LIMB ADJUSTMENTS TO TOVS DATA--A MORE RATIONAL APPROACH

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1. INTRODUCTION

Before the launch of the TIROS-N satellite, it was decided that the TOVS data should be adjusted to the values they would have if all views were in the nadir direction. This required corrections at the outermost beam positions from paths through nearly two air masses to the values at one air mass. The algorithm stated that a linear combination of the radiance temperatures for several channels would lead to the the nadir value for a particular channel.

$$T_{ij} = a_{0ij} + \sum a_{i'ij} T_{i'j}, \qquad (1)$$

where T is radiance temperature, i is the channel being adjusted, j is the beam position, i' is an "associated" channel, a_{0ij} is a constant, and $a_{i'ij}$ is a coefficient for channel i' at position j.

Solution for the coefficients of Eq. (1) is done by computing radiances from a set of 120 atmospheric soundings which cover a wide range of meteorological conditions and inserting clouds in various amounts and at various heights into a part of the sample. Selection of the "associated" channels is performed by stepwise regression, using certain criteria for limiting the number of channels. Radiance temperatures are then computed using the algorithm in reference [1].

2. THE PRESENT TOVS COEFFICIENTS

When the limb-adjustment coefficients are applied, the results are surprisingly good when one considers all of the possible sources of error. However, they are not entirely satisfactory for the task, which is the derivation of vertical profiles of temperature and humidity. For this reason, the procedure has produced a widespread skepticism, which, deserved or not, dominates the thinking of a majority of the workers in this discipline.

1. Because the coefficients are derived from computed radiance temperatures, they carry with them any inaccuracies in the optical transmittances of the atmosphere, which have long been known to be substantial. Methods are employed to overcome these, but residual inaccuracies persist.

2. The clouds which are inserted are placed at arbitrary levels and are considered to be "black" or physically thin. These conditions do not always reflect the true nature of clouds.

3. The 120 atmospheres were selected from a well-recognized set of 1200 radiosondes and rocketsondes. By choosing every tenth sounding, the authors of the procedure have overlooked the manner in which the set was compiled. In most cases the rocketsondes are used more than once in

association with radiosondes several days earlier or later. In addition, there are many soundings which have errors which violate such rules as being superadiabatic. In a separate study, it has been found that there are only 717 independent soundings, and from this set a subset of 117 can been chosen which maximizes the independence of each of the subset.

4. To reduce the computations, coefficients are not generated for each HIRS-2 beam position, but only for a limited number, and each set of coefficients is applied to several beam positions. At large zenith angles this can lead to significant errors.

5. Application of stepwise regression at each angle leads to a selection of "associated" channels which varies with the zenith angle. The effect is to produce discontinuities in the radiances and in the amplification of instrument noise.

3. A NEW APPROACH

To overcome each of these problems, a series of steps have been taken. Foremost among these is the use of the observations themselves, rather than relying upon computed radiances. This circumvents the first three objections above. The other two are handled in ways descibed below.

The procedures are as follows:

1. All of the TOVS data are saved for a period of at least five days. This is the period in which the NOAA satellites view the entire earth, after which there is great redundancy. This results from the fact that there are almost exactly 14.2 orbits per day.

2. Radiances are converted to radiance temperatures to allow a wide range of selection of "associated" channels. No changes in the MSU data to "brightness" temperatures are made.

3. For each channel of each instrument and at each beam position the radiance temperatures are averaged in 2-degree latitude belts. Because the objective is to adjust the values to the nadir, latitudes are limited to the range 82 south to 82 north, the approximate range of the sub-satellite points. The data are further separated into three surface types (ocean, land and ice) to accommodate the MSU data, and into day and night to account for solar effects on the short wavelength channels of the HIRS-2. The result is about 250 sets of averaged data for each beam position. Study of these has shown that each set of averages represents at least one set of observations from within the latitude belt within the average noise level, and that it therefore is a true representation of the upwelling radiances for a particular meteorological condition. Just as importantly, it is also tied to the same meteorological condition at all the other beam positions.

4. Clouds have a profound effect on infrared observations, and their variability over a 5-day period produces a great deal of noise into many of the HIRS-2 channels. To reduce this effect, each channel for each latitude belt and surface type, day and night, is fit to a quadratic in the variable x=sec(z)-1, where z is the local zenith

angle, plus an asymmetry term linear in the scan angle y:

$$T_{ij} = c_{0ij} + c_{1ij}x + c_{2ij}x^2 + c_{3ij}y_j. \qquad (2)$$

This reduces the very large ensemble of measurements to a size easily handled by a personal computer, while at the same time producing data without perceptible noise to assist in further analysis; standard deviations of fit are satisfactory. The small asymmetry proportional to the scan angle (not the zenith angle) was noted in the average data mainly in channels with significant contributions from the stratosphere. It was necessary to divide the data into day and night portions in order to verify the nature of the asymmetry. It may be noted that the constant term in Eq. (3) is the nadir value.

5. The same "associated" channels are used at all beam positions so that no discontinuties noted above will occur. In the selection of these channels, which is done only once, the following rules apply:

a. Not more than three "associated" channels are used, and one of these must be the channel which is being adjusted.

b. Selection is first made by stepwise regression using only "allowed" channels, which are chosen on the grounds of reasonably close physical relation to the channel being adjusted. There may be as many as eight of these. The stepwise process chooses the order of importance of the channels on the basis of standard deviations of fit. Only the outer beam positions are considered because the standard deviations of fit become vanishingly small near the nadir.

c. In a second selection, the combination of channels having the smallest noise amplification, A_{ij}, is chosen,

$$A_{ij} = \{\sum(b_{i'ij}\sigma_{i'})^2\}^{1/2}/\sigma_i \approx \{\sum b_{i'ij}{}^2\}^{1/2}. \qquad (3)$$

After the two selection processes are complete, the results are examined. In many cases, both processes make the same selection. Where there are differences, the residuals are examined and a subjective choice is made.

6. The limb-adjustment coefficients are computed by simple linear regression, using the already-selected channel combinations.

For some MSU and SSU channels the long-wave HIRS-2 channels not sensitive to clouds are candidate predictors. For the MSU Channel 4 only Channel 3 may be used because Channel 2 is sensitive to the surface. Insufficient information is carried by Channels 3 and 4 to produce good results for the limb adjustment of Channel 4, and the use of the HIRS-2 Channel 2, interpolated to the MSU location, overcomes some of this deficiency. In the same way, the SSU Channel 1 makes marginal, but not really necessary, use of the same HIRS-2 channel.

The objective in any limb-adjustment procedure is to produce the radiances for some fixed angle of view without introducing any systematic errors and to amplify the instrument noise as little as possible. The processes described carry out this mission. With a few minor exceptions, noise amplification is not a problem, and in many cases there is an actual noise reduction, with the constant carrying much of the burden. The only question which remains is how well the algorithm performs its task. The answer lies in the average estimated errors of the regressions; this is given by Eq. (9) in reference [2]. At small zenith angles the adjustments are so small that the average estimated errors are necessarily small, and one should examine only the large zenith angles. Table 1. shows the average estimated errors and noise amplification factors for the 27 TOVS channels at the outermost beam position for the appropriate instrument, which represents the worst case. It is seen that for nearly half there is a reduction in the instrument noise effects, and for only three channels does the noise double. The estimated errors in almost all cases depend only upon the sensitivity of the channel to clouds, and imply the probable error of the limb adjustment process itself. They may be compared with SSM/T results at beam positions 1 and 7 given in Table 6. of reference [2], which are at a smaller scan angle.

Table 1. Average estimated errors, <e> in degrees Kelvin, and noise amplification factors, A, for the TOVS channels at the outermost beam position. Data are from the NOAA-11 satellite, taken during the period 18-25 September 1989. Channels are numbered 1-27 in the customary order.

Channel	<e>(K)	A	Channel	<e>(K)	A	Channel	<e>(K)	A
1	0.018	0.820	11	0.181	0.678	21	0.657	2.020
2	0.021	1.083	12	0.158	0.863	22	0.114	1.224
3	0.023	1.482	13	0.254	1.554	23	0.040	0.635
4	0.079	0.670	14	0.191	1.869	24	0.119	2.218
5	0.151	1.336	15	0.133	0.826	25	0.018	0.998
6	0.164	1.560	16	0.101	0.566	26	0.026	0.897
7	0.234	1.229	17	0.293	1.710	27	0.036	0.905
8	0.344	1.739	18	0.333	2.568			
9	0.257	0.951	19	0.381	0.971			
10	0.315	1.349						

The results shown here do not represent the ultimate refinements in deriving limb-adjustment coefficients. The division of the data into day and night portions is providing an opportunity to study the effects of reflected and coherently-scattered sunlight on HIRS-2 Channels 13-19, as well as the diurnal heating and cooling in the stratosphere.

4. REFERENCE

1. Werbowetzki, A. (editor), 1981: "Atmospheric Sounding User's Guide", NOAA Technical Report NESS 83, 82 pp.

2. Wark, D. Q., 1988: "Adjustment of Microwave Spectral Radinaces of the Earth to a Fixed angle of Propagation", NOAA Technical Report NESDIS 43, 40 pp.

MICROWAVE MEASUREMENTS AND THE INFLUENCES OF CLOUDS

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1. INTRODUCTION

A generally overlooked characteristic of microwave measurements is the influence of clouds and preciptiation. The assumption that microwaves are impervious to those aerosols has long been know to be inaccurate, but no sincere effort has been made compensate for the effects.

The SSM/T on the DMSP satellites provides enough spectral information to examine the phenomenon, whereas the MSU on the NOAA satellites is very poorly endowed in this respect. The main purpose of carrying a microwave instrument as part of the TOVS complement of instruments was to monitor the effects of clouds on the infrared measurements. The idea was that the microwave was impervious to clouds and could therefore be used as a quality control on TOVS soundings. However, little thought has been given to the actual effects of clouds and precipitation on the MSU Channel 2, which is the principal quality control device used with the TOVS.

The MSU has only four channels, each sensitive to portions of the atmosphere largely independent from those covered by the other three channels. However, SSM/T on the DMSP satellites is a more complete sounding device, with Channels 1-3 covering approximately the same part of the atmosphere as the MSU Channels 1 and 2. The additional channel sensitive near the surface allows analysis which cannot be done with the MSU.

2. ANALYSIS OF THE SSM/T DATA

An estimate of the total cloud liquid water over oceans has been proposed by Grody (private communication),

$$q = -0.562 + 0.00453T_1 - 0.00172T_2. \qquad (1)$$

It has been found to be rather good algorithm, and it is now used as a filter for deletion of SSM/T soundings.

To exploit this quantitative estimate, some preliminary analysis was done on five days of limb-adjusted (Wark, 1988) SSM/T Channels 1-4. Each hemisphere was divided into four grids of 64 X 64, which is approximately the footprint of the SSM/T. The window channel, Channel 1, was used as the control; each observation was compared with the value at the grid location, and if its value was lower, each of the first four channels replaced the previous value in its appropriate grid point. In this way, the Channel 1 grid became the background, devoid of clouds and with minimum water vapor; the other three grids became observations of Channels 2-4 corresponding to clear conditions but with more or less random meteorological conditions. To assure that areas of persistent cloudiness would not be included, all measurements for which q was greater than 0.02 kg/m^2 were not used. This effectively eliminated most of the ITCZ regions.

The data were examined again, this time computing values of q and finding the differences between individual observations and the grid values. These differences were averaged within increments of q, producing average values of the enhancement of the SSM/T channels versus average values of q at 22 points. The results are given in Table 1; negative values of q represent the effects of noise in Channels 1 and 2. Except for Channel 1, the data are Gaussian in their behaviors about the means, with barely perceptible skewness.

Table 1. Values of modifications of SSM/T Channels 1-4 versus cloud liquid water deduced from the Grody relation. Data were during 21-28 July 1988.

q	ΔT_1	ΔT_2	ΔT_3	ΔT_4	Sample
-0.0427	0.0000	0.0000	0.0000	0.0000	2
-0.0336	0.1855	0.1079	0.0733	0.0018	37
-0.0234	0.5483	0.1423	0.0779	0.0149	346
-0.0140	1.0556	0.3805	0.1624	-0.0017	2012
-0.0045	1.9860	0.4223	0.1286	-0.0104	4717
0.0052	3.3173	0.5007	0.1051	0.0315	7391
0.0149	4.5539	0.6926	0.1235	0.0142	7310
0.0247	6.2730	0.9770	0.2084	0.0758	5083
0.0345	7.9150	1.2341	0.2903	0.1184	3101
0.0446	10.1987	1.6344	0.4308	0.2032	1715
0.0547	12.9725	2.2879	0.6959	0.3058	1044
0.0648	15.5211	2.6342	0.7823	0.2133	638
0.0750	17.9920	2.9753	0.7639	0.1727	386
0.0847	20.3597	3.4384	0.9762	0.2783	310
0.0949	24.4608	4.1507	1.2556	0.1370	214
0.1047	25.5315	3.9295	0.9433	0.0588	168
0.1149	27.5437	3.9783	0.9275	0.0659	122
0.1252	29.9041	3.8300	1.0150	0.2877	80
0.1343	31.0534	3.2389	0.7909	0.1767	59
0.1442	33.3836	3.9971	0.6716	-0.2026	36
0.1548	34.3905	2.7390	0.2511	0.3055	13
0.1635	36.1104	3.7398	0.7604	-0.4295	3

Quadratic fits, with the negative values of q deleted and with equal weights assigned to each value, yield the relations

$$\begin{aligned}\Delta T_1 &= 0.6049 + 246.5410q - 151.8555q^2 \pm 0.7162,\\ \Delta T_2 &= -0.3116 + 64.6047q - 256.9063q^2 \pm 0.3723,\\ \Delta T_3 &= -0.2028 + 22.6095q - 111.4969q^2 \pm 0.1593, \text{ and}\\ \Delta T_4 &= -0.0491 + 7.3530q - 48.8764q^2 \pm 0.1459.\end{aligned} \quad (2)$$

The intercepts have no physical meaning, and are the products only of the procedures followed. It is gratifying to note that the quadratic term is negative for every channel, which is in accord with theory and is confirmed by a study of Fleming (private communication) which used computationally derived radiances.

Using Eq. (2) for Channel 2, the sample shows the difference exceeds the noise of 0.392K for that channel about 46% of the time. The operational standard for the deletion of SSM/T soundings is $q > 0.06\ kg/m^2$. This encompasses 15% of all oceanic soundings, and represents a cutoff of increased Channels 1-4 radiance temperatures by cloud liquid water at about 14.8K, 2.6K, 0.8K, and 0.2K for Channels 1-4. The result is that a very significant portion of the SSM/T data are warmer than they would be in clear conditions, and the ensemble contains a mixture of pure and tainted data.

3. THE EFFECTS ON RETRIEVED SOUDINGS

Temperature soundings are produced from the SSM/T measurements by a regression procedure involving matched SSM/T data and radiosonde data. In such a procedure the mean retrieval should be the same as the mean of the radiosondes, but the clear soundings will be too cold in the troposphere and the cloud-contaminated soundings will be too warm. This produces an increase in the RMS errors, which contributes a share to the comparison statistics which are regularly produced by NOAA and the ECMWF.

To give an estimate of influence of cloud contamination on RMS errors, the data were examined once more. Eliminating all data for which q was greater than $0.6\ kg/m^2$, the means and standard and maximum deviations of the temperature enhancements of Channels 1-4 from Eq. (1) were found to be

Channel 1	3.4251 ± 4.9953,	maximum 10.8204,
Channel 2	0.7604 ± 1.1653,	maximum 2.1910,
Channel 3	0.2525 ± 0.3943,	maximum 0.7027,
Channel 4	0.0741 ± 0.1206,	maximum 0.1911.

At each level of the atmosphere, the effect of this "noise" on the retrieved soundings will be proportional to the weighting functions,

$$e^2(p) = \{\sum_i [d\tau_i/d\log(p)]\sigma_i^2\}/\sum_i [d\tau_i/d\log(p)] \qquad (3)$$

where e^2 is the variance, p is pressure, τ is transmittance, i is channel, and σ is the standard deviation caused by clouds. The standard and maximum deviations, e(p) and m(p), for the troposphere are given in Table 2.

Table 2. Standard and maximum deviations of soundings caused by clouds.

Pressure (mb)	e(p) (K)	m(p) (K)
1000	1.14	2.15
850	1.08	2.04
700	0.96	1.80
500	0.71	1.33
400	0.60	1.12
300	0.52	0.96
250	0.49	0.90
200	0.46	0.84
150	0.38	0.70
100	0.23	0.42

The situation is less favorable for the TOVS soundings, particularly the "cloudy" cases in which the HIRS-2 data are not used for the troposphere. The use of a "physical" solution does not allow the same freedom to account for the influence of clouds, although "tuning" does compensate in a similar way. However, the separation of TOVS soundings into three classes of cloudiness cannot fail to result in soundings which are incompatible. The MSU Channel 2, which is similar to the SSM/T Channel 3, must surely suffer from the same degradation, namely about 0.8K to 1.0K for all "cloudy" soundings.

There does not appear to be any easy solution to this dilemma with the current TOVS system, but the emergence of the AMSU on the NOAA-K satellite should provide a literal spectrum of information to permit some adjustments to the observations and to provide quantitative tools for the elimination of hopelessly contaminated data.

The procedures given here are not recommended for adjusting SSM/T data without further study.

4. REFERENCE

Wark, D. Q., 1988: "Adjustment of Microwave Spectral Radiances of the Earth to a fixed angle of Propagation", NOAA Technical Report NESDIS-43, 40 pp.

TECHNICAL PROCEEDINGS OF THE SIXTH INTERNATIONAL TOVS STUDY CONFERENCE

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