# Operational High Resolution Infrared Radiation Sounder (HIRS) Calibration Algorithms and Their Effects on Calibration Accuracy

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## Introduction

The High Resolution Infrared Radiation Sounder (HIRS) is an operational atmospheric sounding instrument that has been carried on NOAA polar orbiting satellite series for more than two decades. It is a traditional cross-track line scanning radiometer that measures scene radiance in the infrared and visible spectrum. Among the twenty spectral channels, there are twelve long-wave channels (669 to 1529 $cm^{-1}$), seven shortwave channels (2188 to 2657 $cm^{-1}$), and one visible channel (0.69 $\mu$m), all of which use a single telescope with a rotating filter wheel consisting of twenty individual spectral filters. An elliptical scan mirror is stepped 56 times in increments of 1.8 degrees to provide cross-track scanning. The field of view for HIRS (HIRS/3 series) on NOAA-15,-16, and -17 is 1.4 degrees in the long-wave and 1.3 degrees for the shortwave channels. From an altitude of ~833 km, the HIRS footprint on the ground at nadir is 20.3 km in the shortwave and visible channels, and 18.9 km in the long-wave channels (ITT, 1998). Data from the HIRS instruments are used, in conjunction with other instruments, to estimate the atmosphere's vertical temperature profile, outgoing long-wave radiation (OLR), and upper tropospheric humidity. The data are also used to determine sea surface temperatures, total atmospheric ozone levels, precipitable water, cloud height and coverage, and surface radiance.

Calibration of the HIRS infrared channels consists of independent views of the onboard warm blackbody and cold space. This provides a two-point calibration in which the calibration intercept and slope for each channel can be computed and used to convert instrument output counts to radiance. However, there are several complications in the operational HIRS calibration which affect the calibration accuracy. HIRS calibrates only once every 40 scan-lines, or one calibration cycle in every 256 seconds. As a result, the calibration coefficients between the calibration cycles have to be interpolated to the individual scan-lines. In the more than 20 year history of operational HIRS calibration, several interpolation methods have been used and unfortunately, depending on which method is used, these algorithms can produce HIRS level 1b radiance data with significant differences in scene brightness temperature. Operational HIRS instrument calibration has significant impact on products at all levels. Although the effect on weather applications is relatively small, it is important for long term climate studies where high calibration accuracy is required. In this study, the operational HIRS calibration algorithms are evaluated, and sample test data sets are analyzed to quantify the effects. A new algorithm is proposed to reduce the calibration biases caused by the previous calibration algorithms.

## The Calibration Algorithm for NOAA-KLM/HIRS

Prior to NOAA-15/HIRS, a simple calibration algorithm was used for HIRS/2 series of the instrument. This algorithm (Kidwell, 1998) used the fixed calibration coefficients calculated from the last calibration scans on the first half scans of a super-swath and those calculated from the following calibration scans on the second half of the super-swath. This was a relatively robust algorithm for handling the peculiar calibration cycles of HIRS. Unfortunately, this algorithm may cause a jump in the values of the brightness temperatures (Kidwell, 1998), especially when the calibration coefficients changed from one calibration cycle to the next.

With the launch of NOAA-15 in 1998, a new calibration algorithm (for clarity, it is referred to as HIRS operational calibration algorithm version 3.0) was developed for NOAA-KLM/HIRS and has been used in the operations (Goodrum, et al., 2000). In this algorithm, it is assumed that the HIRS instrument gain never changes appreciably within any 24 hour period. Therefore, it was believed that a 24 hour average slope (inverse of gain) can be used to calibrate all the data during the period. This simplified the calibration, especially if the slopes at an individual calibration cycle became unreliable, such as in the event of moon contamination in the space view. In addition, it was believed that the secondary mirror baffle temperature contributes to the background radiation and thus affects the intercepts for the earth view scan-lines between two calibration cycles. Therefore, it was decided that a correlation between the secondary mirror temperature and the intercept should be computed once every 24 hours and used to correct the intercepts. As a result, the intercepts were determined using the following equation:

$$I'_{(n)} = I'_{l(n)} + I'_{T(n)} \qquad (1)$$

Where:

$$I'_{l(n)} = \left( I'_{(k-1)} + n \cdot \frac{I'_{(k)} - I'_{(k-1)}}{40} \right) \qquad (2)$$

$$I'_{T(n)} = b_1 \cdot \left( (T_{(n)} - T_{(k-1)}) + n \cdot \frac{T_{(k)} - T_{(k-1)}}{40} \right) \qquad (3)$$

$I'_{(n)}$ is the intercept for Earth view scan-line n (n=1 to 38), $I'_{l(n)}$ is the linear interpolation of the intercept between the two closest calibration cycles, $I'_{T(n)}$ is the correction to the intercept based on the telescope temperature, $I'_{(k)}$ is the intercept at the calibration cycle k, n is the scan-line number within the calibration cycle (n=1 to 38), $T_{(k)}$ is the secondary mirror temperature at the calibration cycle k, and $T_{(n)}$ is the secondary mirror temperature at scan-line n.

There are several problems with algorithm 3.0 which can cause calibration errors in the operational calibration of HIRS data. The assumption of a stable instrument gain may not be valid. It is true that during normal operations, the instrument gain of HIRS can be stable during a 24 hour period, because the instrument gain is mainly affected by the background flux reaching the detector from the filter wheel, which is normally stable (ITT, 1996). However, the instrument gain will change in response to the filter wheel temperature change. A typical scenario that happened to NOAA-15/HIRS shows this process:

The HIRS filter wheel normally has a temperature of ~285K which is not controlled. The filter wheel temperature is not measured directly but is inferred from the filter wheel housing temperature, which has an operating temperature range of 273.15K to 333.15K. Although in normal operations, this temperature only varies about ~0.1K per orbit, the temperature can increase due to friction in the filter wheel bearing, which also causes increased jitter and higher than normal filter motor current. This may cause the filter wheel to become out of sync. To alleviate this problem, the filter housing heater is turned on to draw lubricants into the bearing, but unfortunately, it also further increases the filter temperature (by as much as 8 degrees). This temperature increase significantly changes the background flux reaching the detector. Since the HgCdTe detector has a nonlinear response, the increase in the radiation reaching the detector causes the operating response range to shift to a different portion on the non-linear response curve, which has a different gain. When this occurs, the 24 hour average slope, which could be 24 hours old, is outdated. The opposite occurs when the filter temperature drops from the high temperature to a normal temperature. As a result, using this 24 hour average slope causes calibration biases (Cao and Hui, 2003; Brunnel 2002). Since the radiance is for the most part a linear function of the slope, a 1 percent error in the slope translates to 1 percent in radiance, or for the long-wave channels, 1 percent radiance error may cause as much as 1 K error in the observations. In reality, errors on the order of 2-3% have been observed in some channels of HIRS on NOAA-15 during such events.

Although the filter temperature is relatively stable on an orbit by orbit basis, there is no guarantee that it will not fluctuate for any of the HIRS instruments. For example, since 2002, the NOAA-15 HIRS filter temperature fluctuates on the order of a few degrees several times a month. At the time of this writing, NOAA-15 HIRS had just recovered from the typical filter jitter problem that lasted a few days, during which the radiance data could not be used in product generation due to significant calibration biases.

In addition to the problem in the slopes, the method for computing the intercepts deserves further analysis because it affects every scan-line of the data at all times. In equation (2), the linear interpolation of intercepts between calibration cycles ($I'_{l(n)}$) is accurate if the change in the intercepts between these two cycles is linear. However, as it was pointed out by algorithm 3.0, the background flux may be affected by the telescope temperature change within a calibration cycle (or 256 seconds). It should be noted that the telescope temperature contributes to the background flux as a whole. Although the secondary mirror temperature has the largest fluctuation, its effect alone may not be accurately determined without a thorough thermal analysis of the system. On the other hand, at the front of the telescope, the only temperature sensor available is located near the secondary mirror. Therefore, the secondary mirror temperature is used to represent the thermal environment of the front of the telescope and its relationship to the intercept is rather empirical. Ideally, the correlation between the intercept and the telescope temperature should be determined in a thermal model. Therefore, it is possible that in the future, $b_1$ in equation (3) will be a variable determined based on various parameters, including instrument component temperatures.

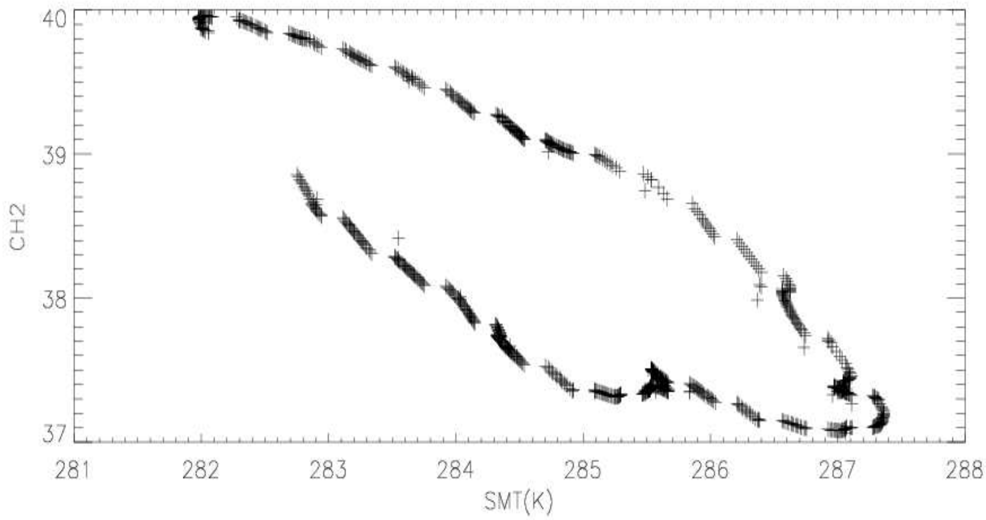


Figure 1. Correlation between secondary mirror temperature (SMT) and channel 2 intercept for one sample orbit

Figure 1 shows the typical correlation between the intercept and secondary mirror temperature for one orbit of NOAA-17 data. It is clear that this correlation is not linear but elliptic in shape. There is a different correlation between day and night time of the orbit, and there is a transition period in the polar regions. Therefore, the linear correlation assumption is not exactly valid, although on the first order, there is a general correlation that is somewhat linear. Another criticism of this analysis is the fact that in computing the intercept it applies a correlation derived from global data to a local problem of secondary mirror temperature fluctuations. The global correlation between the intercept and the secondary mirror temperature is determined by a number of factors at various instrument component temperatures, which is not the case within a superswath, where only the secondary mirror temperature fluctuated. Finally, it is arguable whether the secondary mirror temperature is reliable enough as an indicator of background flux. This is because the secondary mirror assembly has a small thermal inertia and its temperature fluctuates easily. The largest fluctuation occurs in the polar region, where the sun can directly illuminate the back of the secondary mirror. However, not all of the fluctuations may contribute to the change in the intercept. Because of the problems in the slopes and intercepts described above, a new calibration algorithm (algorithm version 4.0) is developed and described in the next section.

## HIRS Calibration Algorithm Version 4.0

The main purpose of the HIRS calibration algorithm version 4.0 was to correct the problem in the calibration slopes in the previous algorithm. In computing the intercepts, a switch is added to make the correction using the telescope temperature optional. Also, the linearly interpolated intercepts is stored in the secondary calibration coefficients field in the level 1b data for comparison purposes. Radiances produced by algorithm 4 and 3 have been compared using NOAA-15, -16, and –17 HIRS data (Cao and Hui, 2003). Additional radiance comparisons with AIRS/AQUA have also been performed (Ciren and Cao, 2003). Algorithm 4.0 is expected to become the operational HIRS calibration algorithm for NOAA-N (Kleespies, 2003). The detailed description of this algorithm is as follows:

### *The slopes and intercepts at the blackbody scan-lines*

For HIRS, the 48 space view samples followed by 56 blackbody view samples establish a calibration cycle, which occurs every 40 scan-lines or 256 seconds. At each calibration cycle, the slopes and intercepts at the blackbody scan-lines or “BB slopes and intercepts” (also referred to as “raw” slopes and intercepts) are computed for the 19 infrared channels and stored with the blackbody view data in the HIRS level 1b file (same as in the previous algorithm). However, due to the increased significance of the individual BB slopes and intercepts in algorithm version 4.0, the following changes must be made.

When screening the space and BB view samples, those that are out of the gross limits for the signed 12 bit counts should be removed, and then the standard deviation of counts computed. If the standard deviation is within the noise level (NEDC = abs{NEDN/slope}, NEDN is the instrument noise specification), all samples passed the screening. Samples deviated from the mean by more than 3 sigma should be removed and the mean recomputed for the next step. On the other hand, if the standard deviation of counts is greater than the noise specification, it must be flagged in the level 1b data. Then use the median value of the samples for further processing.

This method is used for the last 48 samples of both the space and blackbody view in a calibration cycle. As a result, as long as the PRT data are valid, the calibration slopes are always computed unless all counts are out of the gross limits. The quality of the slopes is then evaluated (discussed later).

The method for computing the BB slopes and intercepts at the calibration cycles remains the same as that for algorithm 3.0, with the exception that consideration should be given in software design to a possible non-linearity correction algorithm in the future. Currently spaces are reserved for the quadratic term in the level 1b data, although it has never been implemented due to uncertainties in the prelaunch non-linearity test results.

### *Calibration for a normal super-swath*

#### a) Slope

A super-swath is defined as 40 scan-lines of HIRS data that start with a calibration cycle, followed by 38 Earth view scan-lines (figure 2). For a normal super-swath in the middle of an orbit, the calibration slopes for the 38 Earth view scan-lines of the current super-swath is the running average of three values: the BB slopes of calcycle(k), calcycle(k-1), and calcycle(k-2), i.e.,

```
     calcycle(k-2)                  calcycle(k-1)                 calcycle(k)
  ------||--------------------------------------||--------------------------------------||-----
leading            previous super-swath                current super-swath           ending
partial super-swath                                                           partial super-swath
```

Figure 2. HIRS calibration cycles

$$S'(k-1:k) = [S(k-2) + S(k-1) + S(k)]/M \quad (4)$$

Where:

$S'(k-1:k)$ = the running average of the three slopes, to be used for the 38 Earth view scan-lines in the current super-swath

$S(k-2)$ = the BB slope for the calibration cycle k-2

$S(k-1)$ = the BB slope for the calibration cycle k-1

$S(k)$ = the BB slope for the calibration cycle k

k = calibration cycle number

M = number of qualified BB slopes (see the quality control section) used for averaging (M=1 to 3)

There are several reasons for using a running average for the slopes. First, this will provide fresh slopes that are computed near the time of Earth observations, compared to the 24 hour average slopes in the previous algorithm. Second, using a 3 calibration cycle average reduces fluctuations due to noise. Third, the assumption here is that the slopes at the three calibration cycles do not differ significantly as long as the background flux has not changed significantly during the period. This is a major improvement from the previous algorithm where it was assumed that the slope does not change for any 24 hour period.

**b) Intercept**

First, the intercepts at the calibration cycles are recomputed using the average slopes derived in the previous step.

$$I'(k) = -S'(k\text{-}1{:}k)*C_{sp} \qquad (5)$$

Where: $I'(k)$ = the recomputed intercept for the calibration cycle k

$S'(k\text{-}1{:}k)$ = the average slope for the current super-swath

$C_{sp}$ = space-view count average for the calibration cycle k

Then, the intercept for each of the Earth view scan-lines between two calibration cycles are interpolated using a slightly modified version of equation (1):

$$I'_{(n)} = I'_{l(n)} + \beta * I'_{T(n)} \qquad (6)$$

Where $I'_{(n)}$ is the intercept for Earth view scan-line n (n=1 to 38), $I'_{l(n)}$ is the linear interpolation of the intercept between the two calibration cycles, and $I'_{T(n)}$ is the correction to the intercept based on the telescope temperature. $\beta$ is a switch with values of either 0 or 1. When $\beta$ =0, $I'_{T(n)}$ is effectively turned off.. The above equation for computing intercepts is essentially unchanged from algorithm 3.0, except that the correction based on telescope temperature can now be turned off.

## *Calibration for a partial super-swath*

A partial super-swath occurs when an orbit of HIRS data does not begin or end with a complete calibration cycle. In both cases, the number of Earth view scan-lines in the super-swath could be any number between 1 and 38. Currently most HIRS orbits have both beginning and ending partial super-swaths. Partial super-swaths also occur when the data stream is broken in the middle of an orbit. Furthermore, when the calibration coefficients cannot be computed for more than one calibration cycle (such as in the rare event of calibration breakdown), the remaining data should be treated as a partial super-swath in data processing.

Since the BB slopes and intercepts are missing on one side of the partial super-swath, it is generally recognized that the calibration coefficients for the partial super-swaths will not be estimated as reliably as those for a normal super-swath. However, it should be noted that the six-minute data overlap between succeeding orbits for the current NOAA polar-orbiting satellites is specifically designed to cover the gaps in the HIRS partial super-swath. Since the calibration cycles are 256 seconds apart, in most cases, users requiring a continuous data stream should be able to safely discard both the beginning and ending partial super-swath, because the discarded data are actually available in the adjacent orbit in a full super-swath. Conceptually, if the HIRS orbits were processed sequentially in time, one could use the last BB calibration coefficients from the previous orbit to interpolate the calibration coefficients for the current beginning partial super-swath. However, not all HIRS orbits are processed sequentially in the operations and the following alternative method should be used:

The calibration slope of a partial super-swath is the average value of the qualified slopes (discussed later) from the nearest two (or at least one) calibration cycles available, either from the previous orbit, or from within the same orbit. In case none of them is qualified, use the most recent 24 hour average. The calibration intercepts for a partial superswath are computed using the same method as algorithm 3.0. For local receiving stations, $b_1$ in equation (3) (which is currently derived from 24 hours of global data) may not be appropriate for interpolating the intercepts for the local data. Since the correlation between the telescope temperature and the intercept varies over an orbit, the $b_1$ values can be better estimated using the local data, separating day and night.

### *Data storage in the level 1b file*

At the calibration cycles, the BB slopes and intercepts for each channel are stored along with the blackbody scan-lines (same as algorithm 3.0). The recomputed slopes and intercepts are stored along with the spaceview scan-lines (which were zeros in algorithm 3.0). For Earth view scan-lines, the recomputed slopes for the current superswath and the interpolated intercepts are stored as primary calibration coefficients. The recomputed slopes are also stored as the secondary coefficients, along with the linear portion of the intercept $I'_{l(n)}$. The 24 hour average slopes and the $b_1$ coefficients are stored in the level 1b header.

### *Moon Detection*

It is known that the moon may contaminate the space view for several consecutive orbits in a month. When this occurs, it may corrupt the calibration slopes for one calibration cycle (according to modeling). The AMSU moon detection and correction algorithm by Kigawa and Mo (2002) is being implemented in operations. In this algorithm the moon is detected based on ephemeris data, and the space view count is estimated based on the predicted moon temperature. Preliminary studies for HIRS using the same algorithm suggest that this algorithm can be used for HIRS moon detection. However, correction based on predicted moon temperature requires further study due to complex issues involving moon emissivity in the infrared. Therefore, for HIRS calibration algorithm 4.0, the same AMSU moon detection algorithm will be implemented for HIRS. Once the moon is detected in calcycle(k), the slope S(k) becomes invalid and should be removed from equation (4).

When the space view is contaminated by the moon, the intercepts for the calcycle(k) can be computed using the following equation.

$$I'(k) = R_{bb} - C_{bb} * S'(k-1:k) \quad (7)$$

Where $R_{bb}$=radiance computed based on the PRT data.

$C_{bb}$ = blackbody view count

Here it is assumed that the instrument gain did not change within the last two calibration cycles, and the PRT measurements of the blackbody temperature is valid. The moon as an infrared calibration source for stability monitoring of HIRS is currently under study and more details will be available later.

### *Quality control on the calibration coefficients*

Regardless whether the moon is detected, the surviving slopes will be checked to ensure that their values are within 2% from their mean value. If not, the one furthest from the mean value is removed and the mean recomputed. This process continues till the condition is satisfied, or alternatively, till only one slope is left.

The mean slopes are then checked against their 24 hour orbit averages. If it deviates from the 24 hour average value by more than 10%, it is considered an anomaly and the 24 hour average value should be used instead (flagged in the level 1b data). If the slope for a channel is anomalous, the intercept is also suspect. Therefore, the intercept in this case should be taken from the last qualified intercept (except in the case of moon contamination as discussed above). If this still fails, the 24 hour average value is used. For a newly launched HIRS instrument, the slope values are not checked until 24 hours of HIRS data have been collected and the normal slopes and intercepts for each channel have been confirmed in off-line analysis.

The main assumption for algorithm version 4.0 is that the calibration slope for each of the 19 IR channels does not change for more than 10% within any consecutive 24 hour period. Historical data suggest that the 24 hour variation in the slopes during normal operations is less than 2%. The slopes are most responsive to the filter wheel temperature change. In the extreme case of NOAA-15/HIRS, a ~6% change in the slope has been observed in some channels when the filter wheel temperature changed a few degrees during a 24 hour period.

The 24 hour file used in the previous algorithm should be expanded to include the following items for future use: Corresponding to the slopes and intercepts, for each calibration cycle, the solar zenith angle and latitude at the nadir, the blackbody temperatures from all the individual PRTs, the temperatures from the secondary and tertiary telescope temperature sensors, the filter wheel housing temperatures, and the baseplate temperature. These parameters may be used in the future for modeling the $b_1$ values in equation (3). Finally, all anomalies should be flagged in the level 1b data. The details of the bit usage will be decided in the software design process and documented in the user's guide. All related parameters, such as the percent threshold values, will be subjected to changes during the lifetime of the instrument. The threshold values used in the version 4.0 algorithm are based on NOAA-KLM/HIRS data and their validity for future HIRS instruments needs to be determined post-launch.

## Concluding Remarks

The operational HIRS calibration algorithms have significant impacts on products at all levels. Since the HIRS does not calibration every scan-line, the calibration coefficients between calibration cycles have to be interpolated based on a number of assumptions. At least two calibration algorithms using different interpolation methods have been used in the history of the operational HIRS calibration. The HIRS calibration algorithm 4.0 is developed to correct the problems in the previous version of the algorithm, which has caused calibration biases on the order of a few degrees, especially in the long-wave channels. A switch is added for the intercepts to make the correction using the telescope temperature optional. Also, the linearly interpolated intercepts will be stored in the secondary calibration coefficients field in the level 1b data for comparison. Algorithm 4.0 is expected to become the operational HIRS calibration algorithm for NOAA-N.

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## References

Brunnel, Pascal 2002. ATOVS Navigation and Calibration: Comparison between Local AAPP and Global NESDIS Methods, Conference Proceedings, EUMETSAT STG/SWG.

Cao, Changyong and Hui Xu 2003. Inter-satellite calibration of the High Resolution Infrared Radiation Sounders on NOAA-15, -16, and -17, Proceedings of CalCon2003, Logan, Utah.

Ciren, Pubu, and Changyong Cao 2003. First comparison of radiances measured by AIRS/AQUA and HIRS/NOAA-16/-17, Proceedings of International TOVS Study Conferences, Ste. Adele, Canada, 29 October - 4 November 2003.

Goodrum, Geoffrey, Katherine B. Kidwell, and Wayne Winston 2000. NOAA KLM User's Guide (http://www2.ncdc.noaa.gov/docs/klm), Department of Commerce, Washington DC.

ITT 1996. High Resolution Infrared Radiation Sounder HIRS/4 Technical Description. ITT Aerospace/Communications Division, Fort Wayne, IN.

ITT 1998. High Resolution Infrared Radiation Sounder HIRS/3 Instrument Manual and Alignment/Calibration Handbook & Optical Data, ITT Industries, Fort Wayne, IN.

Kidwell, Katherine B. 1998. NOAA Polar Orbiter Data User's Guide (http://www2.ncdc.noaa.gov/docs /podug/index.htm).

Kigawa, Seiichiro, and Tsan Mo 2002. An Algorithm for Correction of Lunar Contamination in AMSU-A Data, NOAA Technical Report, NESDIS 111, U.S. Department of Commerce.

Kleespies, Thomas J. 2003. Preparations for NOAA-N, Proceedings of International TOVS Study Conferences, Ste. Adele, Canada, 29 October - 4 November 2003.