# System Noise in the NESDIS TOVS Forward Model. Part II: Consequences

M. J. UDDSTROM AND L. M. MCMILLIN*

*National Institute of Water and Atmospheric Research, Wellington, New Zealand*

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## ABSTRACT

To utilize satellite radiance sounding data, in either explicit or implicit retrieval algorithms, a proper understanding of the noise in the measurements is required. Conventionally, to define the expected accuracy of atmospheric profiles inferred from sounder data, instrument noise equivalent temperature difference (NEΔT) noise specifications have been used to simulate spacecraft data. Here it is demonstrated that NEΔT noise specifications are inappropriate for this purpose. Instead, total system noise estimates should be employed since use of sounding data in any type of physical retrieval algorithm implies application of a radiative transfer model, which in turn must be "calibrated" against in situ and satellite data.

It is demonstrated that the accuracy of atmospheric retrievals inferred from the TIROS Operational Vertical Sounder radiometers is limited by the total system noise rather than NEΔT noise, and that modeled radiance temperatures perturbed by Gaussian total system noise very nearly replicate the accuracy statistics of retrievals computed from satellite measurements. The implications of these results for planned high-resolution infrared sounding instruments are briefly discussed.

## 1. Introduction

In Part I of this paper, Uddstrom and McMillin (1994) (which will be referred to by initials UM), discuss the sources and characteristics of total system noise in TOVS satellite sounding measurements when applied to explicit or implicit physical retrieval algorithms. Total system noise is important, since these algorithms utilize a forward radiative transfer equation (RTE) model that must be calibrated through comparison of collocated satellite and modeled radiance temperatures. Uddstrom and McMillin demonstrate that the total system noise is a function of many components, but that the most important contributing error source is that which arises from errors in the forward model. Unfortunately current forward radiative transfer models do not yield unbiased estimates of satellite radiances (UM; Fleming et al. 1986; Kelly and Flobert 1988). Further, these errors are air mass dependent. As a result, either the modeled or satellite measurements must be adjusted so that measured and modeled data are consistent. Consequently, the second moment of the measured (after adjustment) minus modeled radiance temperature difference statistics, defines the total system noise appropriate to the retrieval problem, rather than the sounding instrument's noise equivalent temperature difference (NEΔT) (Planet 1988) specifications.

Using a sample of satellite and radiosonde collocation data, an experiment is reported here where accuracy statistics for an explicit, optimal retrieval algorithm are determined from four different sets of radiance temperature "observations," namely, perfect (i.e., model) radiance temperatures, perfect radiance temperatures combined with Gaussian, mean zero NEΔT noise, perfect radiance temperatures combined with Gaussian, mean zero total system noise, and finally, satellite-measured radiance temperatures. The physical retrieval algorithm used is that of Uddstrom (1988), and the collocation sample is drawn from a global archive of data. It will be shown that using total system noise estimates in place of NEΔT values enables the accuracy of retrievals from the TOVS radiometers to be estimated from simulated data with some confidence, and that this accuracy is much poorer than that obtained when measurement noise is simulated from NEΔT specifications.

## 2. Total system noise characteristics

Using the same DSD5 database as in UM, a sample of 30 000 *NOAA-10* collocations was extracted. These data include clear, n-star (i.e., cloud cleared), and cloudy radiance temperatures from the months October through April, weighted toward January, and years 1989 to 1991. Ninety percent of the sample was used to construct radiance adjustment equations and retrieval estimator constraints, while the remaining 10% of the collocations were used to establish inde-

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* Current affiliation: NOAA/NESDIS/ORA/SRL, Washington, D.C.

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*Corresponding author address:* Dr. M. J. Uddstrom, National Institute of Water and Atmospheric Research, P.O. Box 3047, Wellington, New Zealand.

pendent estimates of total system noise and retrieval accuracy statistics.

Model radiance temperatures were computed from a radiative transfer model that is essentially identical to the NESDIS (National Environmental Satellite Data and Information Service) method (Weinreb et al. 1981). The differences between the model used here and the NESDIS operational method relate only to the approach used to specify the boundary term, and the inclusion of a radiance contribution from above the topmost layer in the NESDIS model (see UM for details). Unit "gamma" transmittance adjustment factors were used.

The mean measured minus modeled radiance temperature bias for the dependent-sample clear and *n*-star data, as a function of TOVS channel number (HIRS 1-20, and MSU 1-4 are TOVS channels 1-20, and 21-24, respectively) and airmass class is plotted in Fig. 1. The airmass classes were defined by typical shape function classification (Uddstrom and Wark 1985) and ordered such that airmass class 1 corresponds to the "most" polar atmospheric class, and airmass class 19 is the "most" tropical. The biases for channels 8, 9, 18, 19, 20, and 21 have been set to zero.

Uddstrom and McMillin indicate that a good method to adjust the measured radiance temperatures to equivalent model values is constrained regression (McMillin et al. 1989; Oman 1982). Here, shrinkage adjustment is employed (Oman 1982), and separate adjustment equations were derived for each airmass class. Applying these equations to the independent sample, the measured, adjusted to model equivalents, minus modeled radiance temperature bias is plotted in Fig. 2. The radiance adjustment procedure has removed, at least on an ensemble basis, the RTE model bias that is so evident in Fig. 1. None of the resulting biases are significantly different from zero. In Fig. 3, the root-mean-square (rms) error in the adjusted radiance temperatures is plotted. These values define the total system noise in the "measurements," and differ in a significant way from the NEΔT values (cf. Table 2) specified in Planet (1988) [or inferred from the noise equivalent differential radiance (NEΔN) values given]. Further, it is apparent from Fig. 3 that the opaque water vapor channels (HIRS 11 and 12) are not well modeled, or else the validating atmospheric water vapor measurements do not describe the state of the atmosphere well. The correlation between the measured, adjusted to model equivalent radiance temperatures, and modeled radiance temperatures is presented in Fig. 4. While the rms error in the adjusted satellite measurements (Fig. 3) is essentially flat with respect to airmass, the information content in the measurements is substantially less in the Tropics than in the extratropics, since the atmospheric variance is less. Apart from the opaque water vapor channels, upper-tropospheric channels in all three spectral regions are the most severely affected in this regard.

## 3. Retrieval experiments

Explicit retrievals of mixing ratio, atmospheric, and skin temperatures were computed using the typical shape function maximum a posteriori sequential (TMS) simultaneous physical algorithm of Uddstrom (1988). This algorithm utilizes pattern recognition in temperature or moisture space to define airmass-dependent first-guess constraints, and radiance adjustment equations, as outlined above. Given a measurement vector, the airmass class of the observation and

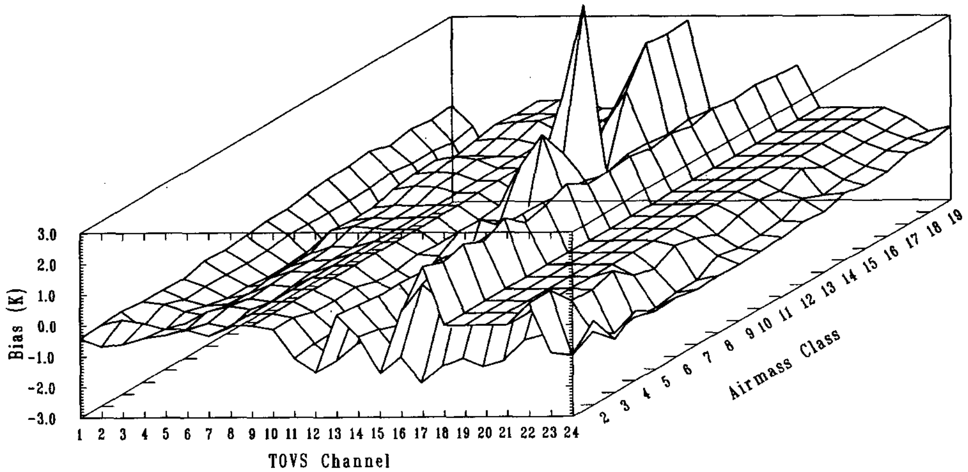

FIG. 1. Mean bias between *NOAA-10*-measured, and collocated modeled radiance temperatures (*z* axis), TOVS channel number (HIRS channels 1-20 are TOVS channels 1-20, MSU channels 1-4 are TOVS channels 21-24) (*x* axis), and airmass class (*y* axis), for the dependent sample. The airmass classes have been ordered by their 1000-250-hPa thickness, so that airmass class 1 is the "most" polar, and airmass class 19 the "most" tropical.

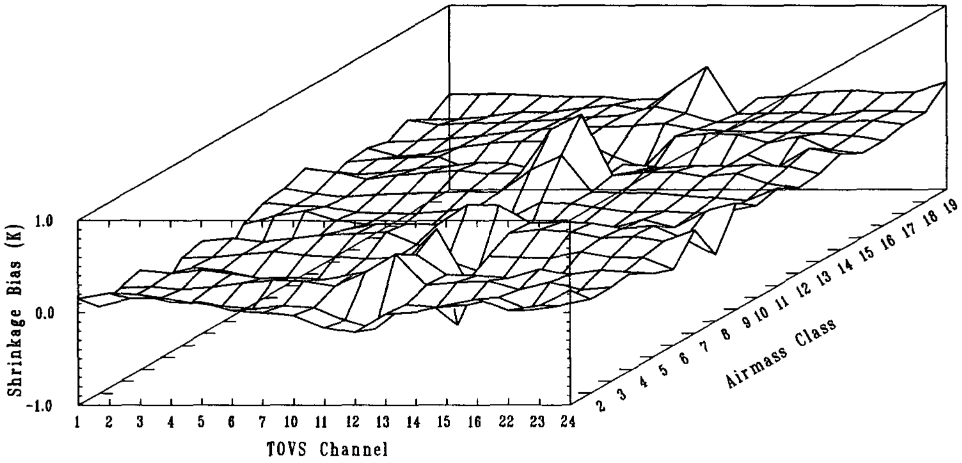

FIG. 2. Mean bias between *NOAA-10*–measured radiance temperatures, adjusted to model equivalents by shrinkage regression, and modeled radiance temperatures for the independent sample. The airmass classes are arranged as in Fig. 1.

its probability of membership may be determined by Bayesian discrimination in the satellite measurement space. Satellite measurements are then adjusted to model equivalents according to the chosen airmass class. The retrieval is performed using an optimal, sequential, simultaneous, physical retrieval estimator. The retrieval portion may be iterated, and a Bonferroni radiance temperature convergence test (Neter et al. 1989) is applied as a final quality control measure. In these experiments, the channels listed in Table 1 were employed in the retrieval algorithm. Cloudy data were not considered, thus reducing the size of the available independent sample by approximately 50%.

Four experiments were conducted in order to estimate the impact of system measurement noise on the retrieval algorithm. In the first experiment, the "measurements" used in the retrieval step (but not the discrimination step) were noise-free modeled radiance temperatures, that is, perfect radiance temperatures. Next, Gaussian single field of view NEΔT noise was added to the modeled values, and the retrievals recomputed. In the third experiment, random total system noise (as defined by Fig. 3) was added to the modeled radiance temperatures, and finally, retrievals were computed from the satellite measurements (adjusted to model equivalent values).

It is important to note that for any particular member of the independent sample, the same first-guess and retrieval estimator constraints are used in all four experiments, since first-guess selection is based on the observed (i.e., satellite) radiances, not the modeled, or adjusted values. Unfortunately, it has not been possible

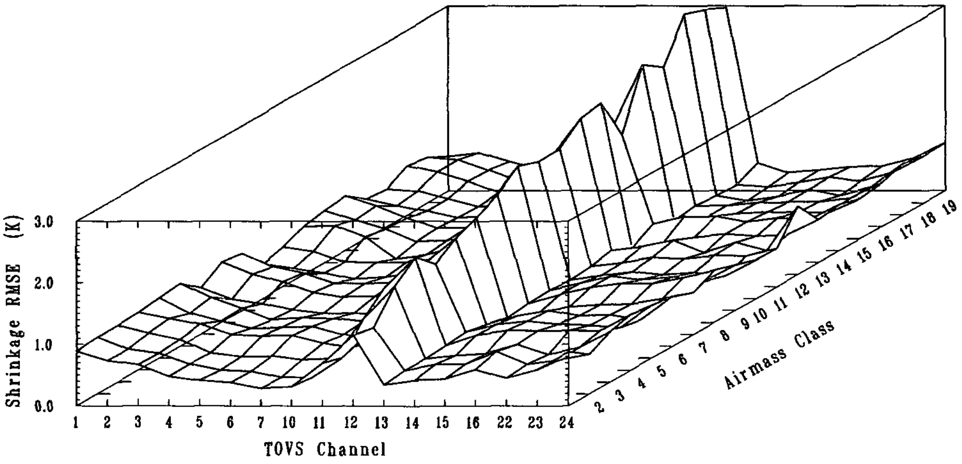

FIG. 3. Root-mean-square difference errors for *NOAA-10*–measured radiance temperatures, adjusted to model equivalents by shrinkage regression, and modeled radiance temperatures for the independent sample. The airmass classes are arranged as in Fig. 1.

to arrange identical samples for each case, since quality control techniques, internal to the TMS algorithm, are dependent upon the expected noise in the data. The small differences in populations are not expected to have any important effect upon the results, however, since the final quality control check, the Bonferroni radiance convergence test, is applied to all retrievals.

### *a. Perfect radiance temperatures*

Figure 5 indicates the bias, standard deviation, and $R^2$ (Kvalseth 1985) retrieval error statistics at the TOVS 40 levels for temperature and mixing ratio, when perfect radiance temperatures are utilized in the retrieval step. The sample size is 1264, with collocations from all latitudes, over both land and sea surfaces. Results from the NESDIS minimum variance simultaneous (MVS) (Dey et al. 1989) operational product are included for reference purposes only (labeled MVS). Evidently, the TOVS instruments, together with the TMS retrieval algorithm are, in principal, capable of resolving many atmospheric features, with resulting thickness errors (not shown) of not more than 12 m for any layer between 1000 hPa and any other standard level, up to 20 hPa.

The poor accuracy of the temperature retrievals near 250 hPa, as indicated by the $R^2$ statistic, is typical of all TOVS retrievals and arises from two sources. First, there is no TOVS weighting function peaking in this region and second there is a natural minimum in atmospheric variance near 250 hPa with the result that temperature retrievals in this region show little skill.

### *b. NE$\Delta T$ contaminated radiance temperatures*

When the radiance temperatures used in the retrieval step are model values contaminated with Gaussian noise having standard deviations as given in Table 2, the accuracy of the resulting retrievals (Fig. 6) is substantially poorer than that for the perfect radiance case. The sample size is larger, at 1301, a difference that is directly attributable to the effect of the Bonferroni test. Temperature retrieval accuracy at all levels has been reduced by approximately 0.3°C, since the bias error characteristics are essentially unchanged between Figs. 5 and 6.

TABLE 1. TMS estimator channels.

| | |
|---|---|
| Clear path | 1, 2, 24, 23, 22, 15, 14, 13, 3, 4, 5, 6, 7, 8, 10 |
| n-star path | 1, 2, 24, 23, 22, 3, 4, 5, 6, 7, 10 |

### *c. Total system noise contaminated radiance temperatures*

The retrieval accuracy error statistics, when Gaussian noise having standard deviations equal to the total system noise is added to modeled radiances, are shown in Fig. 7. The sample size is slightly increased at 1346, and the accuracy of the retrievals is now much like that generated by the NESDIS operational processing, with temperature retrieval accuracy at all levels having been reduced by approximately 0.5°C from the perfect radiance temperature case.

Of particular note is the degradation in accuracy of the stratospheric retrievals, since this change does not arise from first-guess errors, but is instead simply due to noise contamination of the stratospheric channels. Also, there has been a significant loss of mixing ratio retrieval accuracy.

### *d. Satellite-measured radiance temperatures*

Finally, when the TMS algorithm is applied to the satellite measured radiance temperatures (adjusted to

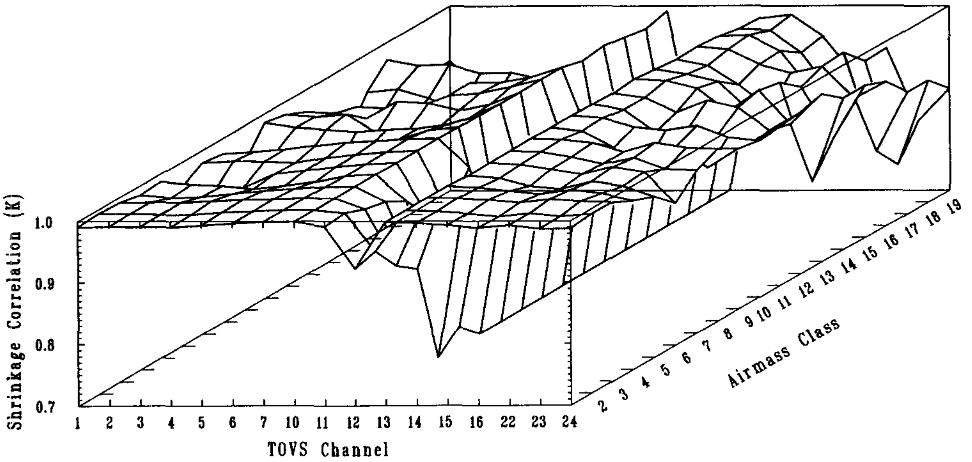

FIG. 4. Correlation between *NOAA-10*–measured radiance temperatures, adjusted to model equivalents by shrinkage regression, and modeled radiance temperatures for the independent sample. The airmass classes are arranged as in Fig. 1.

model equivalents), the TMS results (Fig. 8) can be seen to have properties similar to those of the previous case. Here the sample size is 1203, which is smaller than the above cases because only "clear" radiance temperature retrievals have been included in the statistics. Cloud-cleared (n-star) radiance temperatures are known to have undesirable properties (UM), which can cause a physical retrieval estimator to produce spurious error characteristics. In this case the TMS error statistics are directly comparable with the NESDIS operational (labeled MVS) results since both retrievals are computed from satellite measurements, and the samples are identical.

Although not shown, the radiance temperature residual statistics, measured, adjusted to model equivalents, minus model values computed from retrieved profiles, for this sample indicate excellent convergence in radiance temperature space. Mean radiance temperature biases are not greater than 0.08 K for any channel (and are more typically near 0.02 K), and standard deviation errors are close to 0.1 K for the HIRS and 0.3 K for MSU channels. The source of the resulting bias in the retrieved temperatures is unclear.

## 4. Discussion

These experiments have been designed in order to specify the intrinsic capability of the TOVS sounding system, and to demonstrate the impact of total system "measurement" noise upon an optimal retrieval system. The differences in retrieval accuracy, evident in Figs. 5–8, do not arise from first-guess dependencies, since in all cases the first guesses are identical, being determined from the spacecraft measurements, by the Bayesian procedure indicated earlier. Instead, these differences are driven entirely by the effect of noise in the measurement signal supplied to, in this case, an explicit retrieval operator, and by implication, to the noise term in the retrieval operator. This suggests that the information content in the TOVS data is strongly noise limited. The accuracy of physical retrieval estimators is constrained by the accuracy of the radiance adjustment

TABLE 2. Assumed instantaneous field-of-view NEΔT values (K).

| Channel | NEΔT | Channel | NEΔT |
|---|---|---|---|
| 1 | 0.97 | 12 | 0.87 |
| 2 | 0.76 | 13 | 0.08 |
| 3 | 0.56 | 14 | 0.06 |
| 4 | 0.30 | 16 | 0.27 |
| 5 | 0.18 | 17 | 0.32 |
| 6 | 0.18 | 18 | 0.05 |
| 8 | 0.06 | 19 | 0.04 |
| 10 | 0.15 | 22 | 0.30 |
| 11 | 0.43 | 23 | 0.30 |

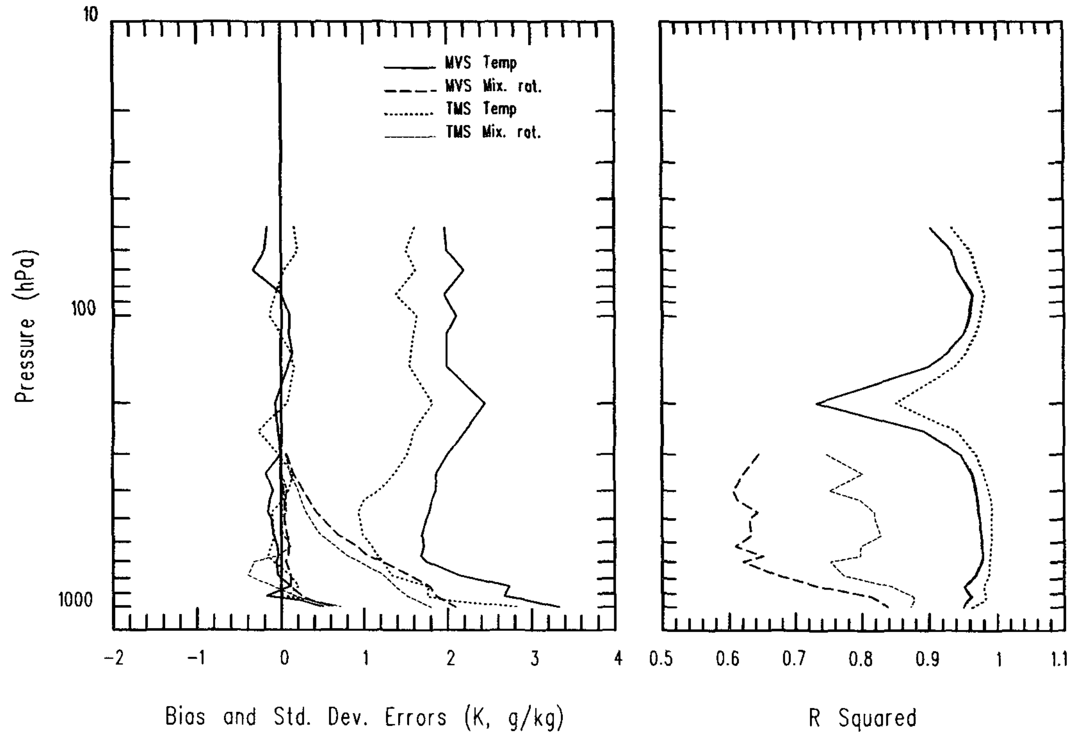

FIG. 5. Temperature (K) and mixing ratio (g kg$^{-1}$) retrieval error statistics (at the TOVS 40 levels) generated from a sample of 1264 perfect radiance temperatures. In the left panel, bias (near the zero abscissa value) and standard deviation error statistics are shown, while in the right panel the $R^2$ statistic is given. MVS refers to the NESDIS operational product, and TMS to the research retrieval method used here.

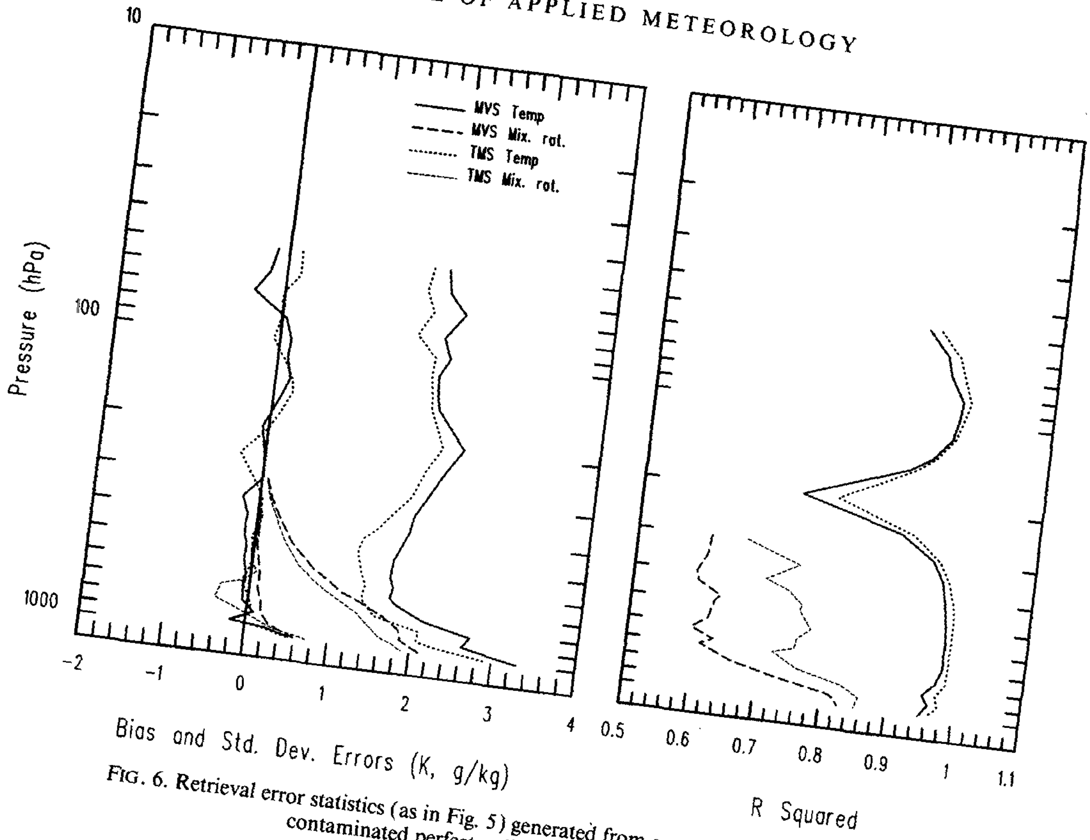

FIG. 6. Retrieval error statistics (as in Fig. 5) generated from a sample of 1301 NEΔT contaminated perfect radiance temperatures.

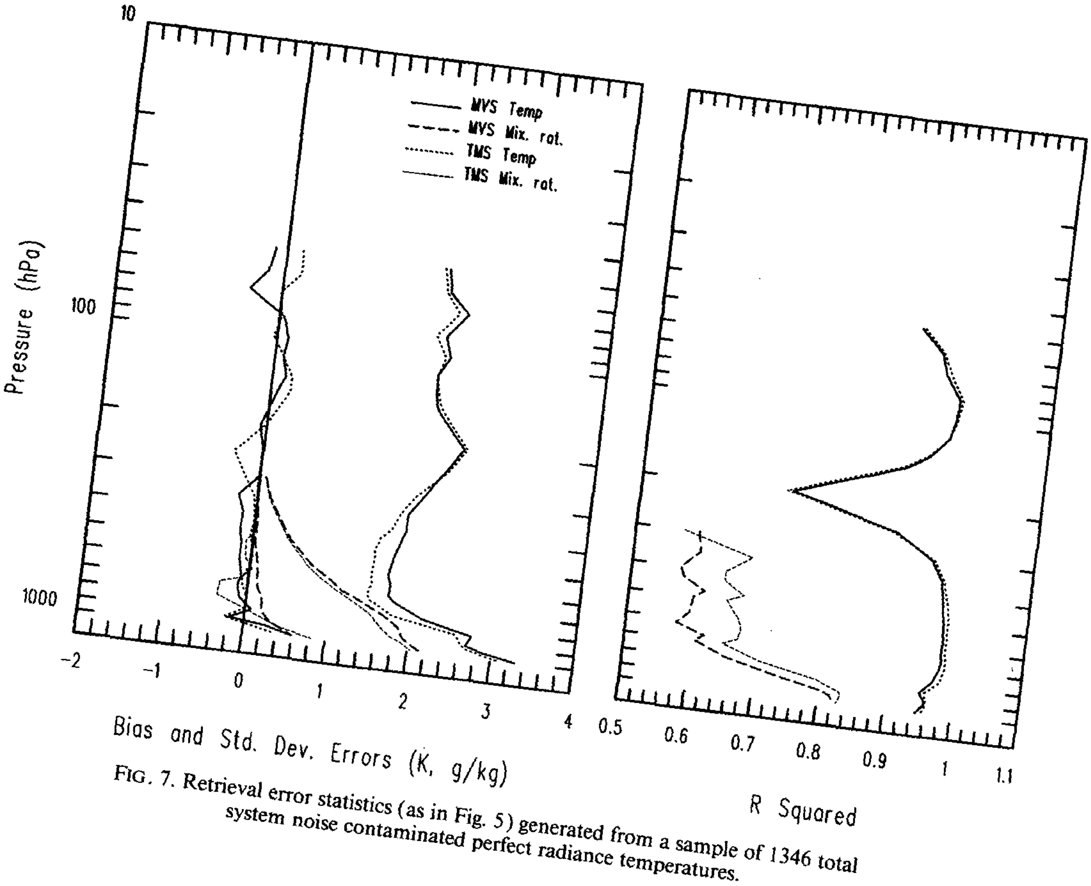

FIG. 7. Retrieval error statistics (as in Fig. 5) generated from a sample of 1346 total system noise contaminated perfect radiance temperatures.

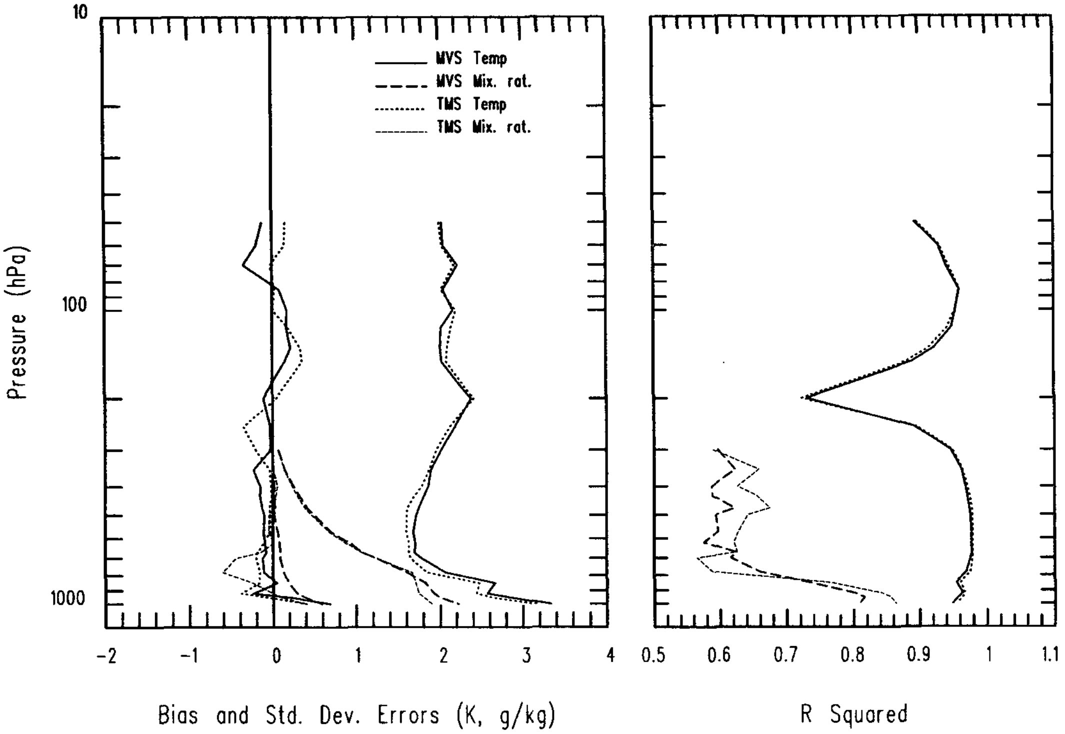

FIG. 8. Retrieval error statistics (as in Fig. 5) generated from a sample of 1203 satellite-measured radiance temperature profiles.

procedure, which is always necessary, and which includes components from measurement errors, both satellite and radiosonde, transmittance, and nonrepresentativeness (of the satellite and radiosonde observations) errors. In essence this noise limits the amount of information that can be extracted from radiances arising from significantly overlapping weighting functions. It is possible, however, to point to a number of areas of endeavor that might provide a better understanding of, and perhaps lead to an improvement in, the situation.

### a. *Satellite measurement errors*

During the period for which data were collected for this experiment, NESDIS performed retrievals from instantaneous fields of view (IFOV). Prior to May 1986 retrievals were computed from an average of up to 9 × 7 IFOVs. While the single-field-of-view retrieval approach was introduced to improve retrieval spatial resolution, it has resulted in an up to eightfold increase in the satellite measurement noise component of the total system noise, assuming no meteorological variance across the 9 × 7 array. Since the latter assumption will generally not be true, and because some of the component IFOVs may be rejected for some reason (e.g., high terrain), averaged tropospheric channels are unlikely to see such a large reduction in measurement noise. However, important gains in noise reduction in upper-tropospheric and stratospheric channels might be expected, and as the present results indicate, that would improve the accuracy of upper-tropospheric and stratospheric retrievals. In this regard it is interesting to note from Table 2 and Fig. 3 that the total system noise for the stratospheric channels is close to (or less than) the nominal NE$\Delta$T value, which would seem to indicate that the instrument is performing rather better than the NE$\Delta$T specifications might suggest, since for these channels, it is known that there will be a contribution to total system noise estimates from radiosonde radiation errors (UM; Schmidlin and Luers 1992). Clearly a retrieval from an array of 9 × 7 IFOVs is not desirable, but the noise penalty incurred from single-field-of-view retrievals is not desirable either. Some averaging in the radiance domain before retrieval would reduce total system noise (Hillger and Purdom 1990).

Another component of the direct satellite measurement noise arises from inappropriate calibration of the satellite radiances. Currently, the NESDIS TOVS calibration procedure results in calibration jumps halfway through each superswath (D. Wark 1990, personal communication). The significance of this noise source is unknown. Further, the present approach to limb correction and cloud clearing at NESDIS, where the former is done before the latter, introduces what are almost certainly nonzero bias errors.

If each of these error sources were removed, it might be expected that the direct measurement noise component of the total system noise could be reduced by a factor of perhaps 2–3 in the lower troposphere and by a greater amount in the stratosphere and upper troposphere.

### *b. Radiative transfer model errors*

According to Scott (1986) current fast radiative transfer models match line-by-line model results with an accuracy that is better than the variations among the different line-by-line models (Spänkuch 1988). However it is also evident that current models suffer deficiencies with respect to the way they handle the continuum, line mixing, and the temperature dependence of the line widths (Chedin 1988). Spänkuch (1988) also indicates that the differences between candidate line-by-line radiance integrations increases, with improving instrument spectral resolution.

It might be hoped that there would be much to gain from significant investment of effort in the forward model physics problem, given the strong evidence for important forward model errors in both infrared and microwave sounding bands.

### *c. Validation data errors*

Current short- and longwave radiation error temperature correction algorithms are rather simplistic. Results from recent experiments (Schmidlin and Luers 1987) and modeling efforts (Luers 1990; McMillin et al. 1992) suggest improved methods for defining and correcting such errors. In particular, infrared radiosonde errors, which may be as large as 2 K at 20 hPa, are now known to be airmass dependent and sensor specific. Shortwave errors are dependent upon both the solar elevation and the albedo of the underflight surface. These errors, which differ from one radiosonde type to another, should be corrected before the true noise in the retrieval estimator signal can be defined. Unfortunately, this remains a difficult task, since the error characteristics of many radiosonde sensors are unknown. Compounding this confusion is the increasing use of undocumented (or proprietary) postflight correction procedures at observing stations. There remains a need for some ongoing BUAN (Baseline Upper Air Network)-type (Reale et al. 1990) monitoring with a very select set of well-defined upper-air observing sites.

Radiosonde measurements of water vapor are becoming increasing suspect, especially above 850 hPa. Validation of radiances from those channels most susceptible to water vapor absorption remains a challenging problem.

## 5. Conclusions

The process of retrieving information from radiance temperature observations is dependent upon an understanding of the noise characteristics of the signal provided to an explicit or implicit retrieval estimator. This noise includes components from direct measurement noise, forward model noise, and validating data errors.

The experiments reported here indicate that when realistic estimates of total system noise are added to modeled TOVS radiance temperatures, the resulting retrieval accuracy is similar to that derived from satellite measurements. In temperature space the accuracy of these retrievals is approximately 0.5 K poorer than for those computed from perfect radiance temperatures. This difference does not arise from first-guess dependencies, since in these experiments, the first guesses are identical. Instead, the differences are driven entirely by the effect of noise in the measurement signal supplied to the explicit retrieval operator, and by implication, to the noise term in the retrieval operator. In effect, the total system noise in the satellite sounding measurement and retrieval processes determines a lower bound to retrieval product accuracy, and strongly limits the amount of information that can be extracted from highly dependent observations. This conclusion has a number of ramifications for planned atmospheric sounders, such as the Advanced Infrared Sounder (AIRS). Fundamental to the concept of an AIRS-type instrument is the idea that significant vertical information may be extracted from measurements in channels having highly overlapping weighting functions (Huang et al. 1992). Under these conditions, given the TOVS experience outlined here, retrieval accuracy may be rather poorer than might otherwise be expected, since total system noise will severely limit the number of channels that may be effectively used in any retrieval or direct assimilation algorithm.

From the TOVS experience it is clear that the opaque water vapor channels cannot simply be used in a physical retrieval algorithm since modeled and measured water vapor radiance temperatures cannot be reconciled, except in the polar regions.

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