SUOMI NPP/JPSS CROSS-TRACK INFRARED SOUNDER (CRIS): CALIBRATION VALIDATION WITH THE AIRCRAFT BASED SCANNING HIGH-RESOLUTION INTERFEROMETER SOUNDER (S-HIS)

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1. INTRODUCTION

The Cross-track Infrared Sounder (CrIS) on Suomi NPP, launched 28 October 2011, is designed to give scientists more refined information about the Earth's atmosphere and improve weather forecasts and our understanding of climate. CrIS is an infrared Fourier transform spectrometer with 1305 spectral channels, which produces high-resolution, three-dimensional temperature, pressure, and moisture profiles. These profiles will be used to enhance weather forecasting models and will facilitate improvements to both short and long-term weather forecasting.

For improved weather prediction and climate change monitoring, there is an established need for higher accuracy and more refined uncertainty characterization of radiance measurements from space and the corresponding geophysical products. This need has led to the use of direct tests of in-orbit performance, referred to as validation. Currently, validation typically involves (1) collecting high quality temporally and spatially co-located reference data from accurately calibrated airborne or ground-based instruments with traceability to absolute standards during the satellite overpass, and (2) a detailed comparison between the satellite-based radiance measurements and the corresponding high quality reference data. Additionally for future missions, technology advancements at University of Wisconsin Space Science and Engineering Center (UW-SSEC) have led to the development of an on-orbit absolute radiance reference utilizing miniature phase change cells to provide direct on-orbit traceability to International Standards (SI) (Best et al. 2010; Best et al. 2012).

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The detailed comparison between the satellite-based radiance measurements and the corresponding measurements made from a high-altitude aircraft must account for instrument noise and scene variations, as well as differences in instrument altitudes, observation view angles, spatial footprints, and spectral response. For the calibration validation process to be both accurate and repeatable, it is very important that the reference data instrument be extremely well characterized and understood, carefully maintained, and accurately calibrated. The Scanning High-resolution Interferometer Sounder (S-HIS) meets and exceeds these requirements and has proven to do so on multiple airborne platforms, each with significantly different instrument operating environments.

The first Suomi NPP airborne calibration validation campaign was conducted May 2013 with a primary objective of providing detailed validation of CrIS radiance observations and meteorological products. During this calibration validation campaign, the NASA ER-2 aircraft instrument payload included the UW-SSEC Scanning-High resolution Interferometer Sounder (S-HIS), the NPOESS Atmospheric Sounder Testbed-Interferometer (NAST-I), the NPOESS Atmospheric Sounder Testbed-Microwave Spectrometer (NAST-M), the NASA MODIS/ASTER airborne simulator (MASTER), and the NASA JPL Airborne Visible / Infrared Imaging Spectrometer (AVIRIS). Eleven ER-2 under-flights of the Suomi NPP satellite were conducted during the campaign.

This paper will include (1) an overview of the radiance calibration approach and radiometric uncertainty of the S-HIS validation data, (2) a detailed assessment of four clear sky under-flights, and (3) a summary assessment of the CrIS spectral radiance observations for the under-flights.

2. THE CROSS-TRACK INFRARED SOUNDER (CRIS)

CrIS (Figure 1) is an infrared Fourier transform spectrometer (FTS) with 1305 spectral channels, which produces high-resolution, three-dimensional temperature, pressure, and moisture profiles. The CrIS optical system was designed to provide an optimum combination of optical performance and compact packaging (Kohrman; Luce 2002; Stumpf; Overbeck 2002). Its key subsystems include a step and settle two-axis scene selection module with image motion compensation capability, a full-aperture internal calibration source, a large-aperture Michelson interferometer, a three-element all reflective telescope, a cooled aft optics module, a multiple-stage passive cooler, and an attached electronics assembly.

The interferometer uses a flat-mirror Michelson configuration equipped with a dynamic alignment system to minimize misalignments within the interferometer and has a maximum optical path difference of ±0.8 cm. Each of the three spectral bands (longwave, midwave, and shortwave) uses 3 x 3 detector arrays to provide 14 km fields of view from 833 km altitude.

CrIS Sensor Features

- Large 8 cm Clear Aperture
- Three Spectral Bands
- 3x3 FOVs at 14 km Diameter
- Photovoltaic Detectors in All 3 Bands
- 4-Stage Passive Detector Cooler
- Plane-Mirror Interferometer With DA
- Internal Spectral Calibration
- Deep-Cavity Internal Calibration Target
- Modular Construction

Physical Requirements	
Volume	80 x 47 x 56 cm
Mass	< 98 kg
Power	< 95 W
Data Rate	< 1.5 Mbps

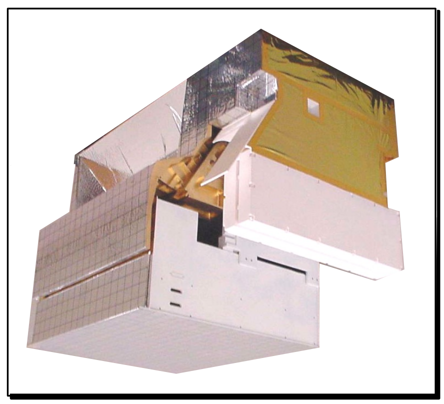


Figure 1: The Cross-track Infrared Sounder (CrIS) (Glumb; Predina 2002).

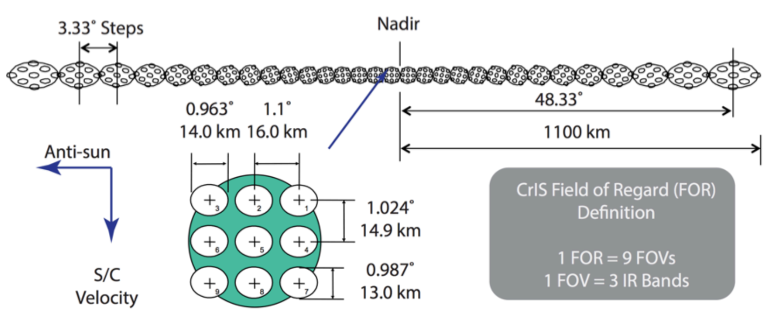


Figure 2: CrIS cross-track scanning, field of regard (FOR), and field of view (FOV) geometry.

3. THE SCANNING HIGH-RESOLUTION INTERFEROMETER SOUNDER (S-HIS)

The S-HIS (Figure 3) is an advanced version of the HIS NASA ER-2 instrument. The S-HIS was initially designed to fly on an unmanned aircraft vehicle (UAV) with limited payload capacity. This drove it to be small, lightweight, and modular, with low power consumption. It was developed between 1996 and 1998 at the University of Wisconsin Space Science and Engineering Center with the combined support of the US DOE, NASA, and the NPOESS Integrated

Program Office. Its design and calibration techniques have matured from experience with the HIS and with the ground based Atmospheric Emitted Radiance Interferometer (AERI) instruments developed for the DOE Atmospheric Radiation Measurement (ARM) program. The nadir-only spatial sampling of the original HIS was replaced by programmable cross-track coverage with similar sized footprints. The S-HIS is also smaller, more robust, and easier to operate. Since 1998, the S-HIS has flown in 30 field campaigns and has proven to be very dependable, effective, and highly accurate (Taylor et al. 2005). It has flown on the NASA ER-2, the NASA DC-8, the Scaled Composites Proteus, the NASA WB-57, and most recently, the NASA Global Hawk. On the Proteus and WB-57 aircraft, an upward (zenith) view is available, providing a means for further calibration verification analysis and upper atmosphere studies.

The S-HIS employs a customized commercial dynamically aligned plane-mirror interferometer (DA5 from Bomem Inc., Quebec, Canada). The Michelson mirror is voice coil driven with a support mechanism that was designed and built at UW-SSEC to make use of a linear bearing approach to minimize vibration-induced tilt errors. The spectral characteristics of the measurements are very well known and stable because of the use of a HeNe laser to control optical delay sampling. A 1/4-wave quadrature system is used to assure that no samples are dropped or miscounted. The laser is also used to maintain alignment via the dynamic alignment (DA) servo. Any residual misalignments are measured as a diagnostic and used for operational tilt correction during data processing.

To achieve the required noise performance, the spectral coverage is divided into three bands with separate detectors for each band (two photoconductive HgCdTe and one InSb). Together, the three detector bands provide continuous spectral coverage from 3.3 to 16.7 μm at 0.5 cm^{-1} resolution, with overlap between the adjacent bands that is useful for instrument diagnostics. Due to the initial design constraints on size, the S-HIS instrument uses a novel detector configuration with the shortwave detector positioned in front of the side-by-side longwave and midwave detectors that share the available aperture. The bands use a common field stop, ensuring accurate spatial co-alignment. This arrangement allows cooling to be provided by a single mechanical cooler and eliminates the need for dichroic beamsplitters. The cooler is a 0.6 W, split-cycle Stirling cooler from Cobham.

The flight calibration assembly consists of a 45° scene mirror, two calibration sources, the scene mirror motor, and front-end hex structure. The S-HIS 45° scene mirror allows the instrument to image using cross-track scanning. It executes a sequence consisting of multiple views of the earth, a zenith view (when available), and the two calibration sources, one at ambient and another controlled to a fixed temperature (typically 305 K in flight). The S-HIS calibration techniques achieve the high radiometric accuracy needed for atmospheric state retrieval, spectroscopic applications and calibration validation activities.

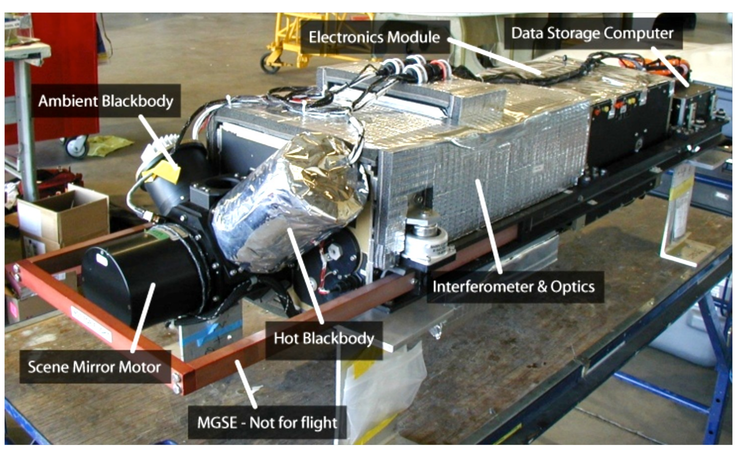


Figure 3: The Scanning High-resolution Interferometer Scanner (S-HIS).

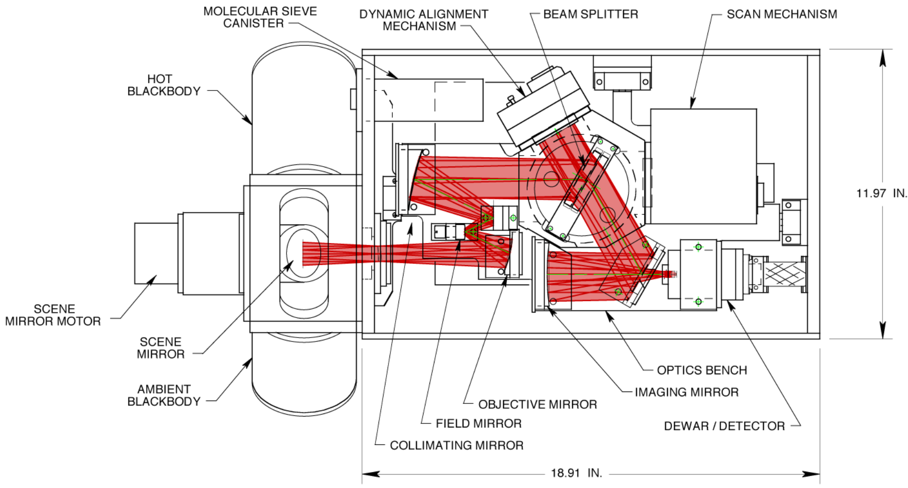


Figure 4: Diagram of the S-HIS interferometer module and flight calibrator assembly viewed from the nadir perspective. The Zemax prescribed IR beams are shown, and have been omitted from the figure between the beamsplitter and the Michelson mirror.

4. RADIOMETRIC CALIBRATION AND UNCERTAINTY

Radiometric Uncertainty (RU) characterization of a sensor dataset describes the various sources of calibration uncertainty and their relevant dependencies. For infrared spectrometers, common examples include the uncertainty in the knowledge of the calibration blackbody temperature and resulting radiance uncertainty as a function of scene temperature, or, the uncertainties in the degree of polarization of a scan mirror and resulting radiance uncertainties as a function of wavelength, scan angle, and scene temperature. RU characterization is required for various applications of the dataset and is particularly important for intercalibration studies, for sensors being intercalibrated as well as sensors serving as a reference. For high spectral resolution infrared sounders, RU estimates have been provided recently for the Atmospheric Infrared Sounder (AIRS) (Pagano et al. 2013) and for the Cross-track Infrared Sounder (CrIS) on Suomi-NPP (Tobin et al. 2013). The CrIS RU contributions and total RU for a typical clear sky Earth view spectrum, shown as 3-sigma brightness temperatures are shown in Figure 5 (Tobin et al. 2013).

For a wide range of scene temperatures, the calibration uncertainty (3-sigma) estimate for S-HIS is less than 0.2 K (Best; Revercomb 2005; Revercomb; Best 2005). The S-HIS RU contributions and total RU for the 2013-06-01 SNPP underpass (S-HIS on the NASA ER-2), shown as 3-sigma brightness temperatures are shown in Figure 6.

The S-HIS radiometric calibration, calibration verification, and traceability can be divided into four primary phases:

- Pre-integration calibration of on-board blackbody references at subsystem level;
- Pre- and post-deployment end-to-end calibration verification;
- Instrument calibration during flight using two on-board calibration blackbody references;
- Periodic end-to-end radiance evaluations under flight-like conditions with NIST transfer sensors.

Pre-integration calibration of the on-board blackbody references is typically completed on the order of every 5 years. The S-HIS thermistor readout electronics calibration is verified to within 5 mK using a series of 6 reference resistors, that are each calibrated to an accuracy of better than 0.5 mK (3-sigma) equivalent temperature, using a Fluke 8508A DMM. The S-HIS On-Board Calibration Blackbody thermistors are calibrated at 10 temperatures over the range from -60 °C to 60 °C. These tests are done in a controlled isothermal environment using a NIST traceable temperature probe that is calibrated at Hart Scientific to an accuracy of 5 mK (3-sigma). Following these tests the On-Board Calibration Blackbodies and Readout Electronics are integrated to the S-HIS Instrument.

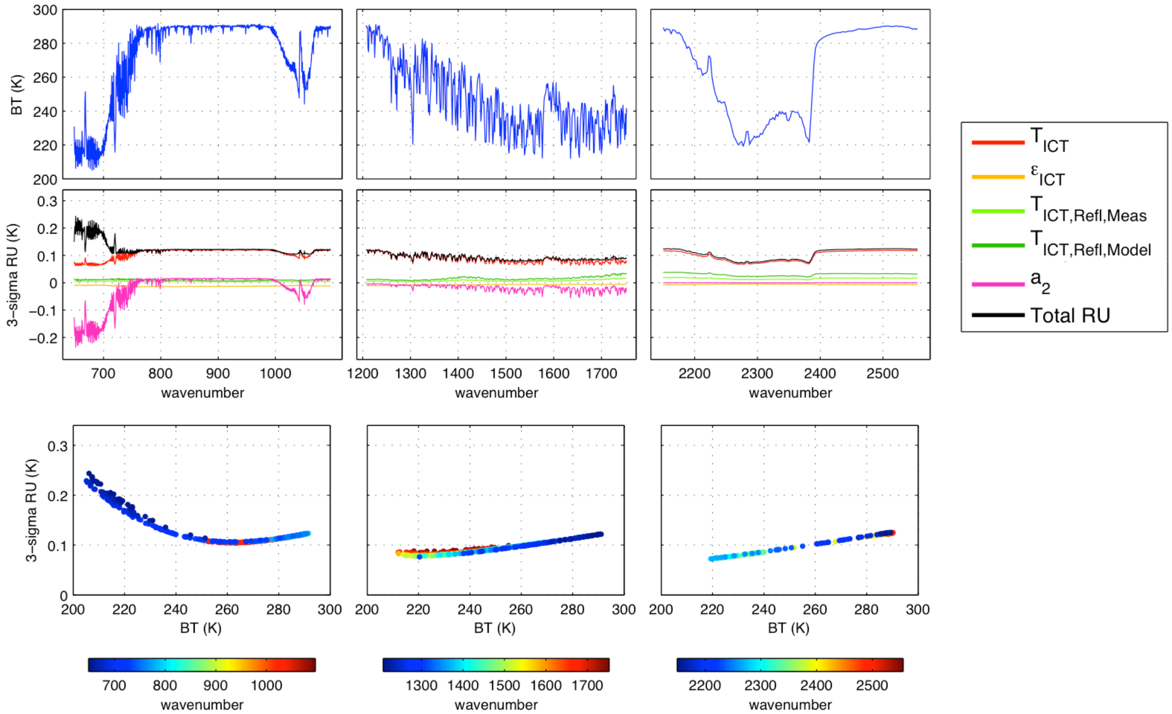


Figure 5: CrIS RU contributions and total RU for a typical clear sky Earth view spectrum, shown as 3-sigma brightness temperatures, for the CrIS longwave (left), midwave (middle) and shortwave (right) spectral bands.

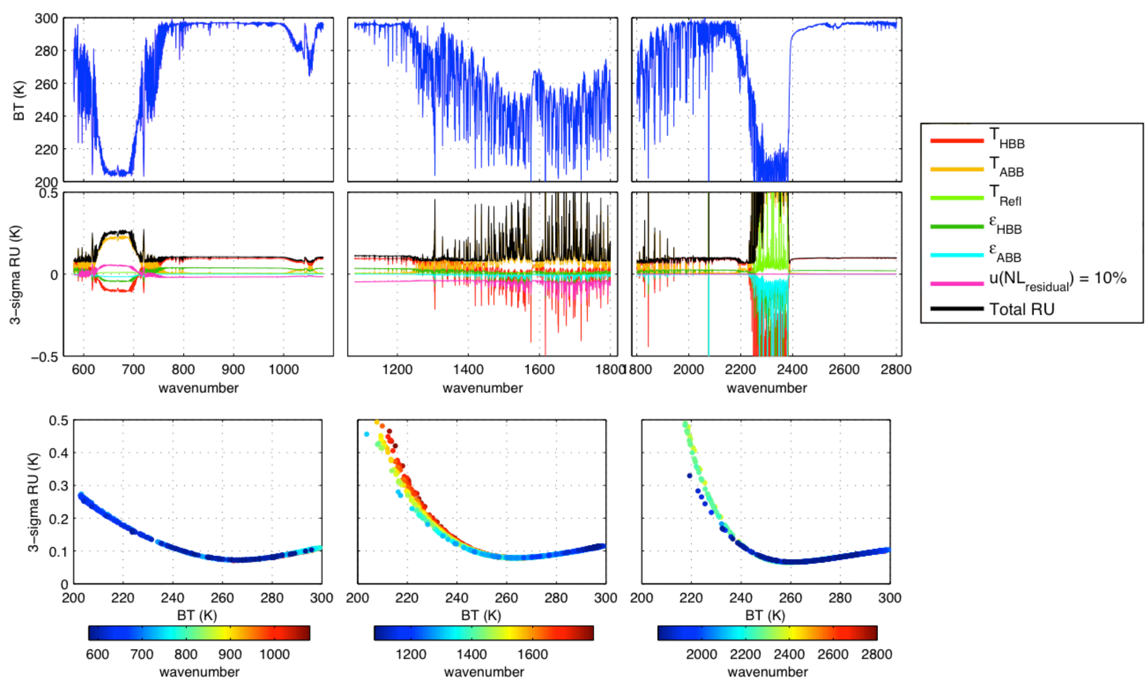


Figure 6: S-HIS brightness temperature spectra, RU contributions and total RU, for flight conditions encountered during the SNPP overpass on 2013-06-01 (S-HIS on the ER-2) and shown as 3-sigma brightness temperatures for the S-HIS longwave (left), midwave (middle), and shortwave (right) spectral bands. The impact of not having a space view for the cold reference is evident in the RU for cold scene temperatures in the MW and SW bands.

Results from the blackbody calibration conducted in the spring of 2012 show no significant change in the key temperature ranges used from the last major blackbody calibration (2004); less than 25 mK change for the ABB, and less than 5 mK for the HBB. It is noteworthy that the duration between tests (2004 and 2012) in this case exceeds the preferred 5-year interval between tests, but the results confirm insignificant change in blackbody thermometry in this 8-year period.

Prior to and after each field campaign, end-to-end calibration verification is performed. End-to-end calibration verification is conducted using a variable temperature blackbody at the zenith view and an ice bath blackbody at the nadir view. Radiances measured by the S-HIS instrument are compared to those calculated for the verification blackbodies, based on the measured cavity temperature, knowledge of the emissivity, and measurements of the background temperature. The variable temperature blackbody used for S-HIS calibration validation has its heritage rooted in the Atmospheric Emitted Radiance Interferometer (AERI) instrument (Knuteson et al. 2004a, 2004b). These blackbodies have had their emissivity verified at NIST to within 0.001 using three methods: the Complete Hemispherical Infrared Laser-based Reflectometer (CHILR); the Thermal Infrared Transfer Radiometer (TXR); and the Advanced Infrared Radiometry and Imaging Facility (AIRI). The ice bath blackbody is geometrically similar to the AERI Blackbody, and is coated with the same paint.

The pre- and post-mission end-to-end calibration verification tests show agreement within the established instrument 3-sigma uncertainty (Figure 7 and Figure 8, respectively).

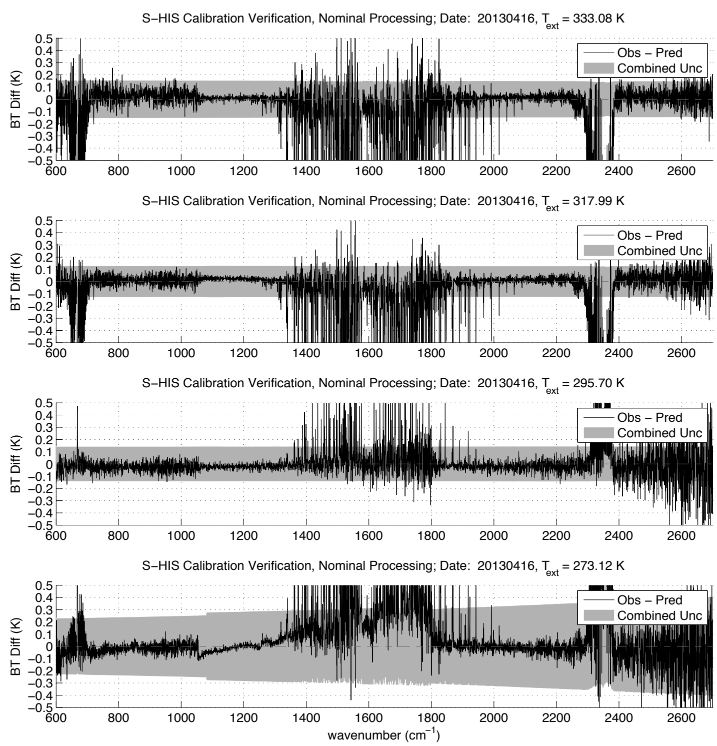


Figure 7: Pre-mission end-to-end calibration verification brightness temperature residuals. Calibration verification target temperatures, from top to bottom panel, are 333.08K, 317.99K, 295.70K, and 273.12K.

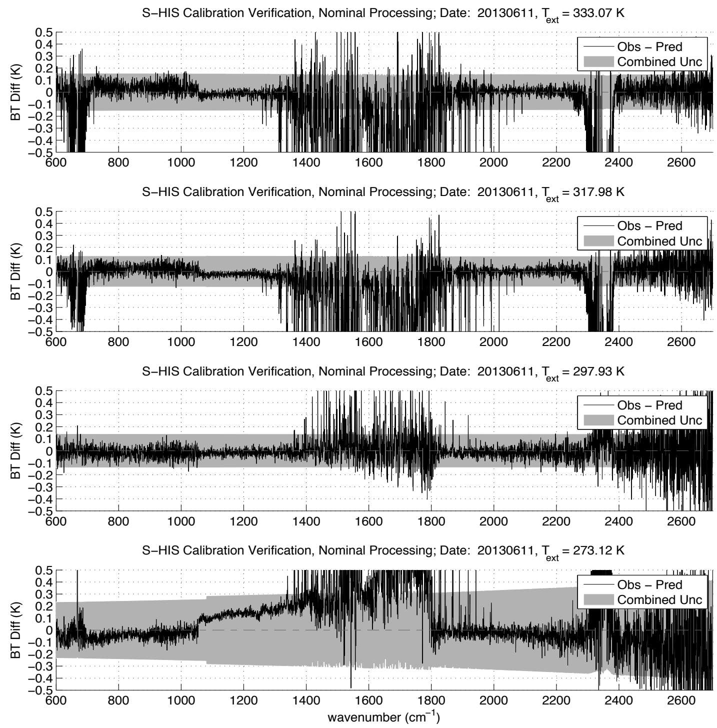
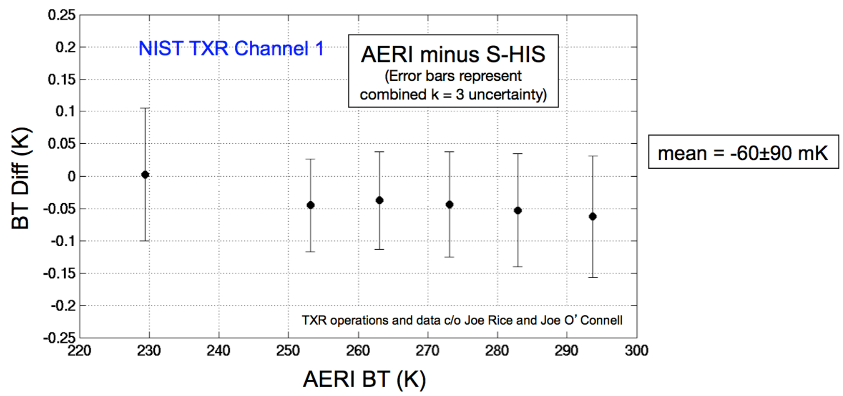


Figure 8: Post-mission end-to-end calibration verification brightness temperature residuals. Calibration verification target temperatures, from top to bottom panel, are 333.07K, 317.98K, 297.93K, and 273.12K.

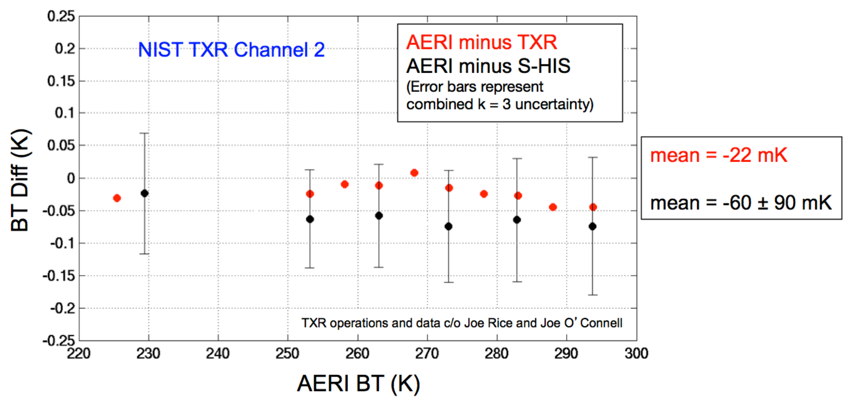
During flight, onboard blackbody reference spectra, used for calibration of the S-HIS Earth scene measurements, are collected several times per minute. The S-HIS Ambient Blackbody (ABB) runs at the pod ambient temperature (between 218K and 245K, depending on the local ambient environment); and the Hot Blackbody (HBB) is typically heated to 305K.

UW-SSEC experience with the S-HIS has led to a more complete understanding of issues with absolute calibration. Tests with the NIST Thermal Infrared Transfer Radiometer (TXR) solidly confirm the calibration uncertainty estimates. To verify the S-HIS calibration accuracy and provide direct NIST traceability of the S-HIS radiance observations, laboratory tests of the S-HIS and the NIST TXR were conducted using a thermal chamber to simulate flight temperatures for the S-HIS instrument. Two basic tests were conducted: (1) comparison of radiances measured by the S-HIS to those from the TXR, and (2) measurement of the reflectivity of a UW-SSEC blackbody by using the TXR as a stable detector (Best et al. 2007a; Best et al. 2007b; Taylor et al. 2007a; Taylor et al. 2008; Taylor et al. 2007b).

The radiance comparison involved the S-HIS and the TXR each observing a highly stable (and accurate) Atmospheric Emitted Radiance Interferometer (AERI) blackbody over a wide range of temperatures (227 to 290 K). The test results showed mean agreement between (1) predicted AERI blackbody radiance and the S-HIS NIST TXR Channel 2 equivalent spectral band of 60 ± 90 mK, (2) predicted AERI blackbody radiance and NIST TXR channel 2 (10 µm) of -22 mK, (3) NIST TXR channel 2 and the S-HIS band equivalent of less than 40 mK, (4) predicted AERI BB radiance and the S-HIS NIST TXR channel 1 (5 µm) equivalent of 40±85 mK. Unfortunately, the NIST TXR uncertainty analysis for the tests, and final calibration of the NIST TXR 5 µm channel remain incomplete. Results are shown in Figure 9.



(a)



(b)

Figure 9: NIST TXR comparison results; (a) NIST TXR Channel 1 (5 µm) (b) NIST TXR Channel 2 (10 µm) (Best et al. 2007a; Best et al. 2007b; Taylor et al. 2007a; Taylor et al. 2008; Taylor et al. 2007b).

5. CRIS CALIBRATION VALIDATION USING THE S-HIS

The ability to accurately validate infrared spectral radiances measured from space by direct comparison with airborne spectrometer radiances was first demonstrated using the S-HIS aircraft instrument flown under the Atmospheric Infrared Sounder (AIRS) sensor on the NASA Aqua spacecraft in 2002. Subsequent AIRS calibration validation under-flights were completed in 2004 and 2006, providing successful comparisons that span a range of conditions, including arctic and tropical atmospheres, daytime and nighttime, and ocean and land surfaces (Tobin et al. 2004; Tobin et al. 2006). Similar comprehensive and successful calibration validation efforts have also been conducted with S-HIS for the MODIS sensors, the Tropospheric Emission Spectrometer (TES) (Revercomb et al. 2005; Sarkissian et al. 2005), and the MetOp Infrared Atmospheric Sounding Interferometer (IASI) (Revercomb et al. 2007). These results show brightness temperature differences that are often better than 0.1 K over much of the spectrum.

The first Suomi NPP airborne calibration validation campaign was conducted May 2013 with a primary objective of providing detailed validation of CrIS radiance observations and meteorological products. Eleven ER-2 under-flights of the Suomi NPP satellite were conducted during the mission (Figure 10).

Selection of the CrIS and S-HIS footprints included in the comparison must take into consideration the spatial and temporal collocation of the two sets of observations, the spatial uniformity of the scene, and measurement noise reduction provided by co-adding individual fields of view for each sensor. The best conditions for radiance validation of CrIS with S-HIS were encountered for the 2013-05-15, 2013-05-30, 2013-05-31, and 2013-06-01 flights. During each of these flights, the ER-2 flew a straight and level flight leg at ~20.0 km altitude (50 mbar) along the suborbital track of Suomi NPP. Brightness temperature maps (895 – 900 cm^{-1}) for these flights are shown in Figure 12. The use of spatially uniform scenes reduces differences due to collocation errors and also removes the need for exact representation of the S-HIS and CrIS footprints.

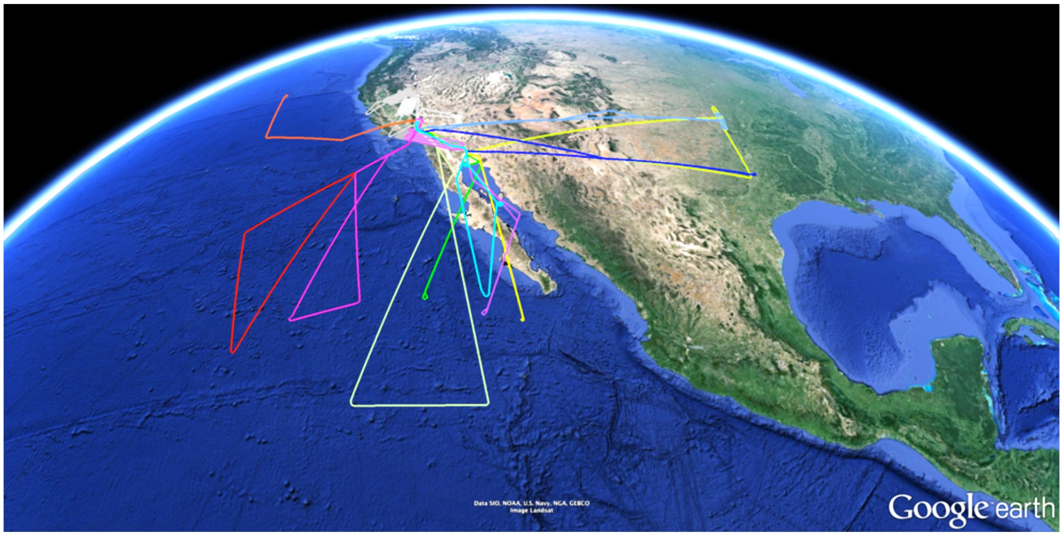


Figure 10: Eleven ER-2 under-flights of the Suomi NPP satellite were conducted during the 2013 airborne calibration validation campaign. Flights were based out of the NASA Dryden Airborne Operations Facility (DAOF) in Palmdale, CA.

The double observation minus calculation methodology described in detail by Tobin (Tobin et al. 2006), is used for the radiance intercalibration. The S-HIS and CrIS have different observation altitudes, footprint sizes, and spectral characteristics. As discussed previously, to avoid collocation errors when creating comparisons of CrIS and S-HIS observations, temporally and spatially coincident data collected under clear sky and spatially uniform conditions are typically used. However, despite a careful selection of such conditions, scene variations within the CrIS footprints can be significant. To ensure that both sensors are observing the same scene it is necessary to use multiple S-HIS footprints collected over a range of view angles to provide contiguous coverage of the larger CrIS footprints (Figure 11).

In addition, different observation altitudes and spectral characteristics of the two sensors need to be accounted for when comparing CrIS and S-HIS spectra. The technique selected for doing this is to make use of calculations that include the actual spectral and spatial characteristics of each instrument. The calculated spectra allow the observed minus calculated residual for each instrument to be compared, avoiding the first-order effects of the altitude and view angle differences. To further improve the comparison, the spectral resolutions of the CrIS and S-HIS instruments are made similar and differences in instrument line-shapes are accounted for.

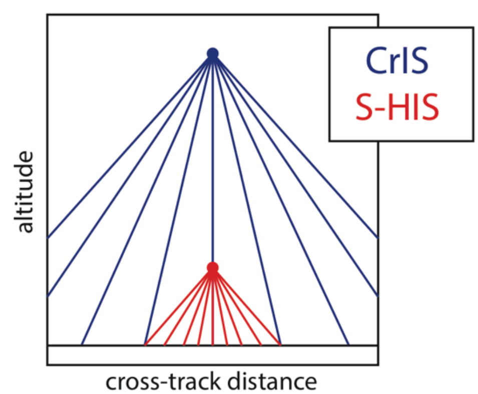


Figure 11: A diagram illustrating the differences between the CrIS (blue) and S-HIS (red) viewing geometries (not to scale).

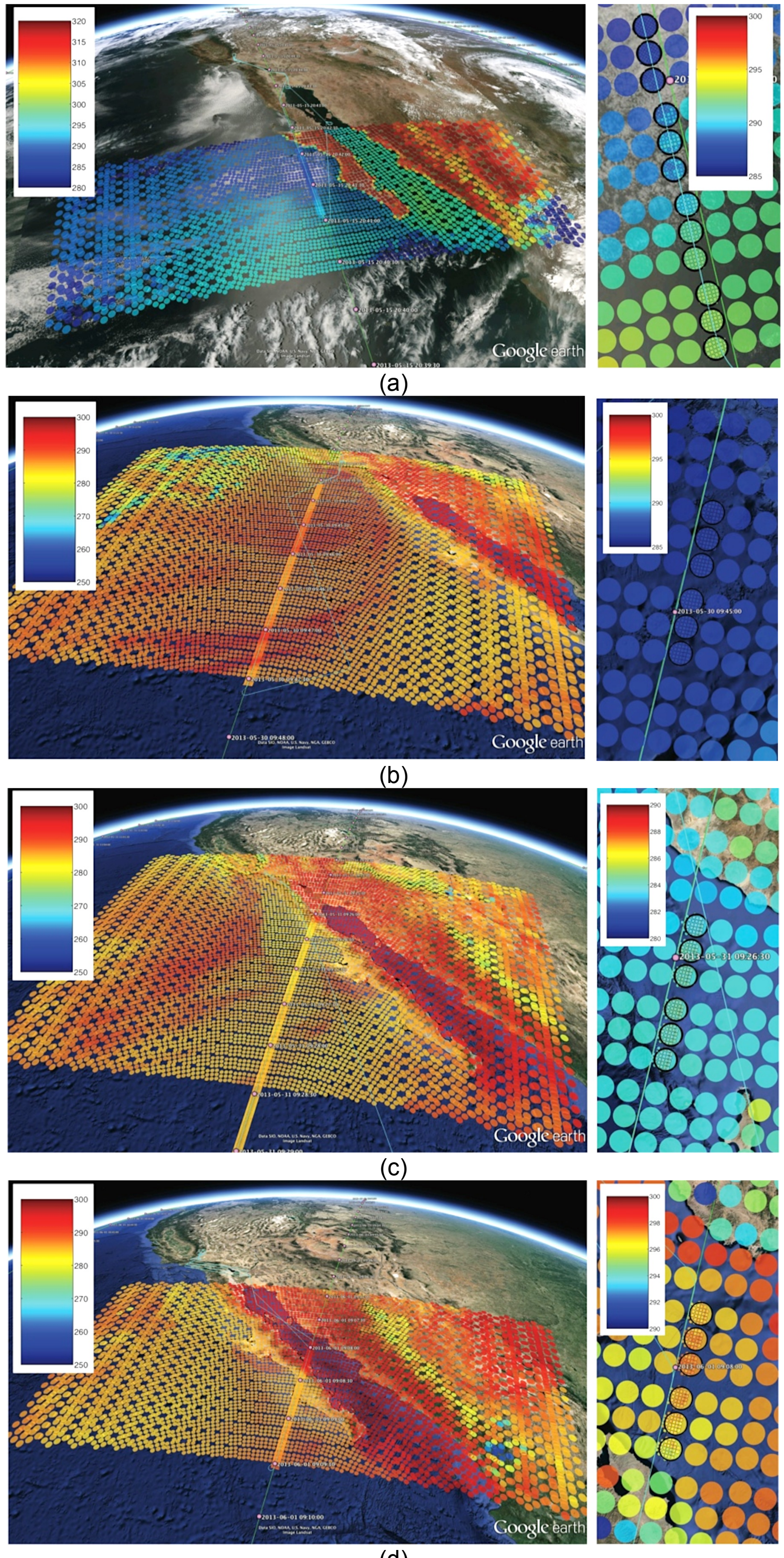


Figure 12: Brightness temperature images (895 – 900 cm^{-1} mean) for (a) 2013-05-15, (b) 2013-05-30, (c) 2013-05-31, and (d) 2013-06-01 SNPP under-flights. The images in the right column show the CrIS and S-HIS footprints over a large region surrounding each underpass, while the images on the left provide a closer view of the overpass region. FOVs used in the intercalibration are outlined in black. CrIS and S-HIS footprints have been approximated as circular in this figure.

The resulting residual difference in this method is essentially the difference between the CrIS and S-HIS respective observation minus calculation residuals, reduced to the lowest common spectral resolution for the two instruments. The radiance calculations for each instrument assume the same surface conditions, atmospheric state, and forward models. This results in systematic errors that are common to both sets of calculations, and to first order removes the fundamental effects of altitude and view angle differences. For the comparisons shown here, the monochromatic calculations are produced using the KCARTA radiative transfer model (DeSouza-Machado et al. 1997) with analysis fields (pressure, temperature, water vapor, ozone, surface pressure and temperature) from ECMWF and the Masuda et al. (Masuda et al. 1988) ocean emissivity. CrIS to S-HIS calibration intercalibration results are shown in Figure 14. The comparison presents the CrIS and S-HIS data reduced to the CrIS spectral resolution. As expected, in spectral regions where the satellite sensor is sensitive to significant contributions from above the aircraft altitude, large differences and radiometric uncertainties are observed. In the spectrally flat window regions the comparison shows excellent agreement, with residual differences less than 0.1K and well within the combined 3-sigma radiometric uncertainty.

The uncertainty associated with the double observation minus calculation methodology for the CrIS to S-HIS radiance intercalibration comparison, including the S-HIS radiometric uncertainty for a representative clear sky Earth spectrum, expressed as 3-sigma brightness temperatures is shown in Figure 13.

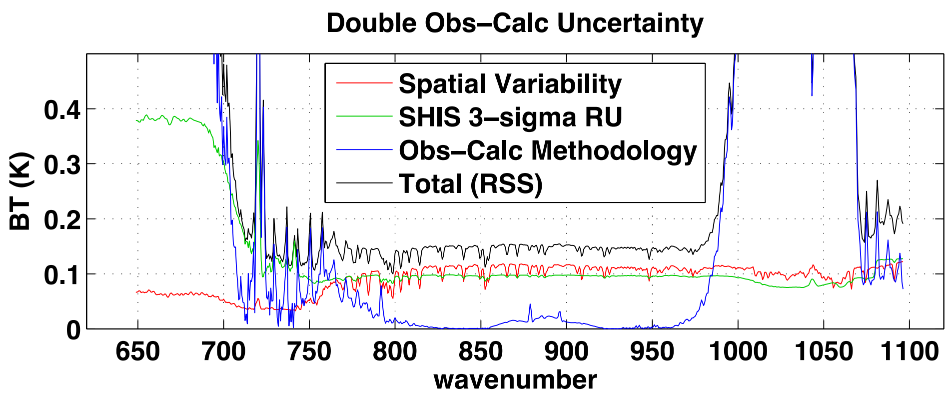
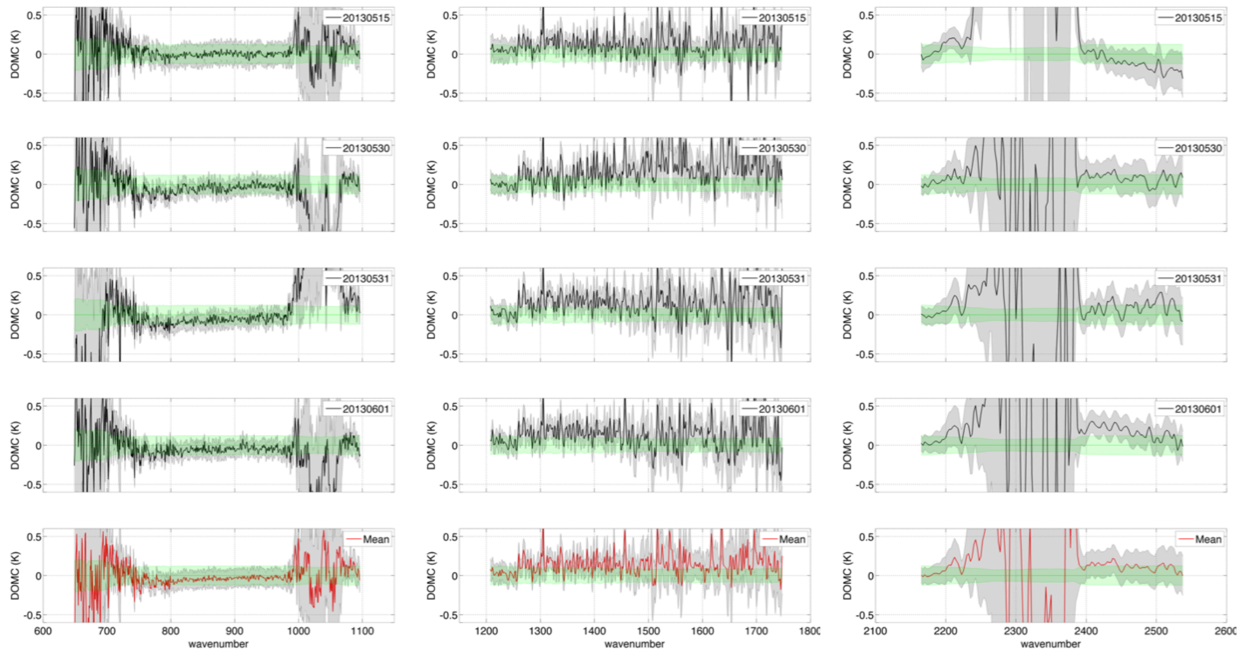


Figure 13: Radiometric uncertainty (3-sigma, expressed as brightness temperature) associated with the double observation minus calculation calibration intercalibration, including the S-HIS 3-sigma radiometric uncertainty for a representative clear sky Earth spectrum.



(a) (b) (c)

Figure 14: CrIS to S-HIS intercalibration results (expressed as brightness temperature) with 3-sigma radiometric uncertainty estimates; (a) CrIS LW, (b) CrIS MW, (c) CrIS SW. The results, ordered top to bottom panel represent 2013-05-15 (day), 2013-05-30 (night), 2013-05-31 (night), 2013-06-01 (night), and mean. The 2013-05-15 result is not included in the SW mean as the intercalibration is susceptible to contamination by unaccounted for observation angle dependent reflected solar radiance.

6. SUMMARY

The first Suomi NPP dedicated airborne calibration validation campaign was conducted May 2013 with a primary objective of providing detailed validation of CrIS radiance observations and meteorological products. During this calibration validation campaign, the NASA ER-2 aircraft instrument payload included the UW-SSEC Scanning-High resolution Interferometer Sounder (S-HIS), the NPOESS Atmospheric Sounder Testbed-Interferometer (NAST-I), the NPOESS Atmospheric Sounder Testbed-Microwave Spectrometer (NAST-M), the NASA MODIS/ASTER airborne simulator (MASTER), and the NASA JPL Airborne Visible / Infrared Imaging Spectrometer (AVIRIS).

Eleven ER-2 under-flights of the Suomi NPP satellite were conducted during the mission. The best conditions for radiance validation of CrIS with S-HIS were encountered for the 2013-05-15, 2013-05-30, 2013-05-31, and 2013-06-01 flights. During each of these flights, the ER-2 flew a straight and level flight leg at ~20.0 km altitude (50 mbar) along the suborbital track of Suomi NPP.

This paper has provided an overview of the radiometric calibration, calibration verification, and traceability of the S-HIS validation data. The S-HIS has proven to be a extremely well characterized and understood, carefully maintained, and accurately calibrated reference instrument with a well defined radiometric uncertainty and traceability path. A detailed intercalibration assessment between the CrIS and S-HIS instruments for four under-flights from the 2013 SNPP airborne calibration validation campaign have been completed and were presented herein. In the spectrally flat window regions the comparison shows excellent agreement, with residual differences less than 0.1K, and well within the combined radiometric uncertainty estimate. The radiometric uncertainty contributions from both instruments, along with the radiometric uncertainty contribution associated with the comparison methodology are a critical component of the intercalibration and have been included in the analysis and summary result.

Acknowledgements: We are pleased to recognize that the on-orbit calibration and validation of the Suomi NPP CrIS has been organized under the leadership of Dr. Yong Han and has included the efforts of several organizations. We would also like to thank Dr. William Smith Sr. and Dr. Allen Larar for supporting the flight planning and organization of the 2013 SNPP airborne calibration campaign.

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