A REVIEW OF INTERSATELLITE CALIBRATION AND RADIANCE BIAS CORRECTION

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Abstract: The procedure known as radiance bias correction has a long history in the quantitative use of satellite data in both retrievals and numerical weather prediction assimilation schemes. Radiance bias correction allows for correction of unresolved errors in a number of areas of the satellite sounding and inversion. These sources include forward radiative transfer errors, in situ validation instrument errors, errors in instrument end-to-end calibration, and errors in the numerical weather prediction models base climate state. Reduction of each of these sources of error is an ongoing effort by many research groups. Recently, interest in the use of operational environmental satellite sounding data for climate monitoring has focused the efforts of another scientific research community on many of the issues related to radiance bias correction.

Progress in intercalibration of satellite sounding channels by the climate research community brings a new perspective to the issue of radiance bias correction. Results from the climate community concerning the use of MSU for long-term temperature monitoring and HIRS channel 12 for monitoring of upper tropospheric water vapor are reviewed. These intercalibrations for climate uses are compared to similar uses for radiance bias correction in inversion and numerical weather prediction assimilation.

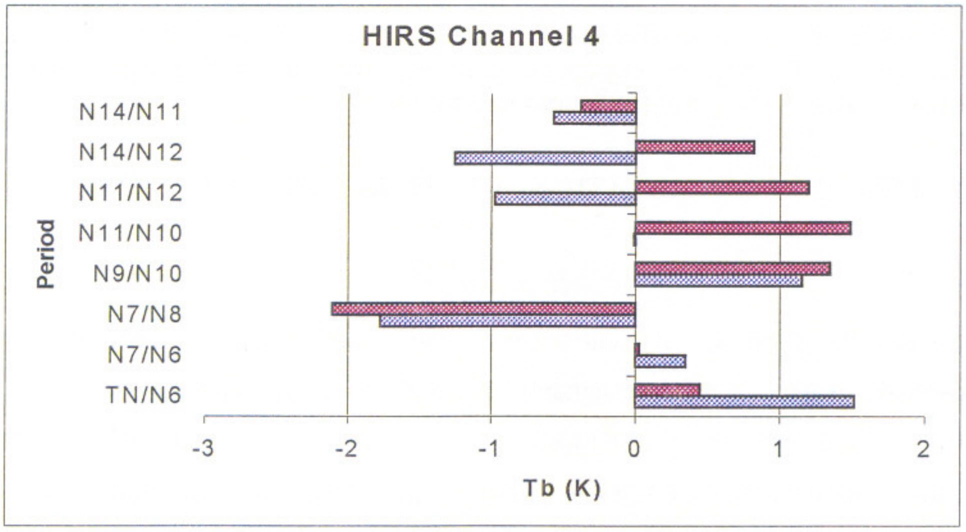
Just as increasing scrutiny has been given to satellite sounding channels, increasing scrutiny has also been given to radiosonde observations. Radiosonde observations of moisture have been shown to be subject to a number of errors depending upon the type of sensor used, aspiration mechanism, and age of the sensor batch. As other sources of error in the radiance bias correction process, particularly progress in forward radiative transfer modeling, are reduced, the quality of radiosonde observations may be the limiting factor in improving the use of satellite data in numerical weather prediction. In addition, the new microwave sensors on the ATOVS provide information on cloud water and surface emission that are not observed by radiosondes. New strategies for the improved use of ground-based and aircraft remote sensing are proposed to provide an ongoing source of high quality data for calibration and validation of the operational satellites.

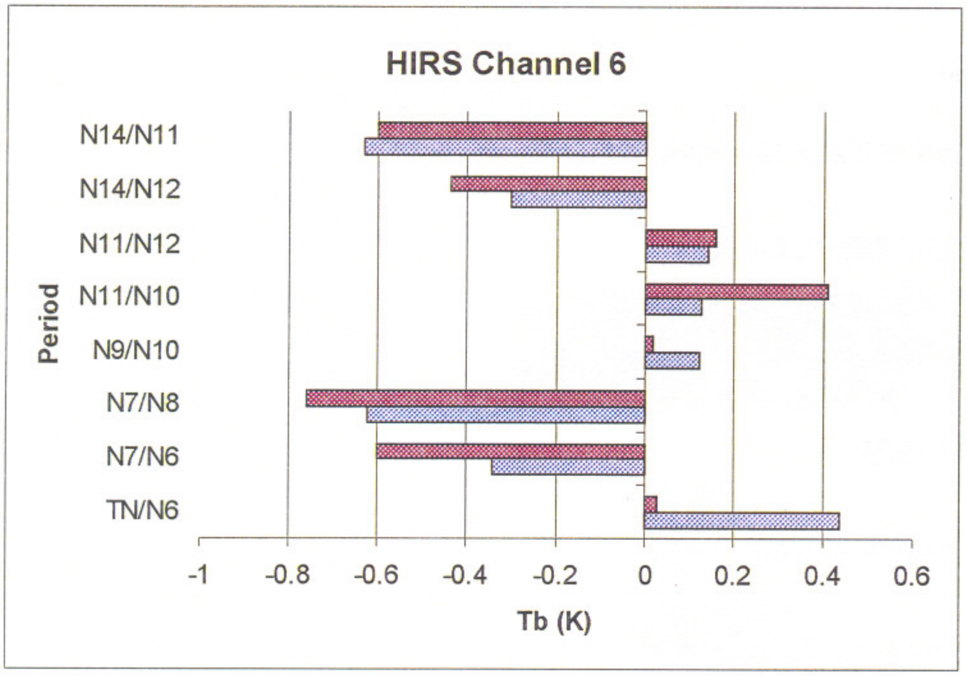
1. LESSONS FROM THE INTERCALIBRATION OF HIRS AND MSU FOR CLIMATE APPLICATIONS

Increasing concern over the possible global warming due to the buildup of anthropogenic greenhouse gasses and the role of upper tropospheric water vapor in enhancing the anthropogenic warming have lead to the examination of the long-term record of the HIRS and MSU data. In particular, HIRS channel 12, centered on the strong mid-infrared water vapor line, has been used in studies of upper tropospheric humidity variations, and MSU channel 2, in the 50 GHz molecular oxygen band, has been used to study the variability and trends in layer-mean tropospheric temperature. Prior to the launch of TIROS-N in late 1978, the only source of upper air data has been radiosonde observations. Radiosondes provide an uneven sampling of the globe since they are mainly over the land regions of the mid-latitude northern hemisphere. Polar-orbiting satellites provide complete global sampling and thus are of great interest in studies of global change.

Since climate studies use temporal and spatial averaging, the random error tends to zero and the systematic error becomes the predominant error term. In general, the intercalibration procedures for both HIRS and MSU data for climate studies use empirical techniques to adjust all satellites to a baseline satellite. The overlaps between different satellites are used to provide a bootstrapping of instruments in order to form a seamless time series over the two decade TOVS instrument period of record [*Bates et al.*, 1996; *Christy et al.*, 1998]. In situ data are then used to provide an independent evaluation of the stability of the empirical intercalibration.

An a priori estimate of systematic biases between the same HIRS channels on different instruments is provided by using the measured filter response function and a radiative transfer model. A representative set of temperature and moisture profiles are run through the radiative transfer model and anticipated systematic biases as a function of climate regime and viewing angle can be generated. Figure 1 shows this procedure for HIRS channels 4, 6, and 12, which we use for computing upper tropospheric humidity. We use the MODTRAN radiative transfer model and a sample set of atmospheric profiles from the TIGR database. Systematic biases from instrument to instrument from the forward simulations (top bar for each set of satellites) range from about –2 to 1.5K for channel 4, -0.8 to 0.4 for channel 6, and –1 to 0.5 for channel 12. The empirically-derived systematic biases are shown by the bottom bar for each set of satellites. The observed biases are usually within the expected sampling uncertainty, but there are several exceptions.





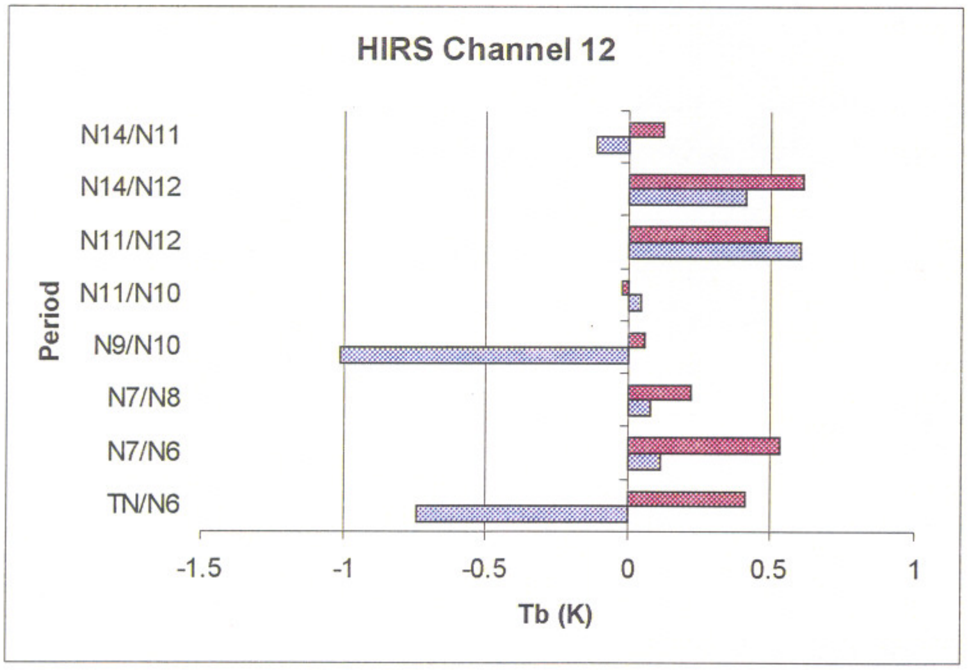


Figure 1. Forward simulated (top bar) and empirically-derived systematic biases.

The analogous procedure for an a priori estimate of systematic biases between different MSU instruments is not possible because the similar measures of central frequency and bandpass half width are identical for each satellite. Ideally this would mean there would be no systematic bias between the different instruments. The empirical intercalibration of the MSU channel 2 (Figure 2), however, reveals systematic biases between instrument of up to 1K. Thus, it appears that there are systematic biases in the central wavenumber and/or bandpass of the MSU instruments and additional refinements in the pre-launch calibration of microwave instruments would be beneficial.

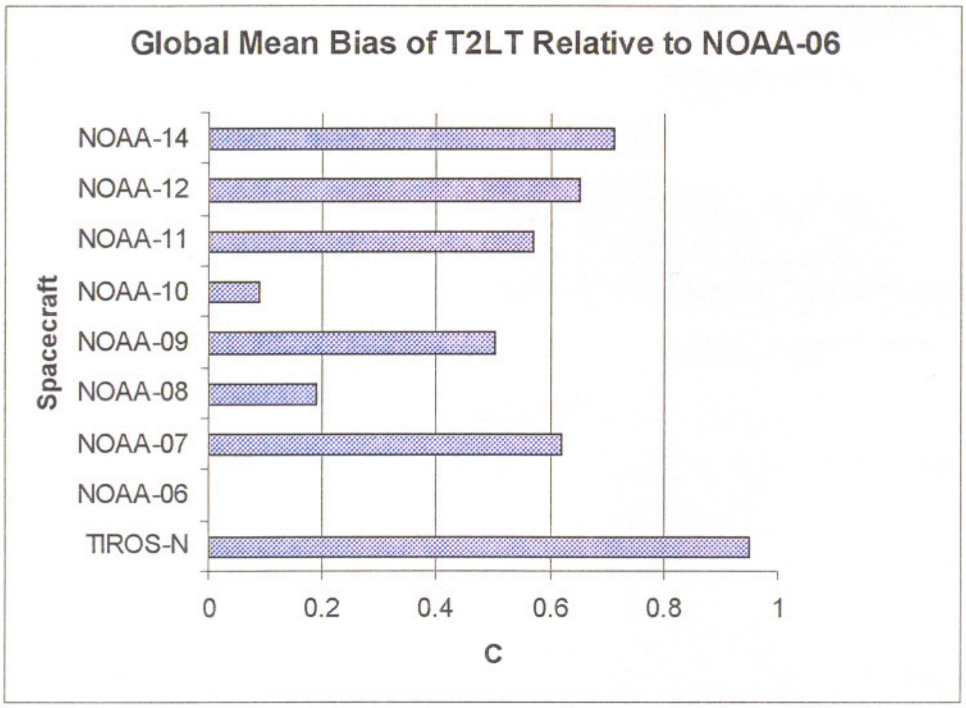


Figure 2. Systematic biases between MSU channel 2 lower troposphere retrievals.

2. RADIANCE BIAS CORRECTIONS FOR INVERSION SCHEMES

Following the derivation by *Eyre*[1987], the linear inversion problem from satellite radiance observations can be expressed as:

$$\hat{x} - x_0 = W \bullet (y_m - y_c\{x_0\}) \tag{1}$$

where,

$\hat{x}$ is the vector of retrieved atmospheric parameters

x_0 is the first-guess value of the vector

y_m is the vector of multi-channel radiance measurements

$y_c\{x_0\}$ is the corresponding vector appropriate to the first guess

W is the ‘inverse matrix’

The inverse matrix W can be obtained through a minimum variance solution via:

$$W = (K \bullet C)^T \bullet (K \bullet C \bullet K^T + E)^{-1}$$

(2)

where,

C is the error covariance of the first guess, x_0

E is the error covariance of the measurements, y_m

K contains the partial derivatives of the measurements with respect to the profile evaluated at x_0

superscripts T and –1 denote matrix transpose and inverse

The linear approximation to the froward radiative transfer problem is:

$$y_m - y_c\{x_0\} = K \bullet (x_T - x_0) + \varepsilon_m$$

(3)

where,

x_T is the vector of true geophysical parameters

ε_m is the vector of measurement errors, assumed to be random, Gaussian, unbiased and includes unbiased errors in the forward radiative transfer model

Combining the forward and inverse radiative transfer equations and rewriting it in terms of the retrieval, first-guess and measurement errors yields,

$$\hat{x} - x_T = (I - R) \bullet (x_0 - x_T) + W \bullet \varepsilon_m$$

(4)

where I is the identity matrix and $R = W \bullet K$

By taking large averages, as is done in climate studies, $\varepsilon_m \rightarrow 0$ so the mean retrieval errors are determined by the R matrix and the mean errors in the first guess.

It has been recognized for some time that owing to uncertainties in the atmospheric transmittances of satellite sounding channels that a correction must be applied to minimize systematic errors in either the forward of inverse processes. On the other hand, the common practice of adjusting the satellite radiances to radiosonde observations is also fraught with error since different countries is different sensors and have different practices for quality control. Because of these problems it has even been suggested that satellites could be used to provide a common transfer standard for adjustment of the differing types of radiosonde data [*McMillin*, 1988]. As outlined by *Uddstrom and McMillin*[1994a; 1994b], three types of errors must be considered when validating satellite data vicariously against in situ data, 1) errors in the in situ data, 2) errors in the radiative transfer model, and 3) errors due to the different temporal and spatial characteristics of the satellite and in situ data.

These sources of error have been particularly severe in the past for the opaque water vapor channels of the HIRS instrument. Radiative transfer models for the water vapor channels contained large uncertainties largely due to uncertainties in the continuum absorption. Recent use of spectrometers and interferometers in field experiments have led to improvements in the radiative transfer models, particularly for the water vapor channels. These improvements in radiative transfer models are reflected in results of recent intercomparisons of codes for the HIRS channel 12 [*Soden and co-authors*, 1999]. The systematic bias between a number of different radiative transfer models ranging from line-by-line models, to band models, to highly parameterized, ultrafast models is quite small. Intercomparisons such as this, and one on comparison of microwave channels presented by Garand in these proceedings, suggest that more confidence can be placed on the radiative transfer models.

There has been no analogous improvement of the radiosonde observational network. In fact there are fewer radiosonde stations now reporting and their observations of water vapor are even more suspect than in the past. Numerous errors have been identified including reporting practices, biases due to packaging materials, and biases due to sensor type and exposure. Progress is being made in understanding and correcting some of these deficiencies, but only in a few countries. It is perhaps unrealistic to expect a disposable package, such as a radiosonde, to provide highly accurate measurement of water vapor over a range of several orders of magnitude in mixing ratio.

3. RADIANCE BIAS CORRECTION IN THE ERA OF DIRECT RADIANCE ASSIMILATION

Bayesian estimation theory applied to NWP shows that the most probable solution to the assimilation of observations is that which minimizes a 'cost' function:

$$J(x)=(x-x^b)^T \bullet C^{-1} \bullet (x-x^b)+\{y^m-y(x)\}^T \bullet E^{-1} \bullet \{y^m-y(x)\} \quad (5)$$

x^b is the forecast background

C is the expected forecast error covariance

y(x) is the radiative transfer model or 'forward model' for the atmospheric state vector x

E is the expected error covariance of the satellite radiance observations and the RT forward model

To find the most probable value of the atmospheric state vector x, we minimize the cost function by setting the gradient of J(x) to zero:

$$J'(x)=C^{-1} \bullet (x-x^b)-K(x)^T \bullet E^{-1} \bullet \{y^m-y(x)\}=0 \quad (6)$$

In the linear or weakly nonlinear case we can solve for x:

$$x=x^b+C \bullet K^T \bullet (K \bullet C \bullet K^T+E)^{-1} \bullet \{y^m-y(x^b)\} \quad (7)$$

Such assimilation systems are subject to many of the same errors as described above, but the constraint is applied in a slightly different way so that the requirement is that the mean systematic bias between the model first guess and the observations is zero. Since the model contains many assumptions and parameterizations of complex physical processes, it can not be expected that there will be no systematic bias. On the other hand, each source of systematic bias should be reduced to the extend possible to ensure that the satellite data have the maximum positive impact on the assimilation and forecasting process. Progress in non-linear assimilation techniques and in other aspects of model physics, as well as the progress in better radiative transfer models, suggests that there is an urgent need for improved in situ data for calibration and validation activities.

4. PROSPECTS FOR IMPROVED RADIANCE BIAS CORRECTION SCHEMES IN THE MICROWAVE SOUNDING ERA

Even before the advent of the advanced microwave sounding era it was recognized that there was an increasing need for improved calibration and validation data. Numerical models are beginning to incorporate prognostic schemes for cloud properties and surface emission characteristics. Optimal use of advanced microwave sounding data requires calibration and validation data for these variables that are not measured by radiosondes. I propose a continuing program of automated, ground-based remote sensing combined with an aircraft-based remote sensing program to ensure we realize the optimal use of the enormous investment in operational environmental satellites.

One source of automated, ground based remote sensing is the long-term monitoring sites being established for climate studies. In the United States, one example of this are the long-term monitoring sites established as part of the Department of Energy's (DOE) Atmospheric Radiation Measurement (ARM) program. Automated, heavily-instrumented sites are now in operation in the southern great plains, the north slope of Alaska, and in the tropical west Pacific. These sites could serve as long-term calibration and validation sites. Several other countries are establishing similar sites in coordination with various climate programs.

In addition to the ARM sites, the satellite operators should work with research organizations who can provide ongoing ground- and aircraft-based calibration and validation data sets. It is not sufficient to run a single validation program at the start of a new suite of sensors. An ongoing, long-term commitment is required. The NOAA Environmental Technology Laboratory has developed a suite of ground and aircraft based microwave sensors that can provide this needed infrastructure.

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