THE FORWARD PROBLEM AND CORRECTIONS FOR AMSU-A

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1. INTRODUCTION

This paper is concerned solely with the forward problem, i.e., developing the proper physical relationships between the atmospheric temperature profile, surface properties, and the brightness temperatures through the radiative transfer equation. The purpose in doing the forward problem is twofold. First, we want to determine the correctness of the radiative transfer physics and data, which ultimately will be used for the inverse problem. Obviously, if the forward problem cannot be done correctly, there is no hope of doing the inverse problem correctly. The second purpose is of equal importance, namely, to be able to calculate correctly the initial (first guess) brightness temperature vector from the initial atmospheric temperature profile, both of which are used in the retrieval algorithm.

The application of our work on the forward problem is to the 15-channel Advanced Microwave Sounding Unit A, (AMSU-A) instrument. In order to do the forward problem we need to know the atmospheric temperature profile, which we obtain from radiosonde observations. To account for all of the Earth's outgoing radiation, we also have to extrapolate the radiosonde temperature profiles above the cutoff level of the observations. A procedure is given for this. In addition, we discuss the determination of surface emissivity and cloud liquid water from the brightness temperature measurements. Cloud liquid water amount is used to ascertain cloud and precipitation contamination, and to make corrections to the measured brightness temperatures.

A natural way of determining the validity of our forward calculations is to compare the calculated brightness temperatures with those observed by the AMSU-A sounding instrument. However, since this instrument is still in the development stage, we use the next best sounder from which data are available. This is the seven-channel microwave sounder SSM/T of the U.S. Defense Meteorological Satellite Program. Thus, all empirical results in this paper are based on space-based measurements from this instrument.

When comparisons between measured and calculated brightness temperatures are made, discrepancies invariably are found. To eliminate those discrepancies for which no physical basis is known, we make a final empirical correction to the forward prob-
lem. This is done with a special kind of regression estimator called a shrinkage estimator for which details are given.

Finally, the work described in this paper has the following limitations:
1) The entire discussion is restricted to ocean areas because previous results from SSM/T were devoted mainly to land areas and since cloud effects are enhanced over oceans, those areas require special treatment.
2) All brightness temperature measurements have been adjusted to be equivalent to the nadir view by the method of Wark (1988).

2. INSTRUMENT CONSIDERATIONS

It was pointed out in the Introduction that the discussions of this paper are directed at the AMSU-A instrument, but that we are forced of necessity to use data from the SSM/T instrument for empirical results. In other words, the SSM/T data are being used as proof of concept for the AMSU-A sounder. Table 1 shows how the two instruments relate to one another.

Table 1. Comparison of the respective channels on the AMSU-A and SSM/T sounders, ordered from the most transparent to the most opaque channels, with the opposing entries being essentially of the same transparency.

<table>
<thead>
<tr>
<th>AMSU-A Sounder</th>
<th>SSM/T Sounder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel #</td>
<td>Frequency</td>
</tr>
<tr>
<td>2</td>
<td>31.4 GHz</td>
</tr>
<tr>
<td>1</td>
<td>23.8 GHz</td>
</tr>
<tr>
<td>3</td>
<td>50.3 GHz</td>
</tr>
<tr>
<td>4</td>
<td>52.8 GHz</td>
</tr>
<tr>
<td>5</td>
<td>53.2 GHz</td>
</tr>
<tr>
<td>7</td>
<td>54.94 GHz</td>
</tr>
<tr>
<td>9 (fLO=)</td>
<td>57.29 GHz</td>
</tr>
<tr>
<td>11</td>
<td>fLO ±322 ±48 MHz</td>
</tr>
<tr>
<td>12</td>
<td>fLO ±322 ±22 MHz</td>
</tr>
<tr>
<td>13</td>
<td>fLO ±322 ±10 MHz</td>
</tr>
<tr>
<td>14</td>
<td>fLO ±322 ±4.5 MHz</td>
</tr>
</tbody>
</table>

The channels listed above the dotted line in Table 1 are the only ones that sense surface and cloud effects over oceans. Furthermore, these effects are sensed with decreasing intensity as one moves down the table. The procedures for accounting and correcting for the effects of the surface and clouds in microwave channels are uniquely different from those used for the infrared channels; therefore, these two topics are emphasized.
3. RADIOSONDE EXTRAPOLATION

In doing the forward problem, one must account for all the radiation emerging from the top of the atmosphere. However, temperature soundings from radiosondes seldom extend above 10 hPa; they typically terminate between 100hPa and 10 hPa. Consequently, a means must be found to extrapolate the radiosonde soundings up to 0.01 hPa, the effective top of the atmosphere.

Our approach to the extrapolation problem is to use a set of 108 temperature variance-covariance matrices described in Crosby, et al. (1973). Each covariance matrix has associated with it a mean temperature profile, which is the average of all the profiles used to produce the given covariance matrix.

In broad outline, the extrapolation procedure is as follows. Given a radiosonde temperature profile to extrapolate, compare it with each of the 108 mean profiles described in the previous paragraph, and choose that mean profile that is closest to the given radiosonde profile. Next, partition the covariance matrix associated with the mean profile into four block matrices, with the lower right-hand, square diagonal block having the dimensions of the given radiosonde profile (vector) and the upper left-hand, square diagonal block having the dimensions of the part of the profile to be extrapolated. Then a regression coefficient matrix is formed from the block matrices according to the formulae found in Crosby, et al. (1973).

4. CLOUD LIQUID WATER

Verification of the forward problem calculations is against SSM/T measurements of brightness temperature. It is assumed that the verifying measurements are not contaminated by cloud liquid water or precipitation. Of the seven channels on SSM/T, only Channels 1 and 2, the two most transparent channels, are affected by cloud liquid water. Since Channel 1 is a window channel, it is affected much more by liquid water than is Channel 2.

Because of their sensitivity to cloud liquid water, Channels 1 and 2 can be used to estimate the total amount of liquid water. It has been found by regression that the following formula provides a reasonably good measure of cloud liquid water Q for the nadir scan position:

\[ Q = -5.62 + 0.045 \, T^* (50.5) - 0.017 \, T^* (53.2) \] (1)

where \( T^* \) is the brightness temperature at the frequency indicated in parenthesis. A different set of coefficients has to be used for each of the seven scan angles of the SSM/T sounder, but if we assume cross-track symmetry, only four different scan angles need be considered. The remaining three scan angles (in increasing order) require the following coefficients for (1):

- Scan Position 2: -5.45, 0.046, -0.018;
- Scan Position 3: -4.90, 0.048, -0.023;
- Scan position 4: -3.66, 0.053, -0.034.
It should be noted in connection with (1) that an exception is made to the Wark (1988) angle adjustment to nadir in that unadjusted brightness temperatures were found to be better predictors than adjusted ones. Also, to derive the coefficients in (1) the data set used consisted of brightness temperatures simulated from model profiles of liquid water for a large range of temperature profiles and cloud heights.

5. LIQUID WATER CORRECTIONS

When the SSM/T Channel 1 and 2 brightness temperatures are contaminated by precipitation and/or cloud liquid water, one can simply eliminate these two channels from the retrieval process. However, in many cases this would degrade the retrieval accuracy more than would using a slightly contaminated Channel 2. (In this case Channel 1 is not used because it will be more contaminated than Channel 2.) Therefore, the following compromise procedure for the contamination problem is used. The liquid water $Q$ is calculated according to (1). Then a correction $\delta T$ to the Channel 2 measured brightness temperatures, based on the calculated value of $Q$, is the following:

$$\delta T = 4.67 \ Q - 3.0 \ Q^2 $$

(2)

As one would expect, the correction is zero for $Q = 0$, but it also is zero for $Q = 1.56$ and negative thereafter. The correction $\delta T$ of (2) is added to the measured brightness temperatures to correct (at least partially) for the effects of liquid water on the measurements.

6. SURFACE EMISSIVITY

Before one can proceed with the forward problem, the surface emissivity $\varepsilon$ must be known. There are two cases to consider: $Q \leq 0.1$ mm and $Q > 0.1$ mm, where $Q$ is calculated from (1).

Case I: When $Q \leq 0.1$, one can assume that Channel 1 is unaffected by cloud liquid water. In this case the known atmospheric temperature profile and sea surface temperature are applied to the radiative transfer equation at 50.5 GHz and the equation is solved for the surface emissivity $\varepsilon$. For details see Section 2.2.2 of Weinreb, et al. (1981).

Case II: When $Q > 0.1$, Channel 1 is too contaminated by cloud liquid water to be useful in determining $\varepsilon$. In this case we resort to the following formula that expresses specular emissivity $\varepsilon_s$ as a function of sea surface temperature (SST):

$$\varepsilon_s = .5911 - .2243 \ X + .08845 \ X^2 $$

(3)

where

$$X = .025 \ (\text{SST} - 270) $$

(4)

Unfortunately, when the calculated emissivities of (3) are compared with those determined directly from Channel 1 for the
cases when Q = 0, there was a bias difference of 0.0203 over the sample set used. This bias apparently is due to the failure to account for the emissivity due to foam and sea surface roughness.

When formulas for foam and roughness emissivities, which depend upon both sea surface temperature and surface wind speed, were used, the specular emissivity bias of 0.0203 was eliminated by assuming an average, global surface wind speed of 6.67 m/sec. This leads to the following formula for the combined emissivities (i.e., specular, foam, and roughness):

\[ \epsilon = 0.0232 + 0.9831 \epsilon_s + 0.0329 \epsilon_s^2 - 0.0213 \epsilon_s^3 \]  

Thus, when Q > 0.1, Eqs. (3), (4), and (5) are used together to determine the composite emissivity \( \epsilon \).

7. THE FORWARD PROBLEM

All preliminary calculations and corrections necessary for doing the forward problem are now in place. Since the radiative transfer model for doing the forward problem is well known, the details are not given here; they can be found, for example, in Section 2.2.2 of Weinreb, et al. (1981). The same reference also provides details for calculating the required effective transmittances and their derivatives from knowledge of \( \epsilon \).

The validity of the brightness temperatures from the forward problem calculations can be judged by comparing them with those observed by the SSM/T instrument. This assumes that the temperature and moisture data used in the forward problem were measured simultaneously with the satellite overpass. When comparisons between calculated and measured brightness temperatures are made, discrepancies between the two invariably occur. To eliminate these discrepancies, we use shrinkage estimation in the final step of the forward problem.

8. SHRINKAGE ESTIMATION

Shrinkage estimation is a linear regression procedure in which the coefficient matrix is constrained by the identity matrix. This constraint is appropriate because the calculated brightness temperature for each channel that is to be corrected receives its radiation from a unique portion of the atmosphere. Therefore, most of the information about the correction of a given channel should come from the measured brightness temperature that corresponds to the calculated brightness temperature of the given channel. For details see Oman (1982), and for an alternative approach see McMillin, et al. (1989).

To calculate the coefficient matrix of the shrinkage estimator, collect sample sets of calculated and measured brightness temperatures, each having a population of \( n \) samples. Let \( k \) be the number of channels being corrected and let \( p \) be the number of channels being used as predictors, then \( k \leq p \). Furthermore, let \( R \) be the \( k \times p \) matrix of regression coefficients, let \( C \) be the
n x k sample matrix of calculated brightness temperatures, and let M be the n x p sample matrix of measured brightness temperatures. The data for matrices C and M are assumed to be centered, i.e., the matrix elements are the deviations of the data from their sample means \( \bar{c} \) and \( \bar{m} \), respectively. Then the transpose of the coefficient matrix of the of the shrinkage estimator is

\[
R^T = (M^T M + \alpha I)^{-1} (M^T C + \alpha J)
\]

(6)

where I is the p x p identity matrix, J is the p x k rectangular matrix (recall that k ≤ p) with the upper k rows being the identity matrix I and the remaining p-k rows being all zeros, and the scalar \( \alpha \) is a stabilizing parameter. Note that the dimensional structure of (6) allows one to use additional predictors that are quantities other than just brightness temperatures. The additional predictors can include quantities such as latitude and longitude, season, satellite scan angle, solar zenith angle, etc., provided scaling is used. Also note that when \( \alpha = 0 \), (6) reduces to the coefficient matrix for ordinary regression.

With the coefficient matrix R in hand, one obtains an estimate of calculated brightness temperature vector \( \bar{c}^\ast \) from a vector \( \bar{m} \) of measured brightness temperatures using the equation

\[
\bar{c}^\ast = \bar{c} + R (\bar{m} - \bar{m})
\]

(7)

where \( \bar{c} \) and \( \bar{m} \) are the sample mean vectors. Thus, (6) and (7) permit one to make the calculated brightness temperatures from the forward problem look like measured ones. Application of (7) to an independent data set reduced the calculated brightness temperature bias in Channels 3 to 7 an average of 76% and the RMS error an average of 39%.

9. SUMMARY

We have discussed the forward problem, which is limited to ocean areas, for the AMSU-A sounder and demonstrated the need to correct it. Correction formulae were derived specifically for the SSM/T sounding instrument, but we wish to apply the results to the AMSU-A. Therefore, once the AMSU-A sounder is in orbit and is transmitting observational data to the ground stations, one needs to tailor the procedures described above to it. The steps needed to carry out the AMSU-A procedures are summarized as follows:

1) Extrapolate the radiosonde temperature soundings to 0.01 hPa, so that all of the outgoing radiation can be accounted for.

2) Derive a formula for cloud liquid water amount \( Q \) as a linear combination of brightness temperatures from Channels 1 through 5, and 15. The coefficients of the linear combination are obtained by regression, which is based on values of \( Q \) simulated from a large variety of temperature profiles, cloud emissivities, and cloud heights.
3) Derive formulas similar to Eq. (2) for correcting the measured brightness temperatures of Channels 4 and 5 for liquid water contamination. This is done by determining the differences between the calculated and measured brightness temperatures of Channels 4 and 5 as a function of $Q$, where $Q$ is obtained from the formula derived in Step 2 and where the data are a large ensemble of measured brightness temperatures from a large variety of atmospheric and cloud liquid water conditions, including a large variety of cloud-free cases.

4) Select the cloud-free cases of Step 3 by determining those cases for which $Q \leq 0.1$ mm and simultaneously compile the sea surface temperature associated with each cloud-free case selected. Then by least squares, fit a polynomial in SST of degree six to these data. This yields an appropriate empirical formula for determining the composite emissivity $\epsilon$ for the cases $Q > 0.1$ mm.

5) Calculate $\epsilon$ from the formula developed in Step 4 whenever $Q > 0.1$ mm, or from the radiative transfer equation and measured brightness temperatures for Channel 3 whenever $Q \leq 0.1$ mm. Then given an atmospheric temperature profile and associated SST, one can do the forward problem (i.e., calculate the brightness temperatures) for Channels 4 through 14.

6) Finally, determine the coefficient matrix of the shrinkage estimator, using the procedures described in Section 8, and apply it to the measured brightness temperatures as in Eq. (7).

This completes the procedures necessary for doing the forward problem for AMSU-A Channels 4 through 14. The remaining channels are window and water vapor channels and normally are not used directly in the temperature retrieval problem; however, as shown in this paper, they all are indispensable for doing the forward problem.

10. REFERENCES


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