SATELLITE AND AIRBORNE IR SENSOR VALIDATION BY AN AIRBORNE INTERFEROMETER*

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ABSTRACT

The validation of in-orbit longwave IR radiances from the GOES-8 Sounder and in-flight longwave IR radiances from the MODIS Airborne Simulator (MAS) is described. The reference used is the airborne University of Wisconsin High Resolution Interferometer Sounder (HIS). The calibration of each sensor is described. Data collected during the Ocean Temperature Interferometric Survey (OTIS) experiment in January 1995 is used in the comparison between sensors. Detailed forward calculations of at-sensor radiance are used to account for the difference in GOES-8 and HIS altitude and viewing geometry. MAS radiances and spectrally averaged HIS radiances are compared directly. Differences between GOES-8 and HIS brightness temperatures, and GOES-8 and MAS brightness temperatures, are found to be with 1.0 K for the majority of longwave channels examined. The same validation approach will be used for future sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Atmospheric Infrared Sounder (AIRS).

1.0 INTRODUCTION

Validation of the in-orbit or in-flight calibration of infrared (IR) sensors is an important step in establishing the reliability and accuracy of the data collected by such sensors, if the data are to be used for retrieval of atmospheric or surface geophysical parameters. In this paper we outline the in-orbit validation of the geostationary GOES-8 sounder longwave channels, and the in-flight validation of the MODIS Airborne Simulator (MAS) longwave channels. The reference used for validation is high-spectral resolution data obtained by the airborne High Resolution Interferometer Sounder (HIS). The validation approach described here should prove valuable for characterizing the in-orbit performance of future advanced IR sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Atmospheric Infrared Sounder (AIRS), both part of the complement of sensors of the Earth Observing System (King et al., 1995).

2.0 SENSOR CHARACTERISTICS

2.1 GOES-8 SOUNDER

The GOES-8 sounder (Menzel and Purdom, 1994) is a filter radiometer with 18 thermal infrared bands in the wavelength region 3.7 to 14.7 μm with a spatial resolution of 10 km at nadir. Radiance data are

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acquired at 13 bit quantization. The sounder design goal was to provide brightness temperatures with 1.0 K absolute accuracy and 0.3 K relative precision. The GOES-8 sounder channel bands were patterned after the High-Resolution Infrared Radiation Sounder (HIRS) (Smith et al., 1979) on the NOAA polar orbiting satellites. Table 1 summarizes the GOES-8 sounder longwave channel spectral characteristics. Calibration is established in-orbit using data acquired during views of space at 2 minute intervals and an onboard blackbody at 20 minute intervals. Space and blackbody view data are interpolated over time between calibration data acquisitions and calibration coefficients are determined for each data sample to account for linear detector drift. The calibration equation relating earth scene digital counts C to radiance R is given by

$$R = qC^2 + mC + b \tag{1}$$

The slope m and the intercept b are determined in-orbit from the space and blackbody view data. The quadratic coefficient q is determined pre-launch in thermal vacuum conditions by viewing a NIST traceable blackbody over the temperature range 180 to 320 K, while holding the instrument at selected temperature plateaus which span the operating temperature range expected. Thus q is determined for each channel as a function of instrument operating temperature. The temperature of the blackbody is taken from an average of thermistor readings, and the blackbody radiance for each channel is computed from the convolution of the Planck function over the spectral response of the channel. Blackbody emissivity and longwave channel spectral responses are determined pre-launch in laboratory conditions. A correction for scan mirror emissivity variation with scan angle was made using emissivity estimates computed from coefficients supplied by NOAA/NESDIS.

2.2 MODIS AIRBORNE SIMULATOR

The MODIS Airborne Simulator (MAS) (King et al., 1996) is a scanning spectrometer with 50 spectral channels in the wavelength region 0.5 to 14.2 µm with a spatial resolution of 50 m at nadir. Nineteen of the spectral channels correspond closely to comparable bands on the Moderate Resolution Imaging Spectroradiometer (MODIS) (King et al., 1992), a facility instrument under development for the Earth Observing System (EOS) to be launched in the late 1990s. The MAS flies onboard a NASA ER-2 high altitude research aircraft at an altitude of approximately 20 km, and views a swath width of 37 km. Radiance data are acquired by the MAS at 12 bit quantization. Table 2 summarizes the MAS longwave channel spectral characteristics. Calibration of the MAS longwave channels is established in-flight from observations of two onboard blackbody sources, one operated at the ER-2 ambient temperature (-40 C to -20 C), and the other at a controlled elevated temperature (typically 30°C). The calibration equation relating earth scene digital counts C to radiance R is given by

$$R = mC + b \tag{2}$$

Laboratory testing has verified the linear response of the MAS longwave channels to 1 part in 10000. The slope m and intercept b are determined from the two blackbody views for every earth scan line. Blackbody view count values are derived from the average of twelve samples across each blackbody surface, and the temperature of the blackbodies is taken from an average of thermistor readings. Blackbody effective emissivity has been estimated for all MAS infrared channels in the laboratory using data acquired while viewing a well calibrated extended area blackbody source. Blackbody effective emissivity E is estimated to be 0.940 ± 0.005 for the MAS longwave channels. A correction to the calibration slope m and intercept b is thus made as a function of both emissivity and MAS instrument surrounding temperature as follows:

$$m_E = mE \quad (3)$$

$$b_E = R_{BB1} + (R_B - R_{BB1})\ (1 - E) - m_E\ C_{BB1} \quad (4)$$

where m_E and b_E are the emissivity corrected slope and intercept, R_{BB1} is the Planck radiance of the ambient blackbody, R_B is the Planck radiance of the MAS instrument surroundings, and C_{BB1} is the digital count for the ambient blackbody view. Thus the calibration equation relating earth scene digital counts C to radiance R with blackbody emissivity correction is given by

$$R = m_E C + b_E \quad (5)$$

MAS spectrometer head temperature (typically 0 to -10°C) is monitored in-flight and is currently used to characterize the MAS instrument surrounding temperature. The MAS spectral response data used to spectrally average the HIS radiance data were acquired in the laboratory using a single grating monochromator. The raw spectral response data were corrected for the background (reference) spectrum, and for atmospheric absorption along the measurement optical path using guidance from FASCODE3 (Clough et al., 1981). A Savitsky-Golay smoothing filter which preserves bandpass halfwidth was applied and the data were normalized to the maximum response in each band. Noise in the spectral response data was thus greatly reduced and most of the spectral features due to atmospheric attenuation were removed.

2.3 HIGH RESOLUTION INTERFEROMETER SOUNDER

The High Resolution Interferometer Sounder (HIS) (Revercomb et al., 1988a, 1988b) sensor developed at the University of Wisconsin acquires nadir view radiance spectra in more than 2000 channels between 3.7 and 16.7 microns with a resolving power on the order of 1000, and a spatial resolution of 2 km at nadir. The HIS flies onboard a NASA ER-2 high altitude research aircraft at an altitude of approximately 20 km. Radiance interferograms are acquired with 16 bit quantization. Calibration is accomplished in-flight at 2 minute intervals using views of two high-emissivity blackbodies, servo controlled to 240 K and 300 K. The blackbodies are blackened cavities with thermoelectric cooler/heaters for temperature control and PRT's for monitoring, and are known to have emissivities > 0.998. During calibration mode, 4 scans of the warm blackbody and 4 scans are of the cold blackbody are acquired. The HIS detectors and associated electronics are designed to yield an output which is linear in radiance, and thus a slope and intercept are determined from the blackbody sources to transform the measured interferograms to radiance spectra. More details on the HIS calibration are given in Revercomb et al. (1988b). The absolute accuracy of the HIS calibration has been demonstrated in the laboratory over the full spectral range by using a third blackbody as a source, and a liquid nitrogen blackbody in place of the servo controlled 240 K blackbody. An absolute accuracy of 1.0 K or better over the full spectral range with 0.1 K RMS reproducibility was thus achieved. Excellent in-flight performance has also been demonstrated by comparing measured radiance spectra to those computed with FASCODE3 using radiosonde data to define the atmospheric temperature and moisture profile (Revercomb et al., 1989).

3.0 DATA COLLECTION METHODOLOGY

Coincident validation datasets from the GOES-8 Sounder, MAS, and HIS were collected during the Ocean Temperature Interferometric Survey (OTIS) experiment (Smith et al., 1996) in the Gulf of Mexico during January 1995. On January 16 an ER-2 flight was conducted in clear skies over the ocean during daylight hours, while measurements of sea surface temperature and emissivity were made from a research vessel (the R/V Pelican) directly beneath the ER-2 flight track. Atmospheric temperature and moisture profile data were obtained by CLASS sondes launched from the R/V Pelican during the ER-2 overflight. Repeated overflights of the research vessel were made over the course of several hours, with continuous acquisition of radiance imagery by the MAS and radiance spectra by the HIS onboard the ER-2. GOES-8 sounder data were acquired hourly. MAS radiance imagery was examined to verify that no clouds were present in the coincident validation datasets.

4.0 DATA ANALYSIS

4.1 GOES-8 SOUNDER AND HIS

A total of 39 HIS radiance spectra collected along an East-West flight line from 26.00 N, 93.62 W to 26.00 N, 93.71 W between 15:21 and 18:12 UTC were used to compute an average HIS radiance spectrum. Coincident GOES-8 Sounder data from 3 consecutive images at 14:46, 15:46, and 16:46 UTC were averaged over a 3x3 pixel box centered at 26.00 N, 93.66 W. The HIS average radiance data were spectrally averaged over the GOES-8 Sounder longwave channel spectral responses. To compare the GOES-8 Sounder and averaged HIS radiances, a correction was computed to account for the difference in sensor altitude and viewing angle. This correction was of the form

$$\Delta R_{HIS\text{-}G8} = (R_{HIS} - R_{G8})_{OBS} - (R_{HIS} - R_{G8})_{CALC} \qquad (6)$$

where $\Delta R_{HIS\text{-}G8}$ is the corrected difference between HIS and GOES-8, $(R_{HIS} - R_{G8})_{OBS}$ is the difference between HIS and GOES-8 observations, and $(R_{HIS} - R_{G8})_{CALC}$ is the difference between HIS and GOES-8 at-sensor radiance calculations. Thus in the ideal case, if the HIS and GOES-8 measurements and the at-sensor radiance calculations are radiometrically accurate, then the corrected difference $\Delta R_{HIS\text{-}G8}$ will be zero.

The HIS and GOES-8 calculations of at-sensor radiance were done using FASCODE3. A CLASS sonde released from the Pelican at 15:05 UTC was used to provide temperature and moisture profile information up to the ER-2 pressure altitude of 55 hPa. The temperature profile data were corrected for solar radiation bias using the method recommended by the radiosonde manufacturer. Temperature profile data from 55 mb to 0.1 hPa were obtained from UARS Microwave Limb Sounder (MLS) (Barath et al., 1993) measurements. Sea surface spectral emissivity was computed using a model derived from high-resolution sea surface radiance measurements by the University of Wisconsin Atmospheric Emitted Radiance Interferometer (AERI) (Smith et al., 1996) onboard the R/V Pelican. The effect of sea surface reflected sky radiation was approximated by a surface reflectance term of ($1 - E_{sfc}$) where E_{sfc} is the sea surface spectral emissivity. No correction was applied for reflected solar radiation. The effect of the chlorofluorocarbons CCl_4, CFC11, and CFC12 and other trace absorbers were included in the FASCODE3 calculations. Concentration levels of these trace absorbers were set at 1.5 times WMO levels for 1987. The self-broadened water vapor continuum component of the computed radiances was adjusted by a factor of 1.55 based on coincident high-spectral resolution measurements of downwelling radiance at the surface by the AERI. The factor of 1.55 provided the best agreement between the surface based AERI measurements and FASCODE3 calculations of downwelling radiance at the surface.

Table 3 shows the resulting corrected difference $\Delta R_{HIS\text{-}G8}$ between HIS and GOES-8 in terms of brightness temperature. Figure 1 presents the same data as a bar plot. GOES-8 Sounder channel 9 was omitted from the analysis because this channel, centered at 9.71 μm, is sensitive to atmospheric ozone. Since most of the total ozone burden is above the ER-2 flight altitude, no meaningful comparison of this channel can be made with the HIS data. It can be seen from the results that for 7 of the 11 GOES-8 Sounder longwave channels, $|\Delta R_{HIS\text{-}G8}| < 1.0$ K. In section 2.1 it was noted that the GOES-8 Sounder design specification called for absolute accuracy of 1.0 K. Further refinements to be made to the analysis include consideration of the effects of aerosols, more detailed evaluation of the water vapor continuum contribution, and inclusion of reflected solar radiation to allow the analysis to be extended to the GOES-8 Sounder shortwave infrared channels.

4.2 MODIS AIRBORNE SIMULATOR AND HIS

A total of 527 HIS radiance spectra were collocated with coincident MAS radiance imagery along the East-West ER-2 flight track on January 16 between 15:20 and 18:10 UTC. For each HIS radiance spectrum, the coinciding MAS fields-of-view within the HIS field of view were used to compute an average MAS radiance. Each individual HIS radiance spectrum was then spectrally averaged over the MAS longwave channel spectral responses. Thus for each HIS spectrum, a radiance difference was computed of the form

$$\Delta R_{HIS\text{-}MAS} = (R_{HIS} - R_{MAS})_{OBS} \tag{7}$$

Computations of the type described in section 4.1 are unnecessary since the HIS and MAS are at the same altitude and have the same viewing geometry of the sea surface at nadir.

Table 4 shows the resulting corrected difference $\Delta R_{HIS\text{-}MAS}$ between HIS and MAS in terms of brightness temperature. Figure 2 presents the same data as a bar plot. It can be seen that for 7 of the 9 MAS longwave channels, $|\Delta R_{HIS\text{-}MAS}| < 1.0$ K. Channels 48 and 50 do not show as good agreement; channel 48 experienced saturation on the warm blackbody view which affected calibration accuracy, and the bias in channel 50 is attributed to an incomplete removal of the effects of atmospheric attenuation in the MAS longwave channel spectral response laboratory measurements. The consistent positive bias in channels 42-47 and 49 may be due to inaccuracy in the representation of the MAS instrument temperature. Future laboratory measurements of MAS spectral response in thermal vacuum conditions and additional in-flight temperature monitoring will be examined to reduce the magnitude of $|\Delta R_{HIS\text{-}MAS}|$, and to extend the analysis to the MAS shortwave infrared channels.

5.0 SUMMARY

In order to validate at-sensor longwave IR radiance measurements by the GOES-8 Sounder and MODIS Airborne Simulator (MAS), coincident measurements by the airborne High Resolution

Interferometer Sounder (HIS) were obtained over the Gulf of Mexico on January 16, 1995. Detailed forward radiance calculations were done using FASCODE3 to account for the altitude and viewing geometry differences between GOES-8 and HIS. MAS radiances and spectrally averaged HIS radiances were compared directly since the HIS and MAS are mounted on the same aircraft platform. In the GOES-8/HIS comparison, the corrected difference $|\Delta R_{HIS\text{-}G8}|$ was less than 1.0 K for 7 of the 11 GOES-8 longwave channels. The residuals remaining are attributed to aerosol and water vapor continuum effects, and instrument noise. In the MAS/HIS comparison, the corrected difference $|\Delta R_{HIS\text{-}MAS}|$ was less than 1.0 K for 7 of the 9 MAS longwave channels. Remaining residuals are attributed to absorption effects in the MAS spectral responses, and inaccuracy in knowledge of the MAS instrument temperature. A comprehensive validation of the GOES-8 and MAS longwave infrared channels has been demonstrated, and should serve as a prototype for validation of IR radiances from future sensors such as MODIS and AIRS.

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Table 1. GOES-8 Sounder Longwave Channel Characteristics

GOES-8 Sounder Channel	Center Frequency (cm^{-1})	Center Wavelength (μm)
1	680	14.71
2	696	14.37
3	711	14.06
4	733	13.96
5	748	13.37
6	790	12.66
7	832	12.02
8	907	11.03
10	1345	7.43
11	1425	7.02
12	1535	6.51

Table 2. MAS Longwave Channel Characteristics

MAS Channel	Center Frequency (cm^{-1})	Center Wavelength (μm)
42	1163	8.60
43	1021	9.79
44	948	10.55
45	907	11.02
46	836	11.96
47	776	12.88
48	756	13.23
49	729	13.72
50	706	14.17

Table 3. Brightness Temperature Differences between HIS and GOES-8 Sounder Longwave Channels with Correction for Viewing Geometry.

GOES-8 Sounder Channel	Brightness Temperature Difference (K)
1	1.08
2	1.33
3	1.57
4	-0.29
5	0.10
6	-0.65
7	-1.21
8	-0.95
10	0.05
11	-0.37
12	0.86

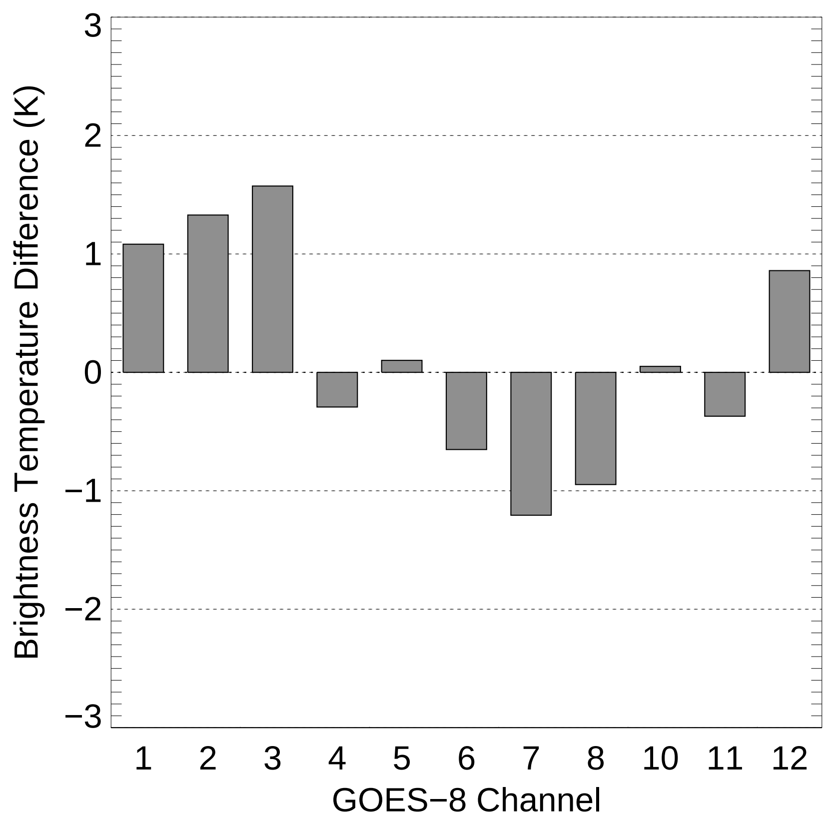

Figure 1. Brightness Temperature Differences between HIS and GOES-8 Sounder Longwave Channels with Correction for Viewing Geometry.

Table 4. Brightness Temperature Differences between HIS and MAS Longwave Channels.

MAS Channel	Brightness Temperature Difference (K)
42	0.89
43	0.61
44	0.58
45	0.61
46	0.51
47	0.35
48	-2.68
49	0.80
50	-2.78

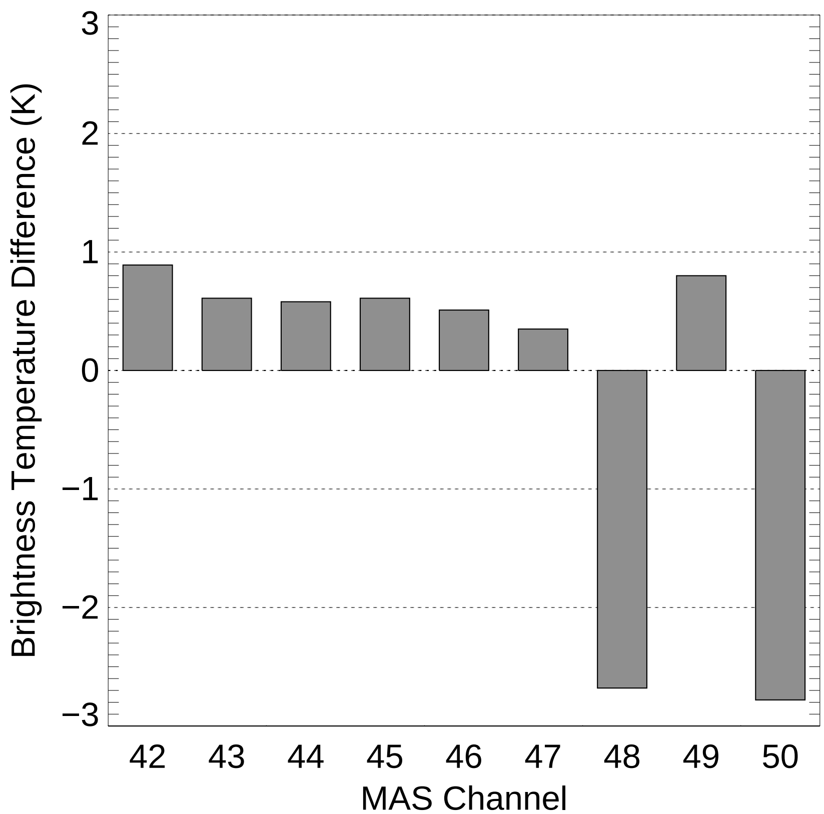

Figure 2. Brightness Temperature Differences between HIS and MAS Longwave Channels.