P2.2 PRELIMINARY EVALUATION OF THE GIFTS CALIBRATION ALGORITHM USING THE GIPS

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Ground calibration algorithms for a Geosynchronous Imaging FTS (GIFTS) are being developed at the University of Wisconsin-Madison Space Science and Engineering Center. This development is being conducted in support of NOAA's GOES-R Risk Reduction program with a focus on the hyperspectral sounder that is anticipated to be a part of the GOES-R Hyperspectral Environmental Suite (HES). The near term objective is to develop calibration algorithms that can be evaluated using thermal vacuum test data from NASA's Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS). The GIFTS is designed to produce 128x128 interferograms in two spectral bands every 11 seconds using a Michelson interferometer and two detector focal plane arrays. In preparation for the thermal vacuum test data, simulated data has been used in the GIFTS Information Processing System (GIPS) to illustrate expected accuracy of a unique on-orbit calibration approach using two high emissivity internal reference cavities plus a space view.

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1. INTRODUCTION

The geostationary imaging weather satellites play a vital role in the global system of operational observing platforms by providing the high temporal and spatial resolution needed for severe storm nowcasting as well as the large scale motion fields that influence events such as tropical cyclone intensity and path prediction. The next generation geostationary satellites is expected to take a revolutionary advance toward improving the determination of atmospheric stability and clear air convective initiation as well as the height assignment of wind vectors derived from putting retrieved water vapor fields in motion (Dittberner et al., 2003). The timely availability of this information will greatly enhance the mesoscale and synoptic information available for Numerical Weather Prediction (NWP) data assimilation. The Geostationary Imaging Fourier Transform Spectrometer (GIFTS) is an instrument development project under the NASA New Millenium Program initiative that addresses the technological needs of the next generation geostationary sounders. The GIFTS instrument was designed as a research prototype and proof of concept demonstration of how new detector focal plane technology can be combined with a mature spectrometer design to accomplish the goals of a future advanced geostationary sounder. The GIFTS instrument has been designed and fabricated under the management of NASA Langley Research Center with Utah State University Space Dynamics Laboratory as prime contractor (Smith et al., 2000; Bingham et al., 2000). At the time of writing, the GIFTS is in thermal vacuum testing to verify the instrument performance characteristics and to validate the new technologies used in the design.

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One of the concepts unique to GIFTS is the use of two high emissivity cavity blackbodies internal to the instrument and behind the scene mirror in addition to a view to deep space. These onboard reference cavities were designed and built at the UW-SSEC (Best et al, 2000, 2004). The expected accuracy of this calibration approach is illustrated in this paper through the use of simulated GIFTS data and the algorithms that make up the GIFTS Information Processing System (GIPS) (Garcia et al., 2005; Knuteson 2004a, 2005).

2. BACKGROUND

The UW-SSEC pioneered the development of absolute radiometric and spectral calibration for “warm” InfraRed Fourier Transform Spectrometers (FTIR) with an accuracy and reproducibility that is sufficient for the use in atmospheric remote sensing (Revercomb et al., 1988). Even though the GIFTS is a “cold” instrument, the same physical principles developed for the UW-SSEC instruments will be applied to the calibration of the GIFTS radiances in order to take into account gain and offset changes in the instrument during normal operation. The GIFTS spectral coverage indicated in Fig. 1 illustrates that the dynamic range of signals from terrestrial thermal infrared radiation spans hundreds of degreees. However, the demands of remote sensing of atmospheric effects are high since the signal of subtle changes in temperature and atmospheric humidity from the mean atmospheric state are only tenths of degrees (Smith, 2000). Achieving absolute calibration at the tenth of degree accuracy level is a goal that is within the reach of high spectral resolution IR remote sensing using precision on-board blackbody references with NIST traceability. This approach has been demonstrated at the UW-SSEC in both the groundbased Atmospheric Emitted Radiance Interferometer (AERI) program and the aircraft-based High-resolution Interferometer Sounder (HIS) program (Knuteson et al., 2004c,d; Revercomb et al., 1988).

In both the AERI and HIS programs, FTIR spectrometers have been used in order to take advantage of the very high spectral frequency knowledge that is inherent in the FTS design. At the relatively high spectral resolutions (resolving power > 1000) in the thermal infrared, the wavenumber sampling and instrument line shapes must be known to better than 1% accuracy or errors will be introduced in the comparison with forward model calculations that exceed the radiometric requirement. With an FTIR sensor, a single parameter determines the wavenumber sampling of each spectral band and all the spectral elements see the same field of view on the Earth. The FTS spectral parameter can be determined pre-launch but also in-flight by comparison to known spectral absorption lines across the spectral band of interest (Tobin et al., 2003). The excellent spectral knowledge and stability of the FTIR system was the primary motivation for the selection of FTS for the GIFTS sensor.

The ability to accurately calibrate high spectral resolution infrared observations is also important for the future of detecting global change from space-borne observations (Goody & Haskins, 1998). The technology exists with precision blackbodies and FTS laser spectral sampling to approach the tenth of degree accuracy and stability desired for the detection of global climate change on decadal scales. Although this is outside the scope of the GIFTS sensor requirements, the GIFTS design shows the feasibility of high absolute accuracy in a practical implementation for sensors in geostationary orbit. The design makes use of two high precision cavity radiometers with high absolute emissivity (>0.998) and good long term stability (diffuse paints). The cavity blackbodies used for GIFTS are built and calibrated at the UW-SSEC based upon heritage with the AERI and HIS programs. The unique approach for GIFTS is to place these reference cavities aft of the Earth viewing telescope with an "on-demand" flip in mirror to direct the IR emission from the blackbodies into the sensor. The main advantage of this approach is that the IR beam is much smaller after the telescope so that a true high emissivity cavity design can be used for the blackbodies while keeping the volume, weight, and power requirements to a minimum. The successful design of these blackbodies for the GIFTS sensor is described in Best, et al., 2004. The high absolute accuracy of the onboard reference blackbodies compensates for the additional uncertainty from degradation of the telescope optics over time. A scheme for monitoring this telescope degradation over time that makes use of the internal reference views and views to deep space has been devised for the GIFTS sensor by the Space Dynamics Laboratory (Elwell et al., 2003).

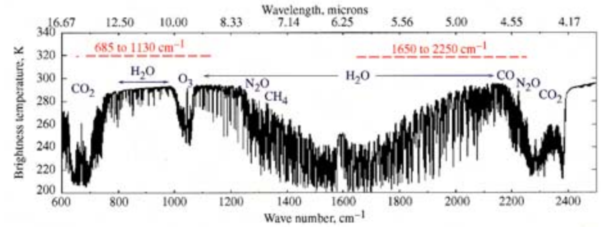

Figure 1. A calculation of the top of atmosphere radiance emitted by the standard atmosphere in units of equivalent brightness temperature (Kelvin). The dashed lines indicate the two spectral bands selected for the NASA GIFTS sensor. The longwave (LW) band covers the traditional "temperature sounding" region for the characterization of atmospheric temperature from the top of the atmosphere to the surface and includes the 8-12 mm IR window for the characterization of land surface and cloud top temperature and emissivity. The shortwave/midwave (SWM) band includes a non-traditional coverage of the shortwave side of the "6.3 mm water vapor sounding" region. The short-midwave band coverage (1650-2250 cm-1) was shown by analysis to be optimal for three reasons; 1) this region avoids the interference of "fixed" gases N2O and CH4 which degrade the water vapor sounding performance, 2) the shorter wavelength (fewer thermal photons) leads to better signal to noise performance for the detectors chosen, 3) provides coverage of carbon monoxide thereby allowing the tracking of air pollution plumes from source to sink.

3. INSTRUMENTATION

The GIFTS radiometric calibration is designed to use two small reference blackbodies located behind the telescope, combined with a space view (Best et al., 2000; Bingham et al., 2000). This is also the location of an image of the aperture stop for each detector in the focal plane arrays. Figure 2 illustrates the "flip mirror" mechanism with a linear slide to position either the warm or cold blackbody into the instrument beam. The blackbody design is scaled from the UW ground-based design used on AERI and S-HIS aircraft instruments. Constraints on the original spacecraft envelope prevented a traditional external large aperture blackbody implementation. The advantages of using two internal blackbodies compared to one large external blackbody include; (1) higher emissivity is practical with small size, (2) effective temperature of the body easier to characterize, and (3) protection from solar forcing gradients. A photo of the GIFTS engineering model blackbody cavity built by UW-SSEC is shown in Figure 2 (Best et al., 2004).

A Monte Carlo ray trace analysis has been performed that makes use of the internal cavity paint reflectivity and the detailed cavity geometry to estimate the cavity normal isothermal emissivity. A spectrum of the cavity emissivity is shown in Figure 3.

The GIFTS calibration requirement has been traced to requirements on the subsystem components, in particular to the blackbody subsystem. The blackbody calibration contribution budget allocation is < 0.5K and the engineering best estimates are <0.35K (LW) and <0.20K (SMW). The uncertainty estimates of the UW-SSEC blackbodies are described in much greater detail in Best et al., 2004.

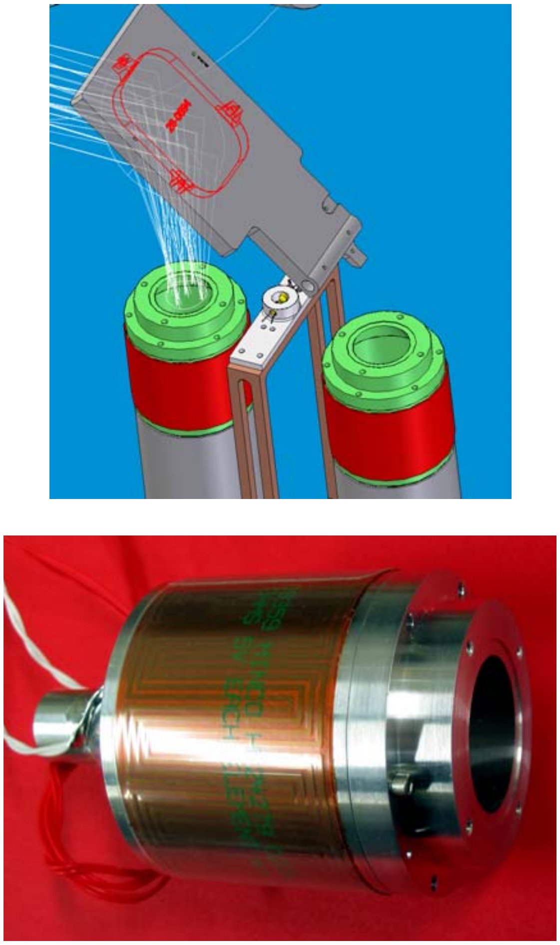

Figure 2. The top panel illustrates two blackbodies and a visible flood source mounted on the same linear slide. One source at a time is correctly positioned under the flip-in mirror. The bottom panel is a photo of the UW-SSEC engineering model of the GIFTS blackbody. The blackbody aperture is 1.00 inches in diameter, the width of the cylindrical body is 1.76 inches in diameter, and the total cavity depth is 3.06 inches. GIFTS sensor module electro-optical design provides for two internal reference cavities aft of the Earth viewing telescope and a fold mirror which directs energy from the blackbodies into the instrument upon command. Since the beam diameter at this location is small, the internal blackbodies can have high emissivity while remaining relatively compact and lightweight. The blackbodies were designed, built, and calibrated at the UW-SSEC using standards traceable to NIST.

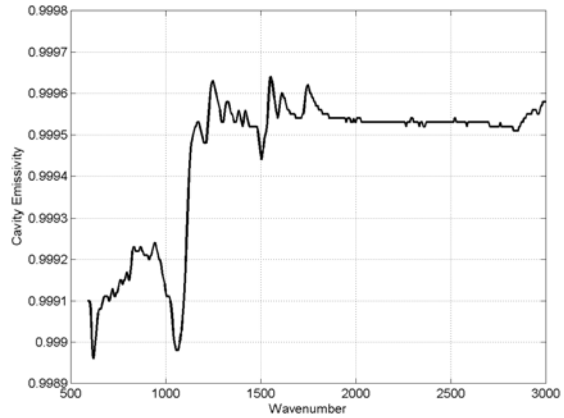

Figure 3. Isothermal normal cavity emissivity estimate for the UW-SSEC blackbodies used as the GIFTS internal calibration references. This estimate is based upon a Monte Carlo ray trace using the cavity geometry and the measured and modeled reflectance properties of the paint used to coat the inner surfaces of the cavity. This estimate includes a wavelength cavity factor due to the spectral variation of specular and diffuse reflection across the wavenumber range of interest.

4. THEORY

Radiometric calibration of the GIFTS spectrometer has the same considerations as that of any radiometer. Key factors include the accuracy of onboard references, thermal stability over calibration cycles, and linearity after correction. The GIFTS's cold spectrometer design places a tight constraint on blackbody emissivity uncertainty since the energy reflected from a cold instrument is very small compared to an instrument that is close to the blackbody temperature. This, coupled with volume and mass constraints for GIFTS led to using small high-emissivity internal blackbody references, plus a space view. The broad spectral coverage from a single detector (inherent to FTS) prevents detector-to-detector FOV variations from altering spectral radiance shapes (greatly simplifying FOV co-alignment and testing requirements). The calibration method is summarized in Eq. 1. This is a modified version of the Revercomb et al., 1988 equation to include the ratio of the transmission of the flip in mirror (labeled "m") to the fore optics telescope (labeled "t") (Knuteson et al., 2004b).

$$N = \left(\frac{\tau_m}{\tau_t}\right)(B_H - B_C) Re\left(\frac{C_E - C_S}{C_H - C_C}\right) + B_S \qquad (1)$$

The radiance N is derived from raw spectra of Earth (C_E), Space (C_S), and the internal Hot (C_H) and Cold (C_C) blackbodies where $B_{H,C,S}$ is the predicted Planck radiance from the Hot, Cold, and Space references including the effective emissivity of the blackbody cavity and the energy reflected off the blackbody from the environment, assumed here to be at 265 K.

Uncertainty in the knowledge of the reference source temperature and emissivity will lead to uncertainty in the calibrated radiances. The space view is assumed to be known exactly so no error is introduced. However, measured characteristics of the UW-SSEC blackbody can be used to estimate a 3-sigma (not-to-exceed) error bound. These parameter uncertainties are summarized in Table 1. The uncertainty estimates in the calibrated radiance are obtained through a perturbation analysis of Eq. 1 where the uncertainties of the blackbody emissivity and temperature are taken into account.

Table 1. On-orbit calibration parameter uncertainties assumed in this analysis. (3-sigma)

On-orbit Calibration Parameter	Nominal value	Assumed Uncertainty
Hot BB Temperature	300 K	0.1 K
Cold BB Temperature	265 K	0.1 K
Hot BB Emissivity	(see Fig. 3)	0.001
Cold BB Emissivity	(see Fig. 3)	0.001
Space View Temperature	2.76 K	0.0
Space View Emissivity	1.0	0.0

5. RESULTS

Simulated GIFTS interferograms were used as input to the modified Revercomb et al calibration equation given in Eq. 1. Details of the GIFTS simulation model have been previously described in Huang, et al. (2000). The complex spectra resulting from the Fast Fourier Transform of the simulated interferograms is shown in Figure 4 as magnitude and phase spectra for each of the four scene views; Earth, hot blackbody, cold blackbody, and deep space. A linearly varying phase has been included in the simulation to force the FFT of the interferograms to have both a real and imaginary component. The responsivity, which is the inverse of the calibration slope, is shown in Figure 5 for each of the two simulated GIFTS spectral bands and illustrates the cutoff assumed for the simulated GIFTS optical pass bands. The GIFTS simulation is not intended to be completely realistic but merely serves as an example of the type of data that will be available from the instrument in flight. The simulation is suitable for illustrating the expected radiometric calibration accuracy of a typical Earth scene. Figure 6 shows the result of application of the calibration equation to the raw complex spectra; the real part of the equation is shown as a brightness temperature spectrum while the imaginary part (not shown) is zero to within the noise level.

A perturbation analysis has been performed using these simulated GIFTS observations to illustrate the uncertainty in the calibration error expected in this typical clear sky scene due to uncertainties in the knowledge of the internal calibration reference sources. Figure 7 shows the brightness temperature error as a function of wavenumber induced by varying the blackbody temperature and emissivity by the amounts shown in Table 1. The label, RSS, indicates the root sum square of the error contributions which represents a 3-sigma estimate of the expected absolute calibration uncertainty. Figure 8 shows the same perturbation analysis as a function of scene brightness temperature.

To illustrate the imaging capability of the GIFTS sensor, an Earth scene data cube (128x128 fields of view) was simulated and the same calibration error analysis was applied to each field of view. The result is shown in Figure 9 as images of the scene brightness temperature in the longwave window and the estimated calibration error at the same wavelength. Note that the colder scenes have slightly smaller errors than the warmer scene pixels. This is further illustrated in the 3-D plot of Figure 10 where the error closely follows the cloud scene temperature.

6. CONCLUSIONS

The GIFTS error budget for the contribution of the internal calibration errors is 0.5 K (3-sigma) out of a total requirement of <1K for all radiometric calibration errors. The current engineering best estimate is < 0.35 K in the longwave and < 0.20 K in the short/midwave bands. The examples shown here are consistent with those previous estimates. Moreover, the analysis shown in this paper for a specific simulation dataset is consistent with the general perturbation analysis described in Knuteson, et al. (2004b)

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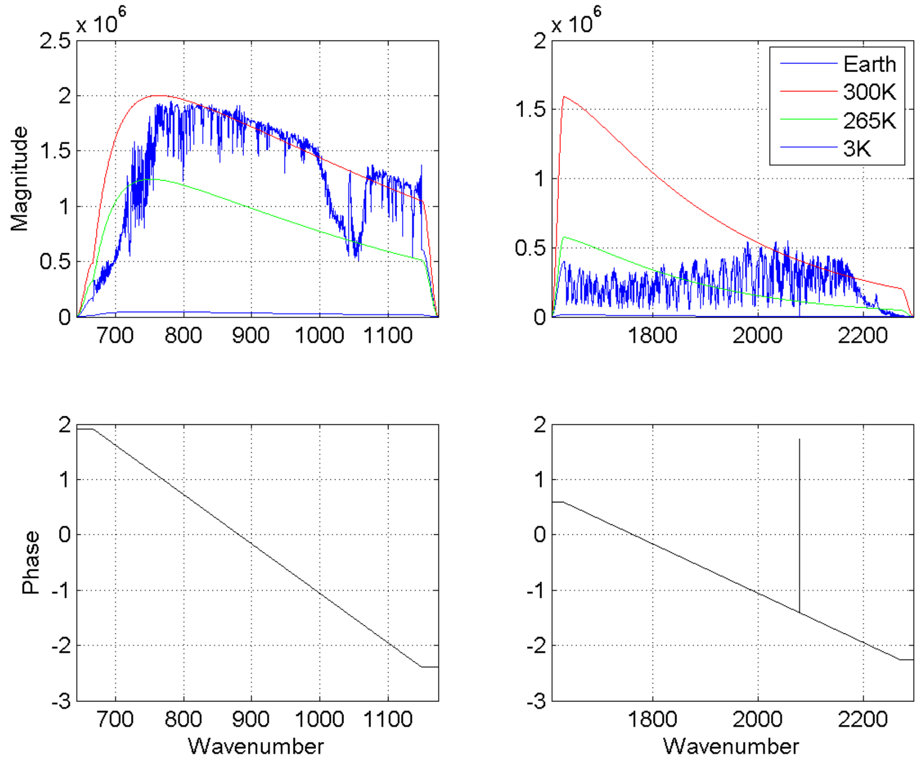

Figure 4. Simulated GIFTS interferograms have been Fourier transformed to show the magnitude and phase of the uncalibrated complex spectra used in this noise analysis.

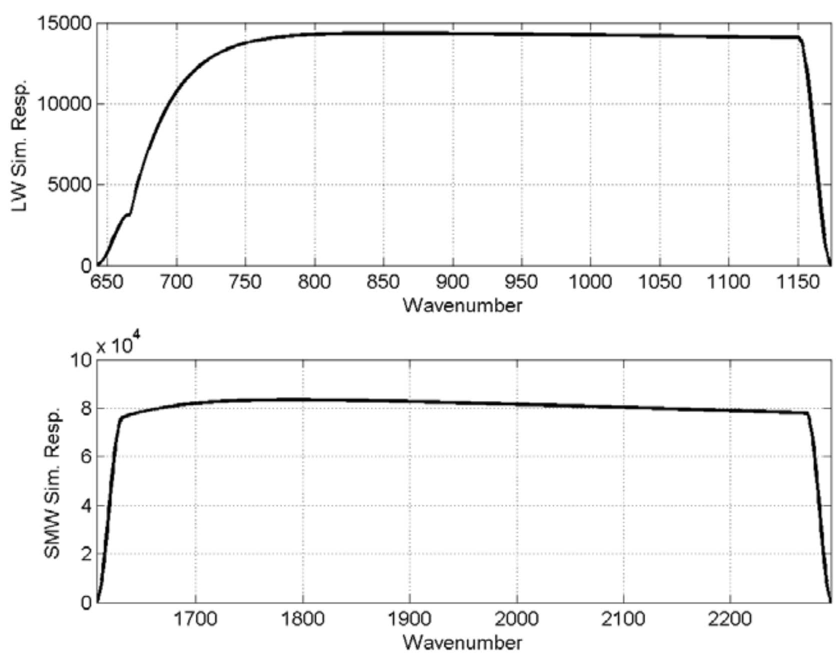

Figure 5. Simulated GIFTS responsivity magnitudes computed from the ratio of the difference of simulated internal blackbody views to the difference of planck radiances at 300 K and 265 K. These simulated responsivities are not intended to mimic the real GIFTS instrument except in defining the approximate spectral cutoffs for the longwave and short/midwave bands.

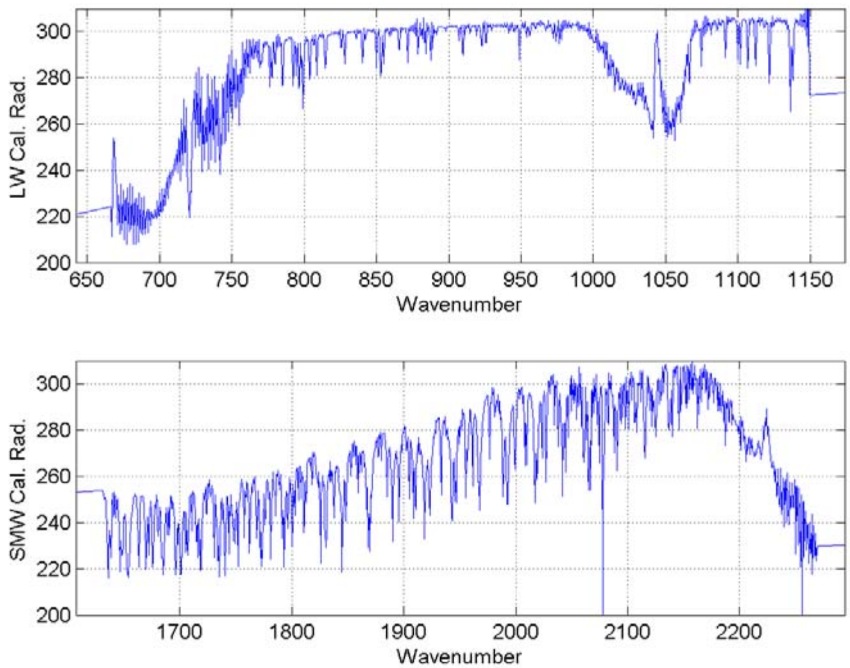

Figure 6. Calibrated GIFTS radiance obtained after applying Eq. 1 to simulated GIFTS interferograms for a warm scene (Central Oklahoma, IHOP case) and simulated views of internal (Hot and Cold) and external (Space) views. Telescope transmission is assumed known in this simulation.

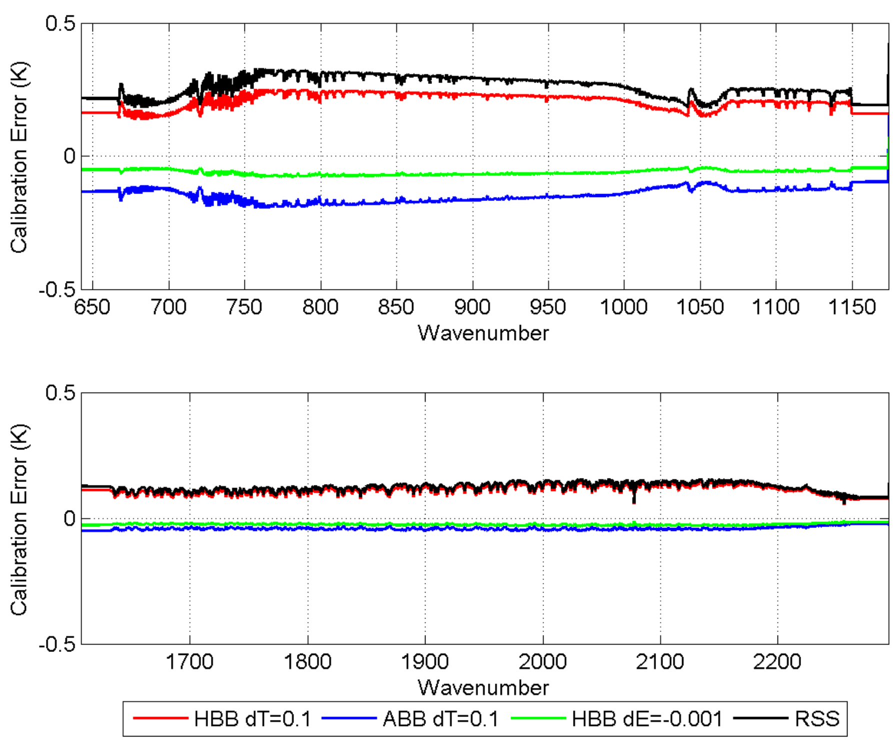

Figure 7. The internal blackbody calibration error of LW and SWM GIFTS bands are shown as an error spectrum for the calibrated scene shown in Fig. 6 and using the uncertainties shown in the figure legend. The GIFTS error budget for the contribution of the internal calibration errors is 0.5 K (3-sigma).

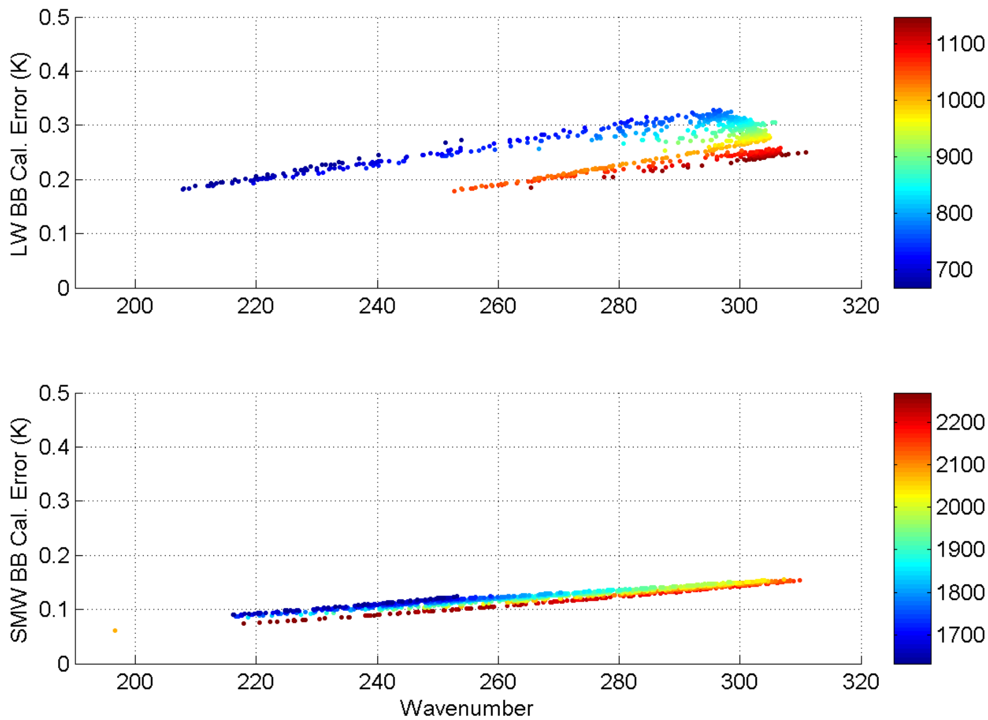

Figure 8. The internal blackbody calibration error of LW and SWM GIFTS bands are shown as scatterplot for the calibrated scene shown in Fig. 6 and using the uncertainties given in Table 1. The points are color coded based upon the wavenumber scale as indicated in the colorbar to the right of each panel. The GIFTS error budget for the contribution of the internal calibration errors is 0.5 K (3-sigma) out of a total requirement of <1K for all radiometric calibration errors. The current engineering best estimate is < 0.35 K in the longwave and < 0.20 K in the short/midwave bands. This example is consistent with those estimates.

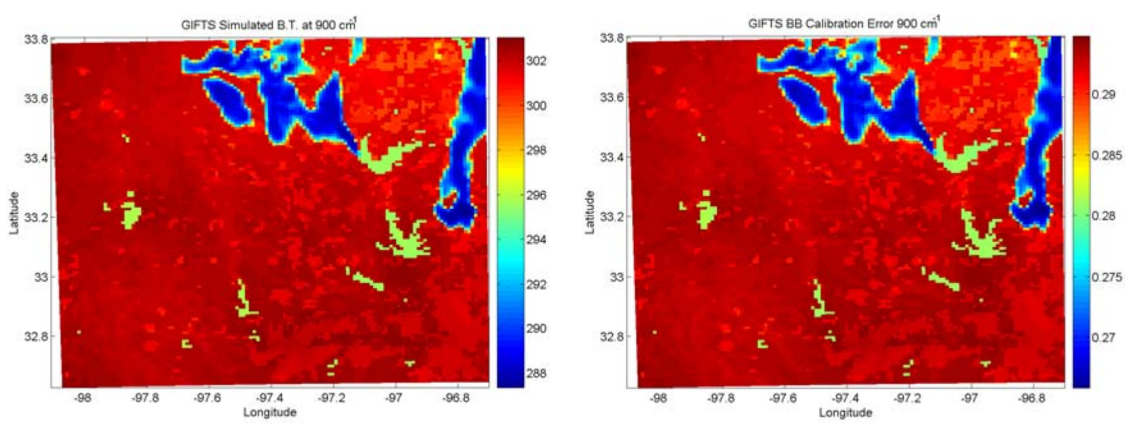

Figure 9. A brightness temperature image of a simulated GIFTS Earth scene (left panel) is shown for the center of the longwave band (900 cm-1). The internal blackbody calibration error at 900 cm-1 is shown in the right hand panel as an image using the uncertainties given in Table 1. The variation in window scene temperature is caused by presence of clouds in the simulation. All units are in Kelvin.

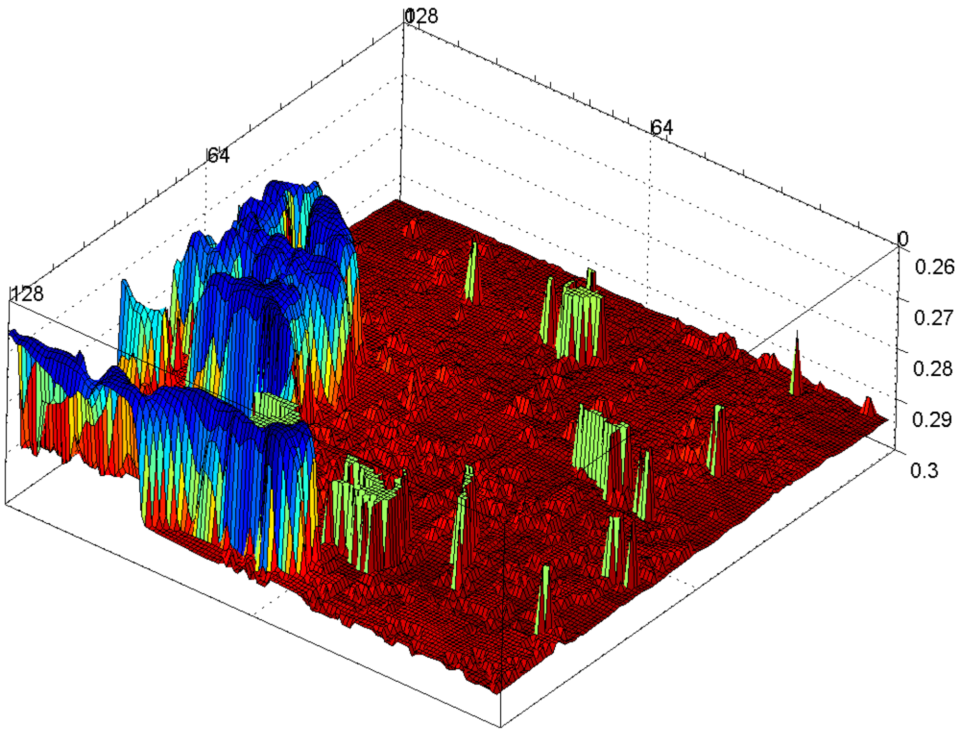

Figure 10. Same blackbody calibration error data as the right hand panel of Fig. 9, but shown here as a three-dimensional surface plot. The internal blackbody calibration error at 900 cm-1 varies across the scene due to the presence of clouds in the simulation. The “peaks” in the surface represent a decrease in the error in the absolute calibration of the GIFTS radiances for the colder cloudy scenes. All units are in Kelvin.