients are computed by least squares and the variance is found. Then the dimension of the matrix is increased to three, and each channel from the list of unused candidate channels is added to the last row of the matrix, and the coefficients and variance are computed. The channel having the

Table 6.1. Candidates for associated channels, marked by X, for the three TOVS instruments, using the accepted numbering system (HIRS-2, MSU, and SSU in that order). Channel 20 is not included.

Ch.	Associated channel																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	22	23	24	25	26	27
1	X	X	X													X										
2	X	X	X													X										
3		X	X	X												X										
4			X	X	X																					
5				X	X	X						X														
6					X	X	X	X			X	X														
7						X	X	X		X	X	X														
8							X	X		X	X															
9	X	X	X				X	X	X	X	X															
10							X	X		X	X															
11						X	X	X		X	X	X														
12				X	X	X	X	X			X	X														
13							X	X		X	X		X	X												
14						X	X	X		X	X		X	X	X											
15					X	X	X				X	X		X	X	X										
16	X	X	X												X	X										
17							X						X				X	X	X							
18							X						X				X	X	X							
19							X						X				X	X	X							
21																				X	X					
22																				X	X	X				
23			X																		X	X	X			
24		X	X																			X	X			
25	X	X	X																					X	X	
26	X	X	X																					X	X	X
27	X	X	X																					X	X	X

smallest variance is chosen, the values for that channel are placed in the last row of the matrix, and the dimension of the matrix is increased by one, repeating the process until all candidates have been exhausted.

Selection of the most appropriate channels is done by a mean reduction in variance as a fraction of the variance with the principal channel alone. To reduce the computing time, scan positions are limited to those with values of [sec(z) - 1] > 0.1, which eliminates HIRS-2 scan positions 16-41, MSU scan positions 4-8, and SSU scan positions 3-6.

There is another factor which can have an influence on the quality of limb-adjusted data. This is called "noise amplification", which results from combining the noise effects of more than one channel through the limb-adjustment coefficients. This can be expressed by

$$A = \text{Amplification} = [\sum_{i'} (a_{i'}\sigma_{i'})^2]^{1/2}/\sigma_i, \qquad (6.1)$$

where σ is the noise, and the other symbols follow earlier practice. Amplification is not always greater than unity, and in many cases it is significantly less. In these circumstances much of the limb effect is in the constant term.

A second procedure was followed in the channel selection by choosing the channel with the smallest noise amplification. To simplify the latter computations, the specific values of noise in terms of radiance temperature were omitted:

$$A = \left(\sum_{i'} a_{i'}^2 \right)^{1/2}. \qquad (6.1')$$

The same process was followed as in the stepwise regression, but the criterion for channel optimization was the smallest value of A. The selection was on the basis of the smallest mean deviations from unity of A over the allowed scan angles.

Results from these two procedures are given in Table 6.2. This table shows by an X the associated channels selected by both criteria; a 1 indicates a channel chosen by minimum variance; and a 2 indicates a channel chosen by Eq. (6.1'). Associated channels are limited to two or three.

For nine channels the selection was the same using each test, and these selections are therefore adopted automatically. For the remaining 18 channels, limb coefficients were computed using both sets of channels, along with the variance of fit and the noise amplification at each beam position. The results were subjected to scrutiny and a subjective selection was made. Selections were made as follows:

1. For Channels 1, 3, 5, 10, 14-16 and 24-27 the advantage was with the maximum reduction of variance procedure. Reasons differ among these 11 channels, but the choice was clear in every case.

2. For Channels 8, 9, 13, and 19 the advantage was with the minimum noise amplification procedure. In all four cases the decision was made on the basis of noise amplification.

3. The remaining two channels, 11 and 18, were assigned to the minimum noise amplification procedure. Channel 11 showed that the roles of the two factors were reversed and that the noise amplification was less than unity in any case. Channel 18 was selected on the basis of noise amplification, the variances being virtually the same for the two sets of channels.

The final selection of associated channels is given in Table 6.3.

The coefficients are too numerous to list here, but Table 6.4. lists both the coefficients and other pertinent data for each TOVS channel at the extreme left beam position (position number 1).

Table 6.2. Associated channels for the TOVS instruments, marked by X for double selection, by "1" for selection by maximum reduction in variance, and by "2" for minimum noise amplification. The same numbering system as in Table 6.1 is used.

Ch.	Associated channel																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	22	23	24	25	26	27
1	X	2	X																							
2		X	X													X										
3		X	X	1												2										
4			X	X	X																					
5				1	X	X						2														
6						X	X	X																		
7							X	X		X																
8							X	X		1	2															
9	1		2					2	X		1															
10							X	X		X																
11						2		1		X	X															
12				2				2				X														
13							2	1			2		X	1												
14								1			2		X	X												
15					1	2								X	X											
16	2		1												X	X										
17																	X	X	X							
18													1				2	X	X							
19								2					1				X		X							
21																				X	X					
22																				X	X	X				
23																					X	X	X			
24		X	2																			1	X			
25	X	1																						X		2
26	X		1																					2	X	
27	X	1																							2	X

Table 6.3. Final selection of associated channels for the TOVS instruments, marked by X. The numbering system in Table 6.1 is used.

Ch.	Associated channel																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	21	22	23	24	25	26	27
1	X		X																							
2		X	X													X										
3		X	X	X																						
4			X	X	X																					
5				X	X	X																				
6						X	X	X																		
7							X	X		X																
8							X	X			X															
9			X					X	X																	
10							X	X		X																
11						X				X	X															
12				X				X				X														
13							X				X		X													
14								X					X	X												
15					X									X	X											
16			X												X	X										
17																	X	X	X							
18													X					X	X							
19								X									X		X							
21																				X	X					
22																				X	X	X				
23																					X	X	X			
24		X																				X	X			
25	X	X																						X		
26	X		X																						X	
27	X	X																								X

Table 6.4. Limb-adjustment coefficients at beam position #1 (extreme left) for the TOVS channels on NOAA-11. Added columns give the standard deviation of fit and noise amplification factors, A. The coefficients are the constant term, followed by two or three channel coefficients given in the order of their appearances in rows of Table 6.3.

Channel	a_0(K)	a_1	a_2	a_3	σ(K)	A
1	-7.504	0.78472	0.24458		0.134	0.8220
2	-5.389	0.00621	1.08673	-0.07080	0.180	1.0891
3	0.411	-0.48993	1.38896	0.09546	0.175	1.4759
4	25.568	0.12677	0.14111	0.61652	0.490	0.6450
5	6.184	-0.22769	0.79315	0.41693	0.962	0.9245
6	37.002	0.99494	-0.69571	0.55332	1.080	1.3342
7	32.374	0.49942	0.72278	-0.35046	1.542	0.9459
8	54.442	-0.31733	1.40542	-0.31661	2.212	1.4752
9	3.523	-0.10024	0.22058	0.87055	1.561	0.9036
10	31.092	-0.22559	0.99158	0.11133	2.047	1.0230
11	46.745	-0.11136	0.37394	0.54439	1.222	0.6698
12	32.770	-0.09546	0.11009	0.84716	1.052	0.8596
13	-24.781	-0.32300	0.04953	1.39713	1.623	1.4348
14	-19.362	-0.23387	1.40981	-0.09268	1.277	1.4321
15	3.049	-0.21452	0.65015	0.55249	0.774	0.8798
16	-2.540	0.13812	0.44949	0.41541	0.445	0.6274
17	1.405	0.38977	1.14551	-0.53033	1.921	1.3211
18	7.935	-0.32483	1.92456	-0.63275	2.239	2.0518
19	-42.736	-0.19477	0.90919	0.47696	2.410	1.0450
21	121.583	1.37364	-0.95277		5.605	1.6717
22	-14.660	0.09880	1.19239	-0.20186	0.718	1.2134
23	7.520	0.46508	0.45996	0.03491	0.252	0.6550
24	58.051	-0.61465	-0.63916	2.01172	0.762	2.1985
25	-0.135	-0.08643	0.15444	0.93134	0.138	0.9480
26	-4.320	0.63892	-0.20410	0.58325	0.169	0.8888
27	-1.061	0.39306	-0.17705	0.79402	0.258	0.9035

7. Discussion of the algorithm

The algorithm posed in Section 2. has been derided as the solution to an "ill-posed" problem, and there is a sizable community which regards angle adjustments as a poor substitute for treating the observations without potential distortions prior to the inversion process. However, there are some counter-arguments which must be made in defense of angle adjustments.

The entire process of using satellite data to derive vertical profiles of temperature and humidity may be termed ill-posed in the sense that there is no unique solution. On the other hand, limb adjustment has a property not found in the inversion process. Somewhat similar to interpolation or mild extrapolation, limb adjustment is a means of combining more than one piece of information about or near the solution into a single piece of information.

If any combination of measurements, be it linear or not, can reproduce the solution within the error of measurement, then the solution may be considered redundant. As an example, the HIRS-2 Channels 1-8 can be predicted from the associated channels in Table 6.3., with one minor change, to the accuracies shown in Table 7.1. Here the standard deviations are shown at nine beam positions to a least sqares fit of 150 values of the channel values as a linear combination of several (2-5) associated channels. For all but Channel 8 the standard deviations are less than the measurement noise, and in that respect each channel is redundant. This redundancy does not, however, imply any channel is superfluous, inasmuch as it is used as a predictor for other channels. Noise amplification was not important.

Table 7.1. Standard deviations of the fit for the NOAA-11 HIRS-2 Channels 1-8 to the prediction of the channel values as a linear combination of the associated channels in Table 6.4.

Beam position	Channel 1	2	3	4	5	6	7	8
1	1.699	0.404	0.969	0.277	0.252	0.255	0.102	0.722
4	1.788	0.448	0.963	0.250	0.250	0.223	0.086	0.698
7	1.659	0.383	0.774	0.258	0.242	0.199	0.076	0.668
10	1.565	0.302	0.622	0.274	0.234	0.177	0.068	0.642
13	1.552	0.251	0.528	0.291	0.227	0.161	0.063	0.622
16	1.559	0.223	0.469	0.306	0.221	0.151	0.059	0.607
19	1.570	0.206	0.433	0.318	0.217	0.144	0.058	0.597
22	1.581	0.197	0.411	0.328	0.214	0.140	0.057	0.591
25	1.590	0.191	0.398	0.334	0.212	0.137	0.057	0.587
28	1.597	0.189	0.393	0.336	0.212	0.136	0.057	0.585
Mean	1.616	0.279	0.596	0.297	0.228	0.172	0.068	0.632

However, we must view this from a slightly different perspective. It is not the redundance which is important. It is whether or not the solution can be demonstrated to lie within the error of measurement. As described in Section VIII.B. of reference [1], the estimated error of the n-th limb-adjusted value can be computed from the matrix equation

$$e_{ikn} = [MSE_{ik}\underline{x}_{ikn}(T_{ik}^{*}T_{ik})^{-1}\underline{x}_{ikn}^{*}]^{1/2}, \tag{7.1}$$

where MSE is the mean-square error of fit to Eq. (2.1) using the associated channels in Table 6.3., $\underline{x}$ is a row vector given by unity and the radiance temperatures of the associated channels, and T is the matrix comprising the N rows of $\underline{x}$; the subscripts i and k follow earlier practice. This is analagous to the standard error of estimate employed in normal statistics. The average values are given in Table 7.2. for the same channels and beam positions of Table 7.1.

Table 7.2. Average estimated errors (degrees K) of limb-adjusted latitudinal mean radiance temperatures for NOAA-11 HIRS-2 Channels 1-8.

Beam	Channel							
position	1	2	3	4	5	6	7	8
1	0.020	0.031	0.030	0.083	0.164	0.184	0.263	0.377
4	0.019	0.028	0.027	0.073	0.139	0.166	0.233	0.336
7	0.017	0.024	0.024	0.059	0.114	0.143	0.200	0.286
10	0.013	0.019	0.019	0.045	0.087	0.114	0.159	0.225
13	0.010	0.014	0.014	0.033	0.064	0.085	0.119	0.168
16	0.007	0.010	0.010	0.023	0.044	0.061	0.085	0.120
19	0.005	0.006	0.007	0.015	0.030	0.042	0.058	0.081
22	0.003	0.004	0.007	0.009	0.018	0.026	0.036	0.051
25	0.002	0.006	0.003	0.005	0.009	0.014	0.019	0.026
28	0.000	0.001	0.001	0.001	0.001	0.002	0.003	0.004
Mean	0.012	0.017	0.017	0.043	0.083	0.102	0.143	0.204

Values in Table 7.2. decrease markedly as the nadir is approached. This is the result of the smoothing of the data, but at least as far as the smoothed data are concerned the values are appropriate. It is perhaps more valuable to look at the mean values given in the last line to get proper insight into the magnitude of errors arising from the application of the limb-adjustment algorithm. Only Channel 8 exceeds the noise, and this is mainly because of the very low noise in this channel of less than 0.1 K. At the individual beam positions, the noise is exceeded only for about half of the beam positions in Channel 8 and in the most extreme angles in Channel 7, mainly as a result of cloud influences.

From the results in Tables 7.1. and 7.2. it may well be argued that the limb-adjustment algorithm satisfies all the requirements for giving coherent fields of consistent data, and that the errors introduced by its application are smaller than the errors arising from errors in the angle dependences of the optical transmittances in the radiative transfer equation.

Table 7.3. Standard deviations in the fit of NOAA-11 HIRS-2 Channels 1-8 latitudinal mean radiance temperatures to the smoothing algorithm.

Beam position	Channel 1	2	3	4	5	6	7	8
1	0.133	0.084	0.088	0.243	0.472	0.663	0.930	1.314
4	0.124	0.071	0.080	0.210	0.402	0.567	0.794	1.127
7	0.111	0.070	0.077	0.198	0.382	0.540	0.757	1.073
10	0.104	0.067	0.074	0.194	0.374	0.528	0.740	1.051
13	0.105	0.066	0.074	0.195	0.377	0.532	0.744	1.056
16	0.103	0.067	0.075	0.196	0.379	0.534	0.745	1.056
19	0.101	0.068	0.076	0.198	0.382	0.538	0.749	1.061
22	0.101	0.069	0.076	0.198	0.382	0.537	0.747	1.055
25	0.101	0.068	0.075	0.198	0.380	0.534	0.741	1.045
28	0.100	0.067	0.074	0.197	0.379	0.533	0.741	1.046
Mean	0.109	0.070	0.077	0.203	0.392	0.552	0.771	1.091

It is seen that approximately four outer beam positions have greater standard deviations of fit to the limb-adjustment algorithm than given by the mean of the smoothing algorithm.

8. Significance of the latitudinal means

There may be a question as to whether the latitudinal means represent individual sets of measurements or whether there are biases which are not found in the individual measurements. To verify the validity of the procedure, several tests have been conducted.

A. The NOAA-11 data during July 6-11, 1991 were gone through once more, comparing each set of measurements of Channels 1-12 with its respective set of means. The means were the smoothed values described in Section 5.; they are not the means derived directly from the observations. There are 27,552 possible means for each channel, but the ascending and descending portions of orbits were combined to yield a possible 13,776 data. The absence of certain surface types in some latitudes and insufficient populations in others reduces this number to 6,889 (50.01%). Channels 13-19 were omitted because because of sunlight contamination and considerations of field alignment.

The set of measurements which had the smallest mean deviation, defined as the sum of the absolute deviations (usually called the ℓ_1 norm), was found:

$$d_{jklm} = \min \sum_i |T_{ijklm} - \bar{T}_{ijklm}|/12, \qquad (8.1)$$

where i is the channel number, j is the beam position, k is the index for surface type, l is the latitude, and m indicates the ascending or descending portions of orbits. Each set of means was tested against from 29 to 1009 sets of measurements, averaging 145.30. Figure 8.1.

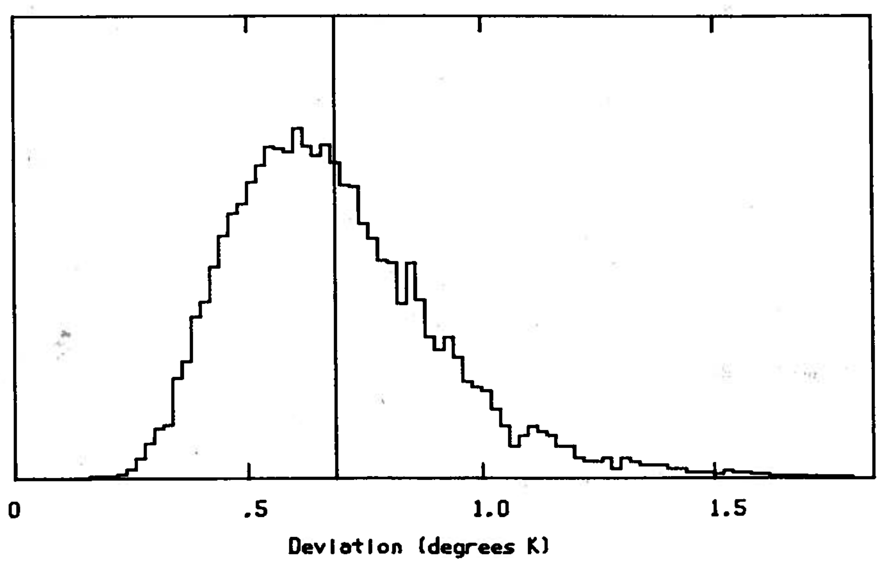

Figure 8.1. Histogram of the best-fit mean deviations for the NOAA-11 HIRS-2 channels 2-12 latitudinal means. The histogram comprises 6889 samples.

shows a histogram of the 6889 best-fit mean deviations, a composite of the four indices j, k, l, and m; and Table 8.1. summarizes the statistical behavior of this set.

B. In addition to the overall behavior of the best-fit data are the deviations of the individual channels. This information was obtained from the set of 6889 best-fit sets of measurements. Figure 8.2. shows histograms of the deviations for each of the 12 channels; statistical data for the deviations are given in columns 3 and 4 of Table 8.2.

Table 8.1. Characteristics of the NOAA-11 HIRS-2 Channels 2-12 best-fit mean deviations.

Surface	Mean d_{jklm} (K)	Max. d_{jklm} (K)	99% (K)	Ave. no. of obs.	No. of means
Water	0.692	2.216	1.403	182.7	3520
Land	0.721	2.103	1.505	94.8	2574
Ice	0.565	1.290	0.941	173.7	795
Total	0.688	2.216	1.403	145.3	6889

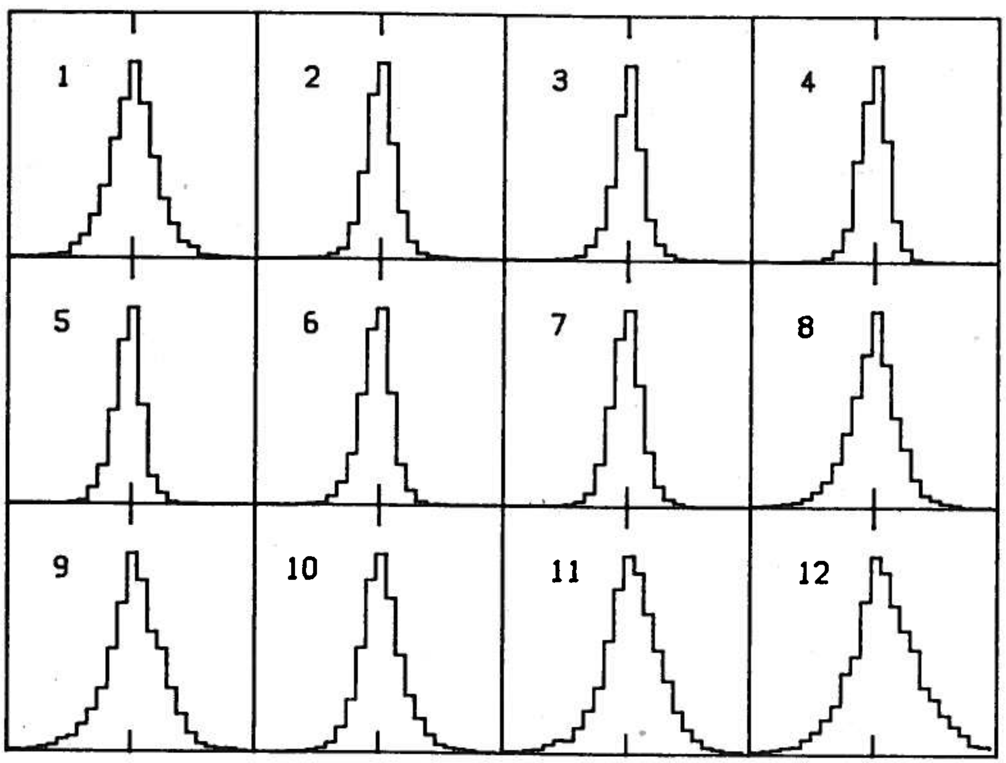

Figure 8.2. Histograms of best-fit deviations from latitudinal means for NOAA-11 HIRS-2 observations. The abscissae cover the range ± 5 K.

C. Another view of the data is the deviation of a sample comprising the means. Figure 8.3. shows histograms of deviations for the 12 HIRS-2 channels, and the standard deviations and standard errors of estimate are given in columns 5 and 6 of Table 8.2. This differs from the information in Fig. 8.2 and in columns 3 and 4 of Table 8.2. by encompassing all acceptable observations (2,175,552) in comparison with the selection of 6889 used in the previous two tests. Standard errors of estimate are the standard deviations divided by 12.054, the square root of the average number of observations in the latitudinal means.

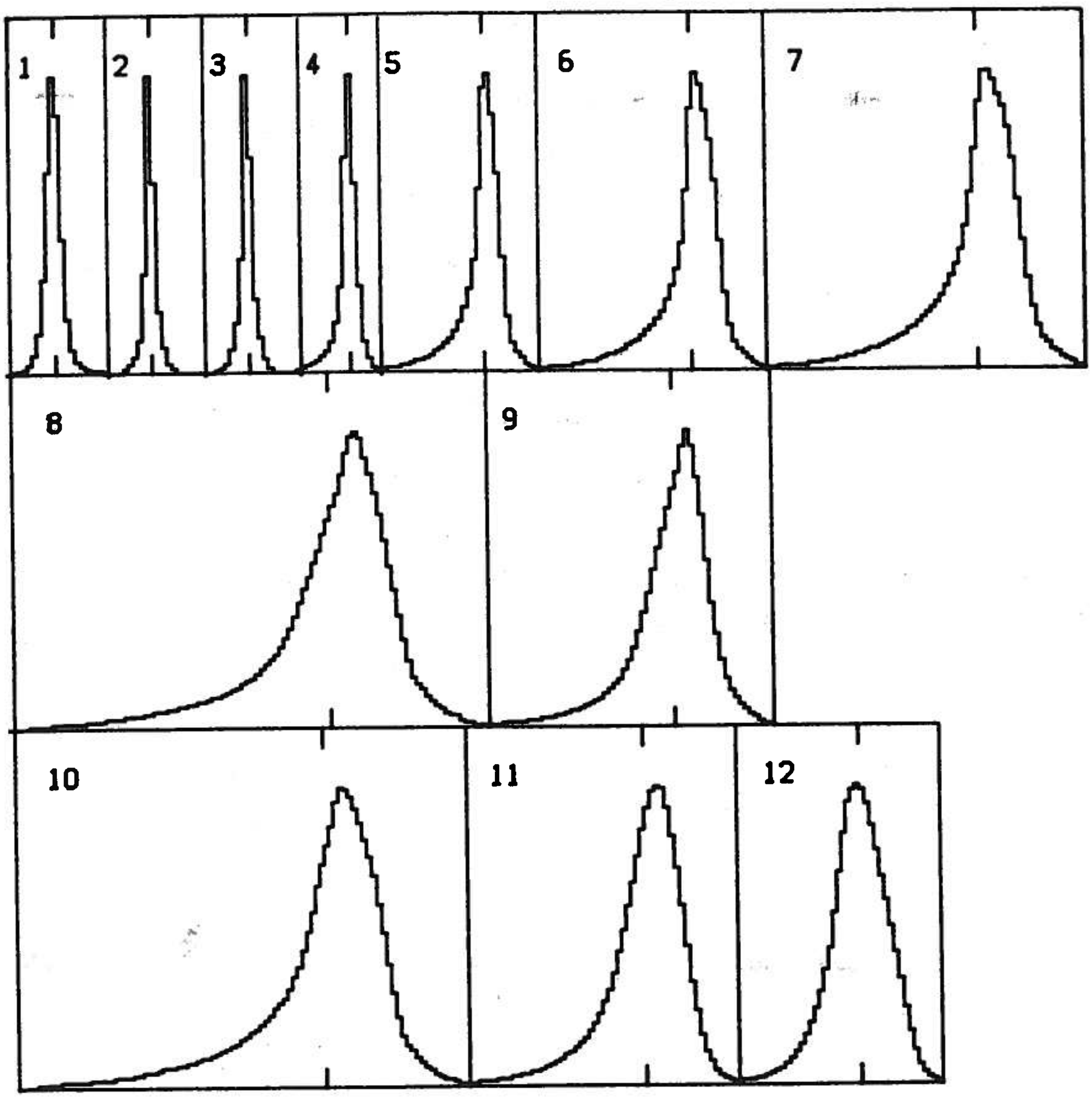

Figure 8.3. Histograms of the deviations of the NOAA-11 HIRS-2 observations from latitudinal means. The range of each histogram for Channels 5-12 indicate extreme deviations of 99% of the samples, which is 80 K for Channel 8; the location of each mean is marked.

Table 8.2. Statitical behavior of two samples. All quantities are in degrees K; instrument noise is at the mean temperature of the sample.

Channel	Instrument noise	Best fit deviations Mean	Standard deviation	Latitudinal Means Standard deviation	Standard error
1	1.052	-0.199	1.042	2.091	0.173
2	0.326	-0.198	0.663	1.469	0.121
3	0.286	-0.222	0.694	1.558	0.129
4	0.130	-0.380	0.651	2.868	0.238
5	0.094	-0.651	0.675	5.348	0.443
6	0.108	-0.749	0.749	7.521	0.624
7	0.071	-0.754	0.754	10.560	0.876
8	0.019	-0.279	1.232	14.754	1.224
9	0.050	0.245	1.334	8.808	0.731
10	0.065	0.108	1.027	13.867	1.150
11	0.223	0.248	1.335	8.668	0.719
12	0.377	0.884	1.803	6.587	0.546
Ave.	0.358	-0.120	1.057	5.648	0.469

D. To gain some perspective on the latitudinal variations of one of the channels most sensitive to clouds, Channel 8, the standard deviations and standard errors of estimate were found for 12 latitude belts at 10-degree intervals over the ocean, and are given in Table 8.3. Figure 8.4. shows the histograms of the data.

Table 8.3. HIRS-2 Channel 8 standard deviations and standard errors of estimate for oceanic observations in several latitude belts. Data are for beam position 29 (nearest nadir). Averages of standard deviation and standard error differ slightly from those in Table 8.2.

Latitude range	Number of obs.	Standard deviation	Standard error
-62 to -60	316	11.55	0.92
-52 to -50	659	14.17	0.78
-42 to -40	630	15.65	0.88
-32 to -30	534	14.41	0.88
-22 to -20	441	6.85	0.46
-12 to -10	455	15.33	1.01
- 2 to 0	389	16.74	1.20
+ 8 to +10	370	26.89	1.98
+18 to +20	279	7.74	0.65
+28 to +30	253	11.08	0.98
+38 to +40	223	15.18	1.44
+48 to +50	166	11.86	1.31
Average	393	15.07	1.05

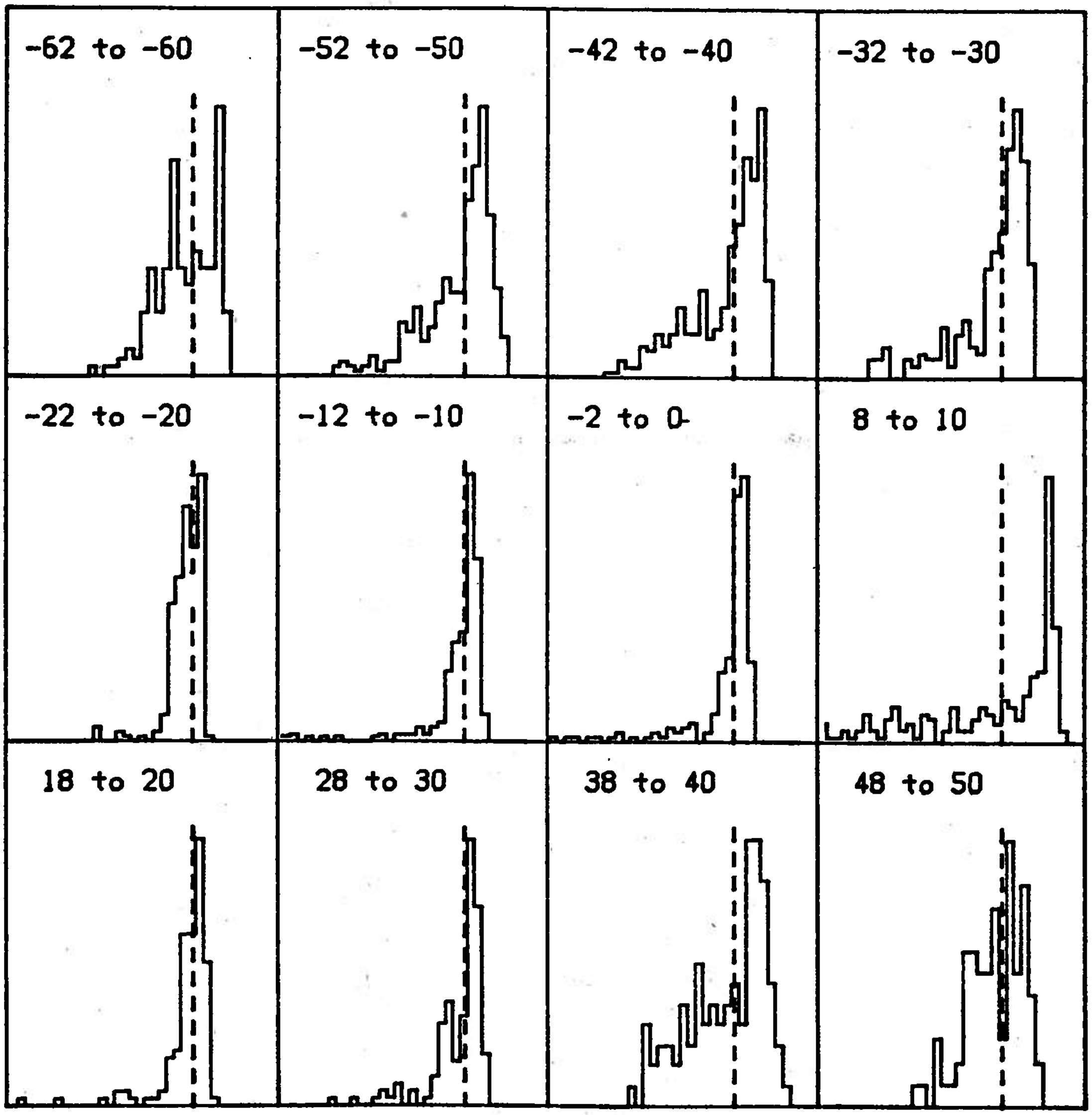

Figure 8.4. Histograms of Channel 8 deviations from latitudinal means in selected latitude belts over oceans. The dashed vertical lines show the means.

With all this statistical information, how are the results to be interpreted and how do they relate to the question as to whether the latitudinal means can substitute for individual measurements under genuine conditions of atmospheric temperature, atmospheric gases, clouds, surface temperatures, and cloud and surface emissivities. It is apparent that if the substitution can be made for one beam position it can be made for all.

A. The mean standard deviation of 0.688 K in Table 8.1 is about twice the average instrument noise for the 12 channels, 0.358 K, given in Table 8.2. In view of the fact that observational data can only increase the instrument noise effects, this appears to be reasonable considering the the mean deviations of the individual channels.

B. The distribution of mean deviations among the channels is different for the instrument noise and the observations, as shown in Table 8.2. Starting from Channel 1 the two are the same, but for Channel 8 one is a minimum and the other a maximum. This is a direct result of clouds and is unavoidable but not a serious matter, leading only to larger errors of estimate for limb adjustments in more transparent channels. It can also be seen in the data presented in Section 7.

C. The only possible concerns at this point are the biases shown in column 3 of Table 8.2. It is difficult to estimate their influences, but the effects are small and are lost in the eventual computations of the limb-adjustment coefficients.

D. Skewness is demonstrated in Figures 8.3 and 8.4, which represent the entire data sample. Statistically this can be deleterious or not, depending upon the problem. In the present instance the skewness appears systematically in all channels influenced by clouds and is therefore not a factor. The same may be said about the rare instances of bimodal distributions as seen in Figure 8.4.

The evidence is that each of the latitudinal means does indeed represent an actual condition which occurs in nature. This is to be expected because the main source of variance is clouds, and the mean cloudiness at a given latitude is likely to represent an actual condition. The natural separation of atmospheric types and cloudiness by latitude and surface type assures that a wide variety is encompassed and that the use of these means in the limb-adjustment algorithm is valid.

9. Global and local limb adjustments

The limb adjustments to a common angle of propagation, in this case the nadir direction, have become known as "global" adjustments. This term refers to the trigonometric globe and not to the Earth. All limb adjustments for the TOVS instruments are in this class.

With the introduction of the next instruments to be flown on the NOAA series of satellites a somewhat different approach will be taken in the processing of the data. The two instruments will be the HIRS-3, a very slightly modified version of the HIRS-2, and the Advanced Microwave Sounding Unit (AMSU), which will replace the MSU and the SSU. The AMSU consists of two versions, the AMSU-A, which will have 15 channels and will scan in 30 beam positions, and the AMSU-B, which will have five channels and will scan in 90 beam positions.

The HIRS-3 data must be "cloud-cleared" before the computation of temperature and humidity profiles. This will be done at the location of one (the primary) of a cross-track pair of HIRS-3, which will require that the measurments at the other must be adjusted to the primary angle. The AMSU-A will be involved in a more complicated procedure of global limb adjustment, cloud clearing, three-dimensional quality checks, and finally adjustment of a select group to the primary angle. After the cloud-clearing of the HIRS-3, which uses some of the AMSU-A channels for consistency checks, the results will be adjusted to the nadir position. The small adjustment of the HIRS-3 data is known as "local" limb adjustment. Consistency checks and other processes requiring fields of data are carried out before the retrievals are made.

It has been seen that the limb-adjustment coefficients described in this paper have utilized all associated channels at all beam positions, which, because of the smoothing of the data, leads to sets of smoothed coefficients. However, because the local limb adjustments are much smaller than global adjustments, only two associated channels are required: the channel in question and one other. By the processes described in Section 6. the associated channels given in Table 9.1. were selected from those given in Table 6.1.

To allow complete flexibility in the HIRS-3 local adjustments with respect to any AMSU-A beam position, each of the three coefficients is subjected to a cubic in the variable x = sec(z) - 1, where z is local zenith angle, which was also applied to the latitudinal means in Eq. (5.1'). This is expressed by

$$a_{im}(x) = b_{ijm0} + b_{ijm1}x + b_{ijm2}x^2 + b_{ijm3}x^3, \qquad (9.1)$$

where a is a coefficient for channel i, m is the coefficient number, varying from 0 to 2, and j is the beam position. Eq. (9.1) is solved by least squares for the b coefficients from the 28 values of a.

It is interesting to compare the standard deviations of fit to those found in generating the global limb coefficients. To do this, the variances

Table 9.1. Associated channels for local limb adjustments of the HIRS-2 data, marked by X. The numbering system in Table 5.1 is used.

Ch.	Associated channel																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	X		X																
2		X	X																
3		X	X																
4				X	X														
5					X	X													
6						X		X											
7							X	X											
8							X	X											
9			X						X										
10								X		X									
11										X	X								
12								X				X							
13							X						X						
14													X	X					
15														X	X				
16															X	X			
17																	X		X
18																		X	X
19																	X		X

from the global calculations for the same HIRS-2 spots used in finding the local limb adjustments were averaged for each MSU beam position. The results are given in Table 9.2.

It is seen the the values for MSU beam position #6 are virtually identical, as might be expected. At beam position #1 the global values are greater in every case except for Channel 2; the degree to which they are greater is clearly dependent upon the degree to which clouds affect each channel. The data in Table 9.2. confirm that clouds are the main contributors to the errors in both the global and local limb adjustments, and the two sets of computations are completely compatible.

The coefficients have not been tested on any set of observations, so there is no absolute assurance that the algorithm does not contain flaws. It is for this reason that some freedom should be given for changing the algorithm and the number of coefficients. Although the changes are very simple to make, involving only a few (perhaps 5) lines of code, dimensions also could be changed. However, there is no change in the input data, which involves only the array of coefficients for the smoothed data.

Table 9.2. Standard deviations of fit (degrees K) for the local limb adjustment of HIRS-2 data to six MSU spots; and for global limb adjustment from the six MSU spots.

Ch	Local (MSU spot)						Global to nadir (MSU spot)					
	1	2	3	4	5	6	1	2	3	4	5	6
1	.096	.081	.047	.029	.016	.004	.122	.107	.165	.088	.029	.004
2	.180	.156	.085	.051	.026	.006	.134	.125	.169	.150	.049	.007
3	.104	.065	.032	.020	.010	.003	.131	.118	.095	.056	.018	.002
4	.239	.209	.118	.072	.037	.009	.430	.338	.176	.122	.064	.009
5	.263	.202	.126	.081	.043	.010	.826	.657	.356	.169	.068	.011
6	.288	.192	.140	.094	.051	.013	.955	.838	.479	.229	.081	.013
7	.389	.236	.183	.126	.068	.017	1.344	1.151	.668	.324	.112	.017
8	.562	.326	.253	.175	.096	.024	1.966	1.673	.968	.470	.158	.024
9	.357	.252	.175	.116	.062	.015	1.395	1.100	.605	.289	.100	.016
10	.521	.306	.237	.164	.089	.022	1.801	1.541	.904	.442	.149	.022
11	.303	.176	.140	.097	.053	.013	1.066	.918	.535	.259	.094	.013
12	.234	.152	.110	.074	.040	.010	.875	.710	.448	.214	.071	.010
13	.383	.226	.176	.121	.066	.016	1.304	1.125	.647	.312	.109	.016
14	.323	.205	.150	.102	.055	.014	1.050	.899	.512	.246	.089	.014
15	.310	.234	.134	.084	.044	.011	.740	.594	.324	.156	.069	.012
16	.317	.245	.157	.101	.054	.013	.639	.514	.307	.161	.080	.014
17	.438	.252	.208	.144	.079	.020	1.695	1.472	.853	.413	.138	.020
18	.553	.308	.255	.178	.097	.024	1.809	1.509	.867	.417	.142	.024
19	.679	.388	.309	.214	.117	.029	1.958	1.556	.891	.429	.146	.028

10. Updating the coefficients

It is critical that the limb-adjustment coefficients should be updated at least once at the time of a solstice. This is most important during the early time after the launch of a satellite, especially if the initial computations are based on a period near one of the equinoxes. The reason for updating is not to revise the data base, but rather to expand it. By including data from at least one solstice period and one equinox period, latitudinal means covers the maximum possible range, and the process of limb-adjustment becomes one of interpolation except for the most extreme conditions, where extrapolation is minimized. The principle is like passing a regression line through a closely grouped set of noisy values or through a widely spaced set of equally noisy values. In the former case the regression line is very inaccurate for values lying outside the range of the data set; and for the latter case the regression line is more accurate for the values outside the range of the data set. At times near the equinoxes, some channels have very limited ranges of radiance temperatures, but near the solstices the same channels cover very large ranges.

The procedure to follow, then, is to add to the data set each time the coefficients are to be updated. In any period when latitudinal means are found, there will be about 125 independent values. When a second period is employed, the number increases to about 250, then to 375, 500, etc. with successive periods.

11. Summary of procedures.

Late in 1990 the procedures for the NOAA-K, L, and M processing were changed, requiring some modest alterations in the procedures and introducing the concept of "reverse" limb adjustment. In this process, all AMSU data are subjected to "global" limb adjustments. This is followed by a cloud clearing process for Channels 3-6, after which the data are interpolated to HIRS-3 locations. Finally, Channels 3-6 are again adjusted to HIRS-3 angles (reverse adjustment). Thus, the AMSU Channels 3-6 require two sets of coefficients for angle adjustment.

A. Preparatory steps.

1. Accumulate five days of observations from all sounding instruments.

2. Convert the radiances to radiance temperatures.

3. Compute the cosine of the local zenith angle of the sun for daytime observations of the HIRS-2 and save as a separate "channel".

4. Add all measurements for each channel for each of the three surface types (ocean, land, and ice) in each of 82 two-degree latitudinal bands and for ascending and descending portions of orbits. Eliminate redundant data and all channels where one of them is flagged of fails other quality checks. Save the numbers of observations separately.

5. Smooth the observations as described in Section 5., eliminating data lacking fewer than one-quarter the average number of observations or with HIRS-2 or HIRS-3 Channel 20 having a value greater than 0.5 percent. Also eliminate complete sets of data where both extreme beam positions are absent, or there are fewer than half the beam positions represented, or the standard deviations of fit are more than three times the ensemble value. Review the results and eliminate all channels for all instruments if any has been eliminated for a given latitude, surface type or orbit portion.

B. Global limb adjustments.

1. Using the smoothing coefficients to compute channel values, compute the limb coefficients for each channel and each beam position, using the associated channels given in Table 6.3.

2. If an update of the process is deemed advisable, repeat Steps 1-5 and use the results with previously-obtained smoothing coefficients in Step 6. That is, do not discard previous data, but use them as independent data in combination with new data.

C. Local limb adjustments.

1. Compute limb-adjustment coefficients for the HIRS-2 or HIRS-3 channels from the associated channels given in Table 9.1.

2. Fit each of the coefficients with the cubic in x.

3. Apply the results at appropriate beam positions in the operations.

D. Reverse limb adjustments (beginning with NOAA-K).

1. Using the smoothing coefficients for AMSU Channels 3-7, compute channel values at the HIRS-3 locations. Compute the reverse limb coefficients for AMSU Channels 3-6 using

$$T_{ij} = e_{ij} + \sum e_{ij} T_{i0}, \tag{11.1}$$

where the subscript j is the HIRS-3 location and the subscript 0 is the nadir value.

2. Adjust the AMSU Channels 3-6 cloud-cleared values to the HIRS-3 locations.

As a one-time action, it will be necessary with a new instrument to generate a table of associated channels, using the first group of accumulated data in Step 4. and following a research path.

12. Special handling of the MSU data

After the completion of this study the author was informed that the inclusion of HIRS-2 Channel 2 data in adjusting the MSU Channel 24 would require major changes in the operational software. In addition, the MSU adjustments had posed some inherent problems.

The MSU had not been designed as a complete sounder, but rather had been included with the TOVS for the express purpose of overcoming cloud influences which render the infrared measurements so intractable. D. Staelin (private communication) had examined the limb-adjustment problem with the MSU and the planned AMSU and confirmed that the MSU lacked sufficient channels to perform the limb adjustments, but that the AMSU filled in the needed information. This was also confirmed by Wark [1] in a study with the SSM/T.

After careful examination of the problems, it was found that good limb adjustments could be made to the MSU if certain rules were applied.

A. For Channels 21-23 there should be separate coefficients for the sea and land areas using the associated channels listed in Table 6.3. On coastlines, if the radiance temperature is less than 258K it should be treated as sea; if the radiance temperature is greater than 258K it should be treated as land.

B. Channel 24 requires four sets of coefficients.

1. Over the seas and low terrain, Channels 22-24 may be used as associated channels without consideration of the surface type. However, over terrain higher than 1.5 km (850 mb), Channel 22 is significantly influenced by the surface, which becomes particularly noticable over Antarctica, Greenland, the Tibetan plateau, and the Andean altoplano. Separate coefficients, using only associated Channels 23 and 24, were generated for use in these areas only.

2. The tropics cannot be fit with a universal set of coefficients, so separate coefficients were generated for the latitude belt 30S to 30N and for the regions with latitudes greater than 30 degrees; separate coefficients are required for low and high terrain, but again without regard for surface type. In the latitudes 15S-30S and 15N-30N the radiance temperatures from the two sets of coefficients are linearly interpolated by latitude.

Although this handling of Channel 24 is cumbersome, the results indicate that, with very few exceptions, the quality of limb adjustments meet the needs for temperature soundings and there are no apparent discontinuities. However, these procedures should be regarded as a temporary measure pending the AMSU.

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