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IN-FLIGHT SPECTRAL CALIBRATION OF HIRS USING AIRS OBSERVATIONS

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1. INTRODUCTION

The High Resolution Infrared Radiation Sounder (HIRS) is a traditional filter-wheel based cross-track line scanning radiometer that measures scene radiance in the infrared and visible spectrum with 20 channels, including twelve long-wave channels (668.5 to 1533 cm^{-1}), seven short-wave channels (2188 to 2660 cm^{-1}), and one visible channel (0.69 µm). The instantaneous field of view for HIRS/3 (HIRS15, HIRS16, and HIRS17) is 1.4 degrees in the short-wave and visible and 1.3 degrees for the long-wave channels, providing a nadir footprint of 20.3 km and 18.9 km in diameter on the earth respectively.

Uncertainties in the spectral response functions of the HIRS have been a major concern affecting the accuracy of HIRS observations. It is well known that infrared atmospheric sounding is extremely sensitive to the spectral response functions because many sounding channels are located on the slopes of the spectral radiance curves. The accuracy of the presumed spectral response functions directly affects the retrievals of the atmospheric vertical profiles.

Since HIRS has no onboard spectral calibration device, prelaunch system spectral response functions (SRF) are determined and used for processing all HIRS data. The prelaunch spectral calibration involves measuring the filter transmittances, and the spectral response of all other optical piece parts including the detectors, beam splitters, mirrors, and lenses. The system level spectral response are generated by multiplying the filter transmittance with the optical piece part response. There are two related issues with the HIRS spectral response functions. First, the prelaunch measurement of HIRS SRF may not be accurate. Second, spectral shift may occur from prelaunch to postlaunch, and whenever the filter temperature changes. For example, it is known that the spectral response of the interference filters for the HIRS shifts to the longer wavelength almost linearly as the operating temperature increases.

Data users have found that there are unexplained biases between observations and forward calculations and suspected the uncertainties in the HIRS SRF to be the cause. Also, studies of the GOES (Geostationary Operational Environmental Satellites) infrared sounder filter transmittances indicated that there are significant uncertainties in the prelaunch spectral calibration (Weinreb, personal communications, 2003). Since HIRS and the GOES sounder have similar designs, it is believed that similar problems may exist with HIRS.

Therefore, there is a need for the inflight spectral calibration of the HIRS. It is hoped that the hyperspectral AIRS sounder (Auman, et al, 2003) and other future instruments such as IASI and CrIS may allow us to perform spectral calibration of HIRS inflight. The AIRS instrument consists of a diffraction grating spectrometer that incorporates numerous advances in infrared sensing technology to achieve a high level of measurement sensitivity, precision, and accuracy (http://www-airs.jpl.nasa.gov). It provides 2378 spectral channels from 3.7-15.4um with a variable spectral resolution of $\lambda/\Delta\lambda = 1200$, with onboard spectral and radiometric calibration performed every 2.67 s scan cycle. The AIRS IR spatial resolution is 13.5 km from the nominal 705.3 km orbit. In this study, a method for the inflight spectral calibration of HIRS with AIRS observations is presented, and a preliminary analysis with sample data sets is performed. The data used for the spectral calibration are collected from the simultaneous nadir overpasses (SNO) at the orbital intersections of Aqua and NOAA-16 & -17 satellites (Cao, et al., 2004a). Since the match-up data are collocated and coincidental, this method greatly reduced the uncertainties in the radiance intercomparisons which is essential for the inflight spectral calibration of HIRS. Preliminary results indicate that this method has a lot of potential for the inflight spectral calibration of HIRS, although several calibration issues, such as nonlinearity and blackbody spectral emissivity, have to be resolved to reduce uncertainties with this method.

2. METHOD

In this study, we use Simultaneous Nadir Overpass (SNO) observations at the orbital intersections of the NOAA-16/-17 and Aqua polar-orbiting satellites. An SNO occurs when the nadirs of two satellites cross each other within a few seconds at their orbital intersections. For sun synchronous polar-orbiting satellites, this occurs in the polar regions (+70 to +80, and –70 to –80 latitude zones). The mechanism of the orbital intersections and the SNO between two polar-orbiting satellites, and the prediction of such events are described in Cao, et al. (2004a). The SNOs occur once every 2 to 3 days between NOAA and EOS/Terra/Aqua satellites.

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Radiance intercomparison with SNO observations has a number of advantages compared to the alternatives. First, this eliminates uncertainties due to rapid scene temperature changes, especially when clouds are moving within the field of view. Second, forward calculations are not needed because both observations are at nadir with identical atmospheric profile. Third, SNOs occur both in the arctic and antarctic regions, which allows us to evaluate the calibration biases for a relatively large range of scene temperatures. Finally, a long-term time series of such biases can be constructed to reduce scene specific uncertainties, such as clouds. A persistent bias in this time series over a long period of time represents the instrument calibration bias.

Several studies have been done with the SNO method for quantifying intersatelltie radiance biases (Cao, et al, 2004a; Cao, et al, 2004b, Cao and Heidinger, 2002). Using the SNO method for inflight spectral calibration is a further step forward with this method for calibration. In general, there are several potential sources for intersatellite radiance biases using earth targets, which are summarized in the following radiance bias model:

$$\beta = f(\tau, \varepsilon, \iota, v, e, g, s, \alpha, o) \qquad (1)$$

Where:

β = *radiance bias*

τ =*observation time differences (this is reduced to a negligible level with the SNO method).*

ε =*blackbody spectral emissivity and discrepancies between skin and bulk temperatures*

ι =*nonlinearity*

v =*spectral uncertainty*

e=*calibration algorithm*

g=*geolocation, including location differences and navigation errors.*

s=*scene uniformity and sensor modulation transfer functions (MTF)*

α=*calibration anomaly*

o=*other factors*

Equation (1) suggests that radiance bias in the intersatellite radiance comparison with earth targets is a function of many variables involving both instruments, including observation time differences, blackbody spectral emissivity and temperature discrepancies, nonlinearity, spectral uncertainty, calibration algorithm, geolocation, scene uniformity and sensor MFT, calibration anomaly, and other factors (such as software errors). Each of these variables has certain characteristics. Some of them can be reduced to a negligible level through data selection and analysis while others may be inseparable from each other. Many of these variables for the HIRS instruments and the strategies for their uncertainty reduction are discussed in detail in Cao, et al. (2004b). For example, stratosphere channels are relatively spatially uniform and therefore are more suitable for quantifying radiance biases between satellites; geolocation uncertainties can be reduced through pixel-by-pixel scene radiance correlation analysis, and by averaging pixels within a nadir window; calibration anomalies can be identified by trending the calibration slopes; and reprocessing with alternative algorithms can resolve algorithm related issues. However, three unknowns in equation (1) - blackbody spectral emissivity, nonlinearity, and spectral uncertainty, are often mixed and their effect on radiance biases can not be easily separated. Fortunately, significant progress has been made in these three areas in the AIRS instrumentation. As a result, we can simplify equation (1) by assuming that AIRS has no issues in any of these areas, that it has no blackbody problems, it is a linear system, and it is spectrally well calibrated (Faiser, et al, 2003). While this may not be entirely true, it allows us to focus on the major variable in the equation, which is the radiance bias due to spectral uncertainties of HIRS.

For HIRS, the blackbody has not been fully characterized. HIRS also has a known nonlinear response due to the use of photoconductive HgCdTe detectors in the longwave. In a previous study (Cao, et al., 2004b), we have assumed that HIRS blackbody related problems typically cause biases in all channels in the same direction. And we further assumed that the nonlinearity effect is small due to the fact that HIRS is a background radiation dominated system (scene radiation is a small portion of the total radiation reaching the detector). Therefore, it is reasonable to assume that spectral uncertainty is the dominate variable that causes radiance biases between HIRS and AIRS. This assumption may not be always valid but it does allow us to analyze the effect of spectral uncertainty on radiance biases, and thus will facilitate the understanding of radiance biases in intersatellite comparisons.

The data used in this study are level-1b radiance data from HIRS/NOAA-16&17 and that from AIRS/AQUA. Although AIRS has much finer spectral resolution than that of HIRS, AIRS has spectral gaps and only channels 1, 4, 5, 6, 7, 10, and 11 of HIRS in the longwave are spectrally fully covered by AIRS channels (shortwave channels have low signal-to-noise in the polar regions and therefore are excluded in the analysis). To reduce uncertainties associated with scene nonuniformity, in this study we focused on HIRS channels 1 and 4, both of which are stratosphere channels.

Figure 1 compares the spectral response functions of HIRS channel 1 (NOAA-17) to the corresponding AIRS channels. It is shown that in the 660 to 680 cm-1 spectral range, there are 79 AIRS channels with a variable spectral interval (between adjacent channel SRF centroids wavenumbers) of 0.24 to 0.26 cm^{-1}. This is compared to the HIRS spectral response curve for this channel, which is defined with 61 data points (NOAA-17/HIRS). Therefore, it appears that AIRS has sufficient spectral resolution for the spectral calibration of HIRS. The AIRS channel full width at half max (FWHM) varies from 0.43 to 0.46 cm^{-1} in this spectral range, which is nearly twice as much as the spectral interval, indicating that there is spectral overlap between AIRS channels.

The following procedure is used in the analysis:

1). Predict the date, time, and location of the SNOs between Aqua and NOAA-16, and between Aqua and NOAA-17 satellites with the orbital Perturbation model SGP4. The standard two-line-elements are used with the SGP4 model to predict the occurrence of the SNOs (Cao, et al. 2004).

2). Obtain matchup radiance data sets from AIRS and HIRS. These are level 1b geolocated and calibrated radiance data downloaded from the archives.

3) Find the exact point of SNO observations: with the latitude/longitude information in the AIRS and HIRS level 1b data, compute the ground distance between the nadir pixels in the two matching datasets. The pixels at the orbital intersection are found when the nadir distance is less than the size of one pixel, or 20 kilometers for HIRS. The exact times at the intersection from the two matching orbits are compared based on the time stamps in the level 1b data. If the time difference is less than 30 seconds, it is considered an SNO event and the data will be used in subsequent analysis.

4) Collocate the pixels: A pixel-by-pixel match between the two matching subsets is performed based on the ground distance between the pixels.

5) Define the nadir window (NADWIN): A nadir window consisting of 10 cross-track pixels (out of the 56 pixels) and 11 scan-lines (5 before and 5 after the SNO pixel) is defined and the subset data extracted.

6). Compute the simulated HIRS spectral radiance from AIRS radiance: If n AIRS channels are needed to spectrally cover a HIRS band, the in-band radiance (*L"*) of AIRS integrated over the HIRS SRF is defined as:

$$L'' = \sum_{i=1}^{n} R_{AIRS}(i) \bullet w(i) \qquad (2)$$

Where $R_{AIRS}(i)$ *is the AIRS channel spectral radiance for channel i, and w(i) is the weighting function for the AIRS channel.*

There are different methods for computing the weighting function *w(i)* for each AIRS channel. In this study the formula for computing the area of a trapezoid is used, after the HIRS SRF is interpolated at the AIRS spectral interval and multiplied with the AIRS SRF:

$$w(i) = [\tau_{1(k)}(\nu)\tau_{2(k)}(\nu) + \tau_{1(k+1)}(\nu)\tau_{2(k+1)}(\nu)]/2*\Delta\nu \qquad (3)$$

where $\tau_{1(k)}(\nu)$ is the HIRS SRF interpolated to the AIRS spectral interval at point *k*; $\tau_2(\nu)$ is the AIRS SRF at the centroids (with a value of 1.0); $\Delta\nu$ is the spectral interval between the two adjacent AIRS channels(between SRF centroids of adjacent channels). This method does not use the true AIRS SRF which is Gaussian in shape, but it is a close approximation for in-band radiance, since the HIRS has much broader spectral response than that of AIRS.

An alternative method is available for computing the weighting function with the AIRS SRF, which was the same method proposed for aggregating Hyperion hyperspectral bands to Landsat-7 bands (Jarecke, et al.,), and used in previous intercomparisons of AIRS and HIRS (Ciren and Cao, 2003).

$$w(i) = \int_{\nu_1}^{\nu_2} \tau_1(\nu)\tau_2(\nu)d\nu \qquad (4)$$

where $\tau_1(\nu)$ is the HIRS SRF; $\tau_2(\nu)$ is the AIRS SRF, both with peaks normalized to 1.0, v1 and v2 are the beginning and end of the SRF for an AIRS channel. However, we believe that this weighting function may introduce errors when the equivalent width of the AIRS SRF ($\int_{\nu_1}^{\nu_2} \tau_2(\nu)d\nu$) is significantly different from the spectral interval Δv between two adjacent AIRS channels. If the equivalent width is larger than the spectral interval, it tends to over estimate the inband radiance (because the spectrally overlapped areas are counted twice), while underestimating the inband radiance when the equivalent width is smaller than the spectral interval. For example, the spectral interval varies from 0.238 in the longwave to 1.1 in the shorwave, which are about half of the equivalent with (or FWHM) of the corresponding channels.

The integrated AIRS radiance (to HIRS inband radiance) are converted to spectral radiance (*L'*) with the following equation:

$$L' = \frac{L''}{eqw} \qquad (5)$$

Where *eqw* is the equivalent width of the HIRS channel spectral response and is computed as:

$$eqw = \int_{\nu_1}^{\nu_2} \tau_1(\nu)d\nu \qquad (6)$$

Combining equations 2, 3, 5, and 6, we have:

$$L' = \frac{\sum_{i=1}^{n} R_{AIRS}(\nu)[\tau_{1(k)}(\nu)\tau_{2(k)}(\nu) + \tau_{1(k+1)}(\nu)\tau_{2(k)}(\nu)]/2*\Delta\nu}{\int_{\nu_1}^{\nu_2} \tau_1(\nu)d\nu} \qquad (7)$$

The bad channels in AIRS are excluded in the analysis and it has a small impact in the calculation with equation (6) because of increased Δv.

7). Compute the radiance bias between HIRS and AIRS for each HIRS channel

Diff = L – L’

Where: diff = channel radiance differences

L = HIRS measured spectral radiance

L’ = AIRS radiance convolved with HIRS SRF

8). Repeat steps 6 and 7 with shifted HIRS spectral response functions (Figure 2) (with 0.25 cm^{-1} step size from -1.0 to 1.0 in this study)

Assuming that other variables in the bias model (equation 1) have no effect on the radiance bias, the spectral shift that produced the smallest radiance difference in step 7 would represent the correct HIRS SRF in flight.

3. PRELIMINARY RESULTS

To demonstrate our approach presented in the previous section, we selected and analyzed two sample data sets. The first was for an SNO between Aqua and NOAA-16 on March 22, 2004 at 19:13:30 UTC (location: -80.8, 29.4). The corresponding AIRS granule is AIRS.2004.03.22.192.L1B.AIRS_Rad.v3.2.7.0.N04082154511.hdf, with matching NOAA-16/HIRS orbit NSS.HIRX.NL.D04082.S1755.E1942.B1803436.WI. The second data set was for an SNO between Aqua and NOAA-17 on May 5, 2003 at 01:14:00 (location: -71.4, 341.9). The software was run multiple times with different amounts of spectral shift. The radiance biases as a function of spectral shift for HIRS channels 1 and 4 for both data sets are summarized in Table 1 and Figures 3&4, in which the horizontal axis represents the spectral shifts from -1.0 to +1.0 with a step size of 0.25 cm^{-1}, and the vertical axis represents the radiance bias with a unit of mW/m^2-sr-cm^{-1}. The curves show that radiance biases change with the spectral shift. For example, for the AIRS and NOAA-17/HIRS data set, the bias of 0.459 mW/m^2-sr-cm^{-1} for channel 4 decreased as the spectral shift increases and it reaches a minimum with a spectral shift about 0.5 cm-1, while the biases becomes large if the spectral shift is in the opposite direction. The curves in Figure 3 and 4 show a monotonic relationship between spectral shift and radiance bias. One exception is channel 1 for the NOAA-16 vs AIRS data set (Figure 4), where there appear to be multiple solutions that the radiance biases would reach zero with different spectral shifts. This shows that some prior knowledge about the general magnitude of the spectral shift should be known to study this effect. This can be done by assessing the accuracy of prelaunch measurements of the HIRS spectral response functions, and applying the knowledge about the theoretical behavior of spectral shift of interference filters in response to temperature changes. For example, independent measurements of HIRS filter witness sample indicate that measurement uncertainties on the order of 1 cm^{-1} may exist for some models of HIRS for channel 4, and larger for channel 1.

The sample data shows the relationship between radiance bias and spectral shift for the particular data set used. It should be noted that since the spectral profile of the atmosphere varies, this relationship may not be the same for a different atmosphere. On the other hand, a time series of the radiance biases with spectral shift can be constructed with all the possible SNO data to reduce uncertainties in the analysis. Once the results are confirmed, its implication on different atmospheres can be studied.

In this study, only the stratosphere channels (ch1 and ch4) of HIRS are analyzed. Other channels can be studied in the future with further assessment on scene uniformity and target spectral variation, which may cause additional uncertainties in the analysis with this method. The intent of this study was to demonstrate the methodology of inflight HIRS spectral calibration with simultaneous AIRS nadir observations. We believe that further studies with additional data sets, and further refinements in the method itself will ultimately allow us to perform accurate inflight spectral calibration of HIRS with this method.

4. CONCLUSIONS

The broad band HIRS has spectral uncertainties due to the lack of stringent specification and onboard spectral calibration. It is possible that spectral calibration can be performed with the hyperspectral AIRS observations at the simultaneous nadir overpasses. Analysis presented in this study shows that the radiance bias between HIRS and AIRS changes as a function of spectral shift, and it is possible to find the spectral shift that produces the smallest radiance bias. However, radiance bias can be affected by many other variables, as suggested by our radiance bias model. The relationship between spectral shift and radiance bias provide an important piece of information for solving the radiance bias equation, and can potentially be used for the inflight spectral calibration, once other major variables in the model are quantified. A time series analysis of this relationship will further reduce the uncertainties in the spectral calibration.

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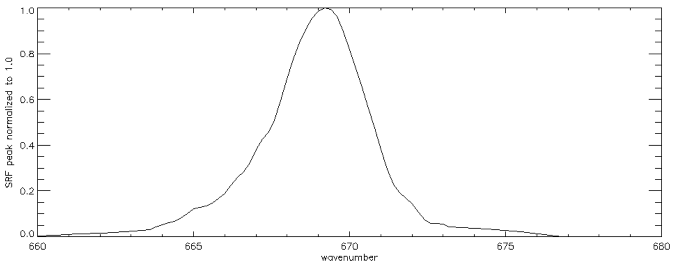
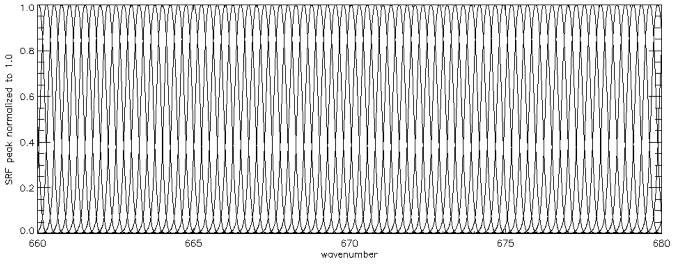
Table 1. Preliminary Results of Radiance Bias vs. Spectral Shift
(sample data from AIRS and NOAA-16 &17 HIRS)

HIRS SRF shift (cm^{-1})	N17Ch1 bias	N17Ch4 bias	N16Ch1 bias	N16Ch4 bias
-1.00	-1.236	1.186	2.735	0.080
-0.75	-1.047	1.006	2.071	0.012
-0.50	-0.693	0.840	-0.692	0.061
-0.25	-0.190	0.683	-0.335	0.117
0.00	0.369	0.459	-0.936	0.095
0.25	0.881	0.274	-0.099	0.114
0.50	1.369	0.073	1.278	0.105
0.75	1.834	-0.126	1.637	0.108
1.00	2.283	-0.329	0.859	0.093

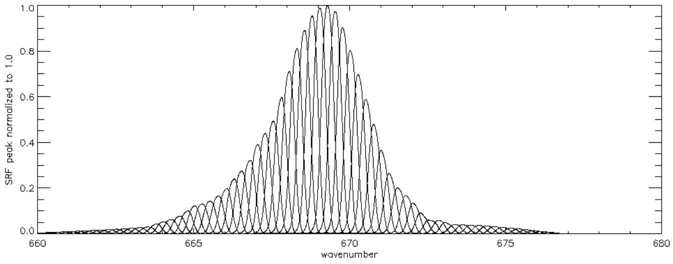
Note: bias unit: mW/m^{-2}-sr-cm^{-1}



(a) HIRS/NOAA-17/SRF band 1 (660-680cm^{-1})



(b) AIRS/AQUA/SRF (channels in the 660-680cm^{-1} range)



(c) AIRS/AQUA/SRF multiplied with HIRS/NOAA-17/SRF

Figure 1. AIRS vs. HIRS spectral response functions in the 660-680 cm^{-1} range

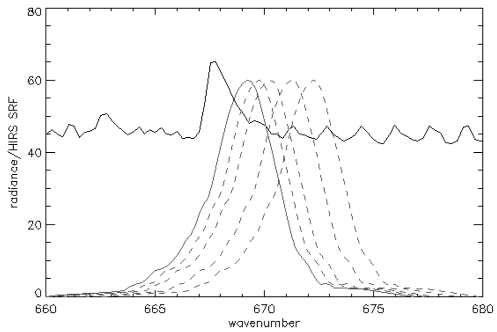


Figure 2. Shifting HIRS SRF relative to AIRS sample spectra (HIRS/NOAA-17 channel 1 shown here)

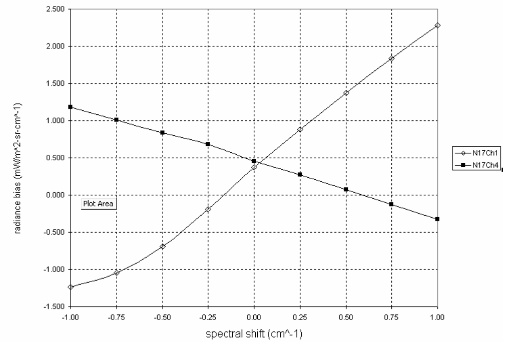


Figure 3. Sample data for AIRS vs. NOAA-17/HIRS

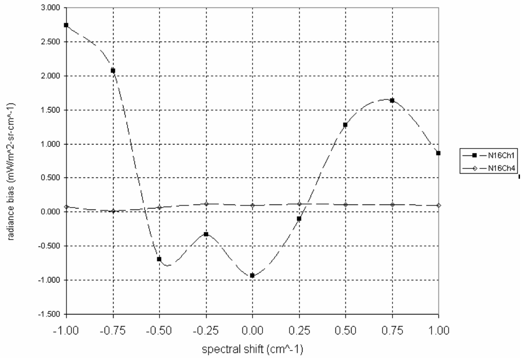


Figure 4. Sample data for AIRS vs. NOAA-16/HIRS