Summary of Research Report

University of Wisconsin, Space Science and Engineering Center
Scanning High-resolution Interferometer Sounder (S-HIS) Participation in HS3

NASA Grant NNX10AV08G

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Introduction

This is the summary of research report for NASA Grant NNX10AV08G to the University of Wisconsin (UW) Space Science and Engineering Center (SSEC) for the Scanning High-resolution Interferometer Sounder (S-HIS) instrument and team participation in the NASA EV-1 Hurricane and Severe Storms Sentinel (HS3) project with the goal of enhancing our understanding of the processes that underlie hurricane intensity change in the Atlantic Ocean basin. Primary activities include:

(1) Support of S-HIS for NASA Global Hawk flights conducted during the HS3 campaign (range, transit, and science) and subsequent data analyses;
(2) Laboratory verification of S-HIS reference blackbody temperature calibration and pre-campaign and post-campaign testing of S-HIS performance;
(3) Development and optimization of architecture and software to implement real-time, near real-time, and long-term data handling, processing, and display for long duration Global Hawk flights;
(4) Further development and implementation of improved temperature, water vapor, and cloud retrieval capabilities; and
(5) Support HS3 Science Team teleconferences and the Science Team Meetings.

This report consists of a brief summary of each of these activities.

1 Support S-HIS for HS3 range, transit, and science flights and subsequent data analyses

The UW S-HIS team supported instrument integration onto NASA Global Hawk AV-6, as well as range, transit and science flight operations. Flights were conducted from 2011 through 2014.

1.1 2011 Test Flights

In 2011, the UW S-HIS team supported flight operations of the NASA AV-6 Global Hawk from the NASA Dryden flight facility in Southern California. Two long test flights were conducted with an instrument complement that included the hyperspectral infrared S-HIS sensor, the microwave HAMSR sensor, and dropsondes from the AVAPS system. Two flights were successfully conducted; a Pacific flight on 2011-09-09 which made a North/South transition along longitude 155W near Hawaii and a flight on 2011-09-14 from Dryden to the Gulf of Mexico for a dropsonde comparison with the NOAA G-4 aircraft. The S-HIS instrument successfully collected high quality data from take-off to landing for both flights, however the engineering data from the flight indicated that the instrument electronics and calibration blackbody were operating at or near the upper range of acceptable limits. This problem was identified as due to inadequate cooling in the Zone 25 instrument bay of the Global Hawk. Subsequently this problem has been successfully resolved by routing air from outside of the aircraft through a contained system in Zone 25. Refer to Section 1.2 for the details of the required instrument and aircraft modifications that were completed to resolve this issue.

Figure 1 through Figure 6 summarize the analyses of the S-HIS data products for the 2011-09-09 Pacific flight (presented at the May 2012 science team meeting). These figures illustrate the vertical resolving capability of the hyperspectral IR retrievals from the aircraft down to opaque cloud top. The performance in these test flights meets all the HS3 requirements for a successful mission.

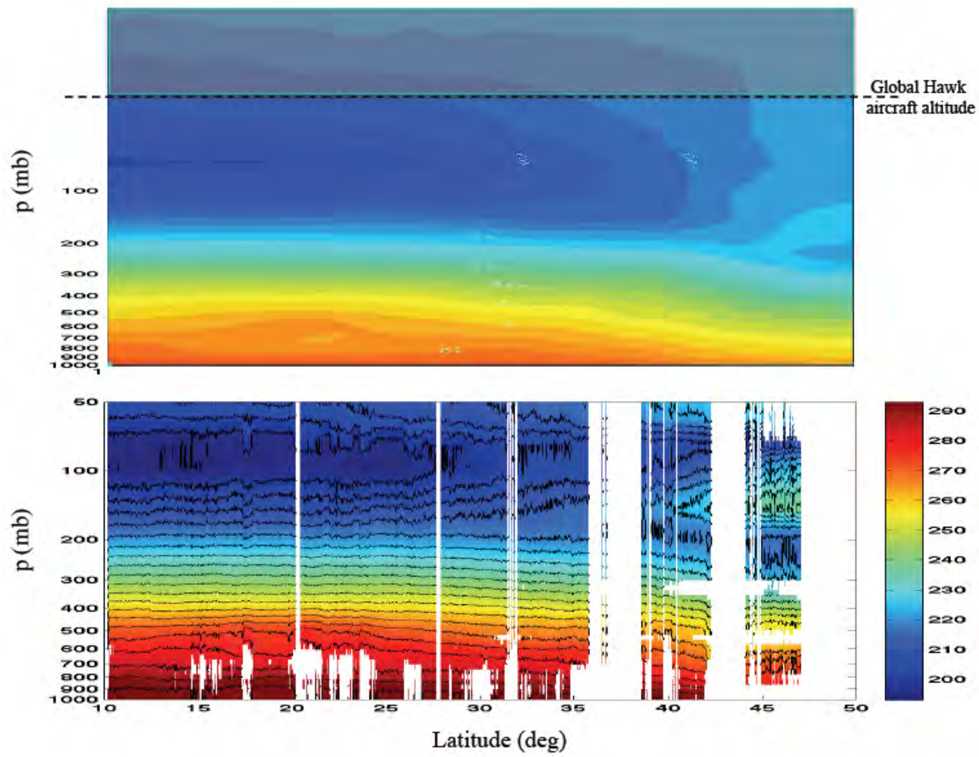

Figure 1: Vertical cross-section of GDAS NWP model (upper) and SHIS retrieval (lower) of atmospheric air temperature along longitude 155W on 2011-09-09 near Hawaii. The polar jet maximum is clearly defined in the S-HIS retrievals of temperature.

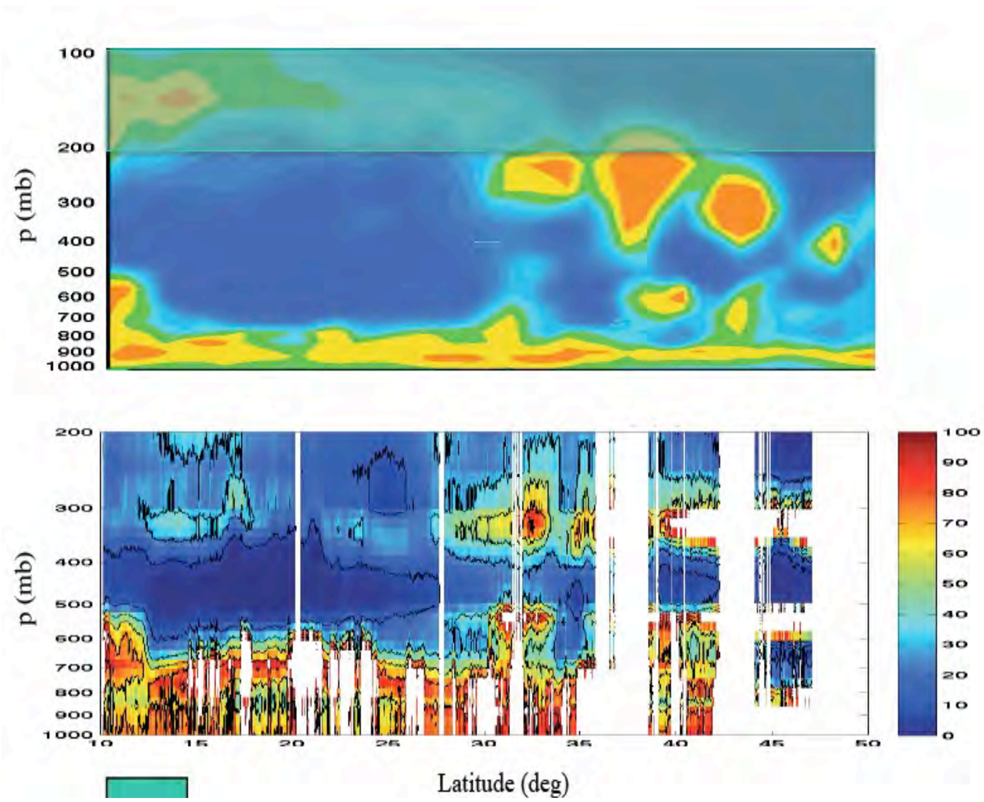

Figure 2: Vertical cross-section of GDAS NWP model (upper) and SHIS retrieval (lower) of atmospheric water vapor relative humidity along longitude 155W on 2011-09-09 in the Pacific passing near Hawaii. The S-HIS moisture layers illustrate the higher vertical resolution of the hyperspectral IR observations.

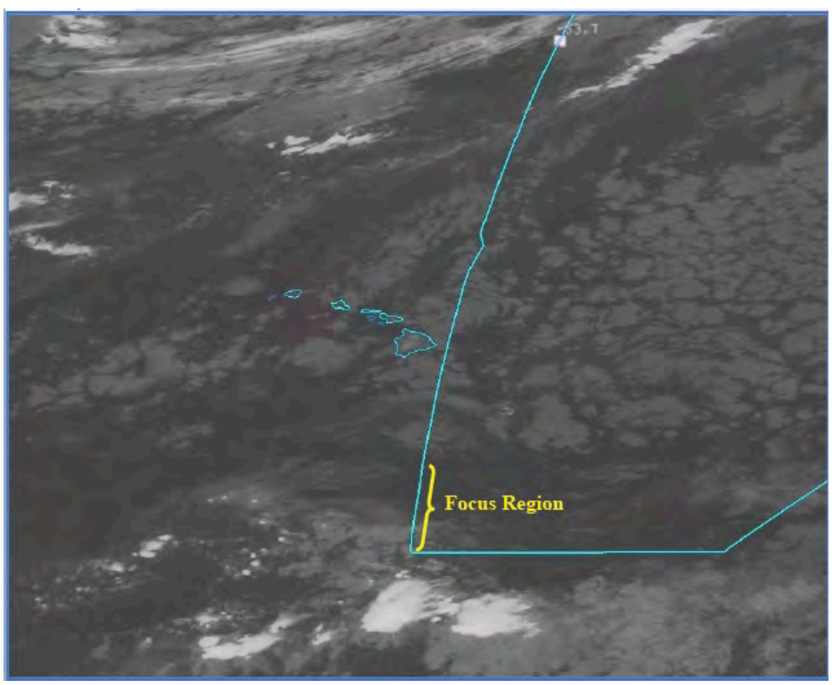

Figure 3: Global Hawk flight track for 2011-09-09 along longitude 155W. The focus region indicated marks the transition from sub-tropical to tropical air masses.

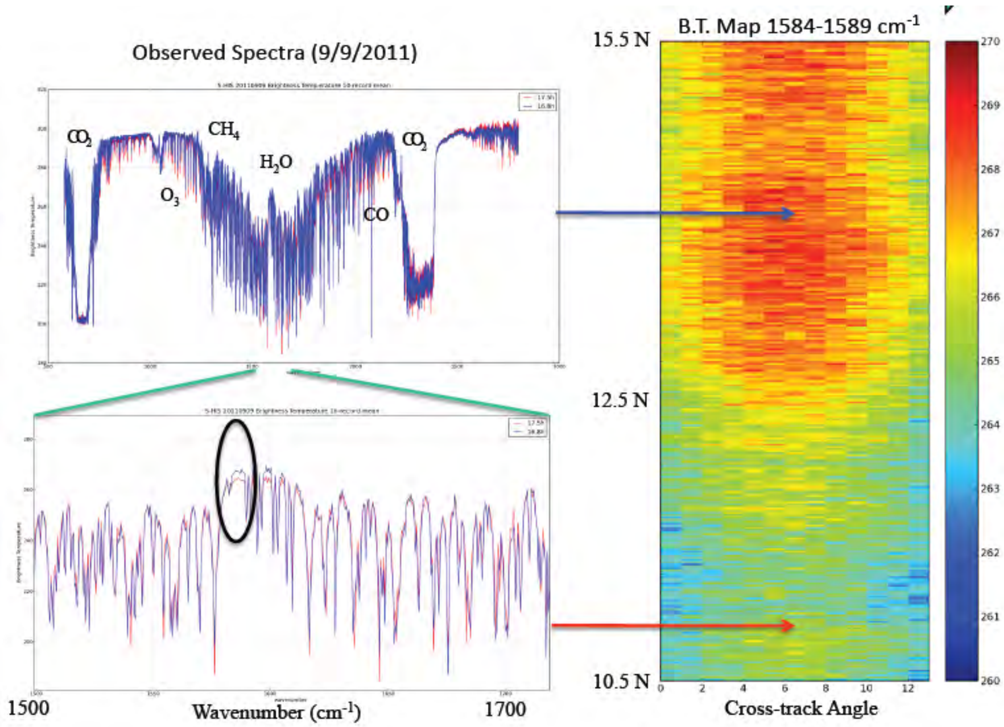

Figure 4: The transition between the subtropical and tropical air masses within the focus region is illustrated by observed brightness temperatures. The brightness temperature image is created using narrow spectral channels in the center of the 6.5 micron water vapor band and clearly shows a transition from dry (warm) to moist (cold).

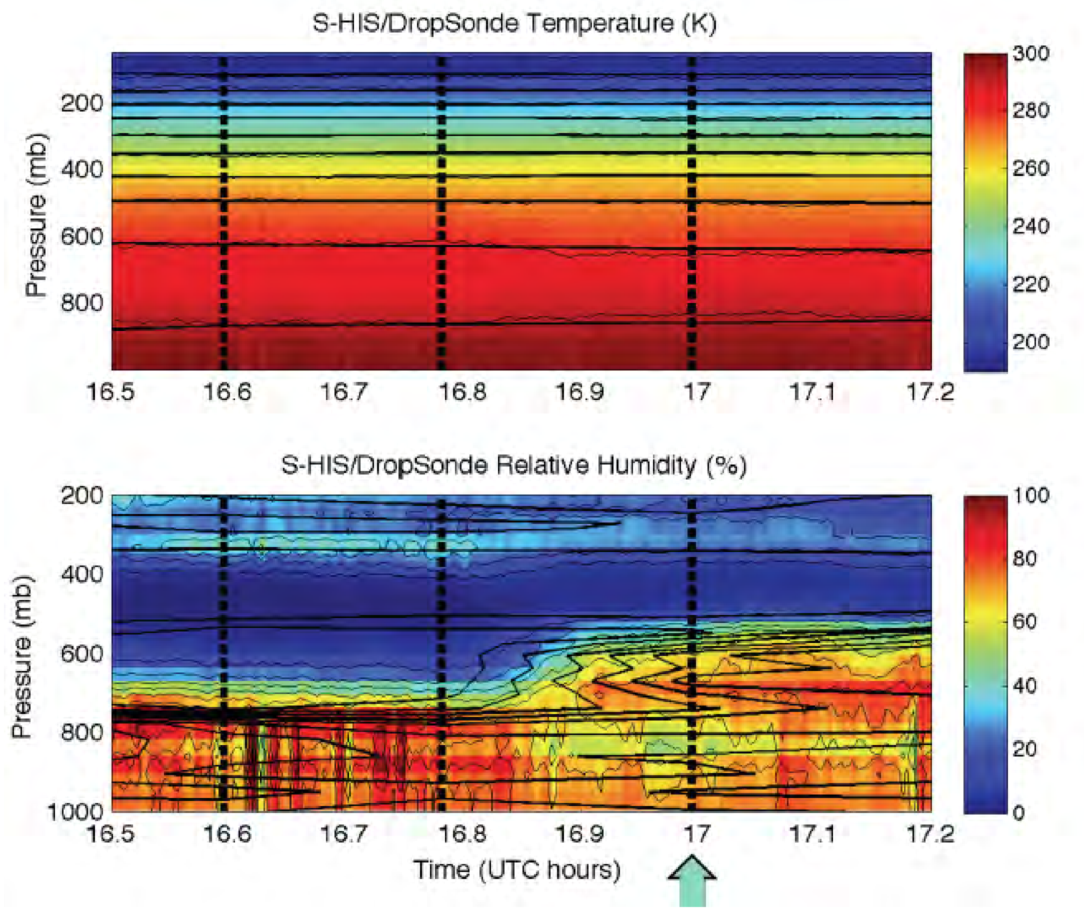

Figure 5: S-HIS retrievals of temperature and water vapor across the transition from sub-tropical to tropical air masses on 09 Sept 2011 in the Pacific Ocean south of Hawaii. The water vapor relative humidity cross section indicates an abrupt change in the height of the moist depth of the atmosphere. The solid black lines are contours created from the dropsonde profiles launched at times shown by the vertical dashed lines.

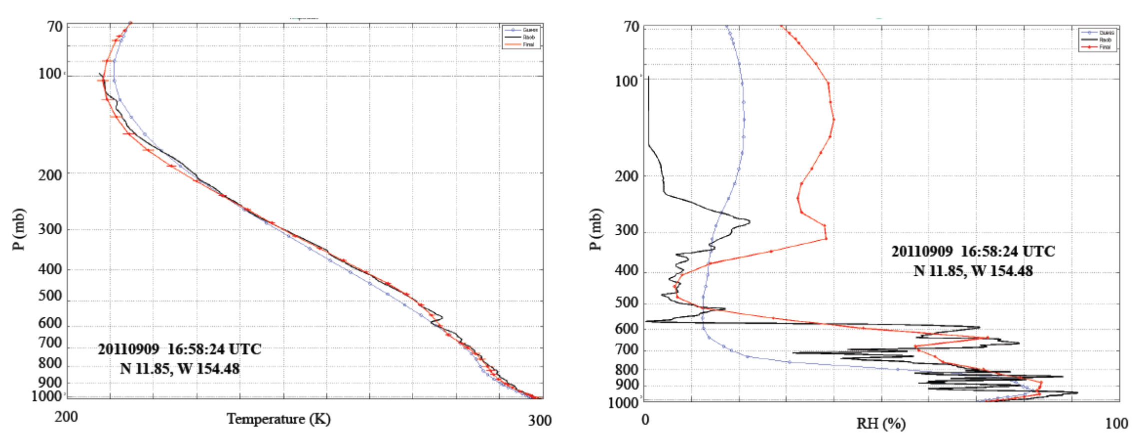

Figure 6: Comparison of the S-HIS retrieval (red) to a coincident AVAPS dropsonde from the Global Hawk in the moist region indicated in the previous figure. Good agreement is found below 400 mb but the sonde is clearly too dry above about 300 mb. Also shown (blue) is a tropical climatology profile.

1.2 Optimization of S-HIS interface to Global Hawk zone 25 thermal environment

For operation on high altitude airborne platforms (WB-57, ER-2, Proteus) S-HIS is typically mounted in an unpressurized wing pod and is exposed to the outside ambient pressure and temperature environment. It was originally planned that such a pod would be added to the Global Hawk for the S-HIS accommodation during the HS3 mission, but due to aerodynamic and funding considerations the wing-pod additions were not completed. As a result, the S-HIS was accommodated in the Global Hawk Zone 25 payload bay for all flights. The 2011 test flights showed temperatures in this location were warmer than desired for S-HIS at altitude, and close to the operational limit for some key S-HIS subsystems. To alleviate this issue for subsequent flights, the S-HIS team worked with NASA Dryden Flight Research Center (DFRC) engineers to provide a method to passively cool these subsystems at altitude while leaving the Zone 25 ambient temperature unchanged for other instrumentation and aircraft equipment. A 3" diameter rigid tube that housed multiple heat exchangers was mounted directly to the S-HIS instrument. The rigid tube was plumbed via flexible tubing to inlet and outlet ports on the Global Hawk, allowing outside air to flow freely through the tube. Five flexible heat straps were used to thermally couple key areas on the S-HIS instrument to the heat exchangers within the 3" rigid tube. This provided a thermal path for the key S-HIS components in need of additional cooling to the cold air flow within the tube, while leaving the temperature of Zone 25 unchanged as desired by DFRC. The key areas on the S-HIS in need of cooling below the Zone 25 ambient temperature are the ambient blackbody (ABB), the Stirling cooler expander and compressor (within the interferometer enclosure), the electronics enclosure, and the data storage computer enclosure. Each of the unique thermal straps were designed by and fabricated at UW-SSEC. Table 1 shows key information for each strap and the anticipated flight temperatures that were predicted to result from the implementation of the new thermal scheme. The expected performance is based on an ambient instrument environment of -11 °C (based on experience from the 2011 flights), and an effective cooling air tube temperature of -50 °C.

Table 1: Key Thermal Strap Information with Predicted Performance

	ER-2 Source Temp (C)	ER-2 Enclosure Temp (C)	GH Source Temp (C)	GH Enclosure Temp (C)	Power Input (W)	Strap Length (in)	Number of strap wires	Strap wire gage	Wire Area (kcmil)	Strap Thermal R (K/W)	Strap Conducted Power (W)	Predicted GH Source Temp (C)	Predicted GH Enclosure Temp (C)
ABB	-48		-8.8	-8	0	2.5	3	6	26.3	4.2	0.5	-47	--
Compressor	-22	--	12	--	11.5	5	5	4	41.7	3.2	17	-1	--
Expander	-15	--	15	--	5.8	7.1	5	6	26.3	7.1	6.9	4	--
Electronics	0	-16	23	12	52	1.94	5	6	26.3	1.9	26	12	1
Computer	21	12	37	27	52	17.5	6	4	41.7	9.2	6.6	33	23

*Note predicted temps are based on GH pod temp of -11 C and cooling tube air temp of -50 C

Table 2 shows a comparison of relevant measured temperatures for the 2011 flights and the 2012 flights with implementation of the new thermal scheme.

Figure 7 and Figure 8 illustrate the heat straps and their connection to the 3" tube with internal heat exchangers. The left end of the tube is connected to a new forward inlet port of the Global Hawk (Zone 25), and the right end to a new outlet port.

Table 2: Comparison of relevant measured temperatures for the 2011 flights and the 2012 flights with implementation of the new thermal scheme (@~18km altitude, takeoff+12hrs). Note that Zone 25 temperature is approximately unchanged, as desired by DFRC.

Location	2011 Temperature Original Thermal Scheme [K]	2012 Temperature New Thermal Scheme [K]
Zone 25 Temperature	260K	258K
Ambient Blackbody	262K	242K
Cooler Compressor	285K	270K
Cooler Expander	287K	273K
Electronics (Science Processor)	300K	285K
Interferometer Electronics (SEK31, trim heaters with setpoint at 295K)	315K	295K
Data Storage Computer (PCI)	320K	310K

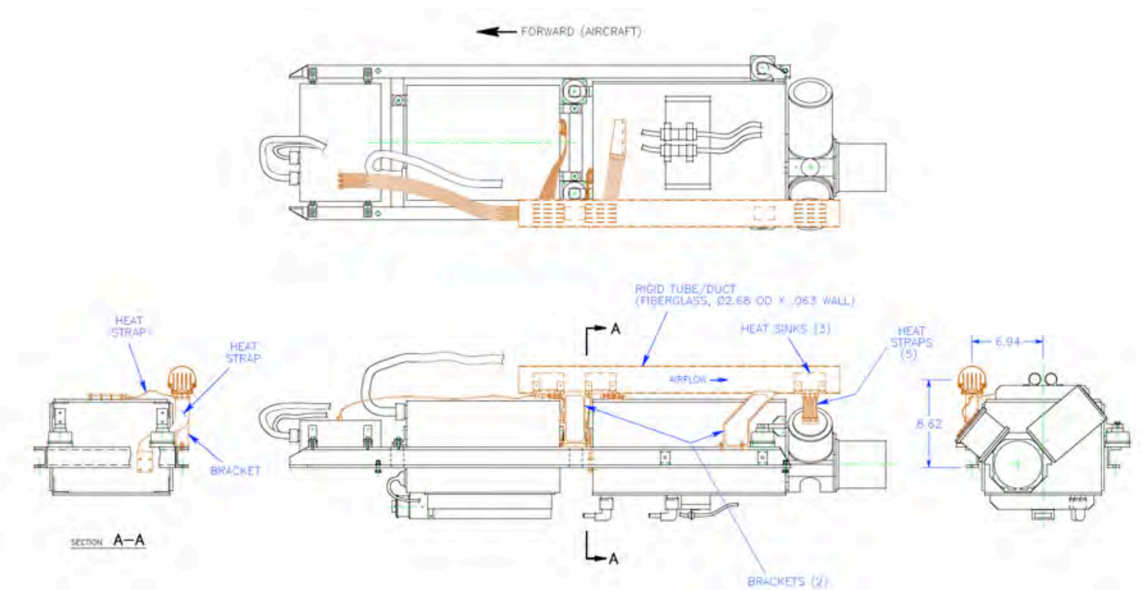

Figure 7: The new flexible heat straps that are connected to heat exchangers within the rigid tube. Outside air travels through the tube and helps reduce key temperatures in the S-HIS. The end-views at lower left and right show the heat exchangers mounted inside the flow tube.

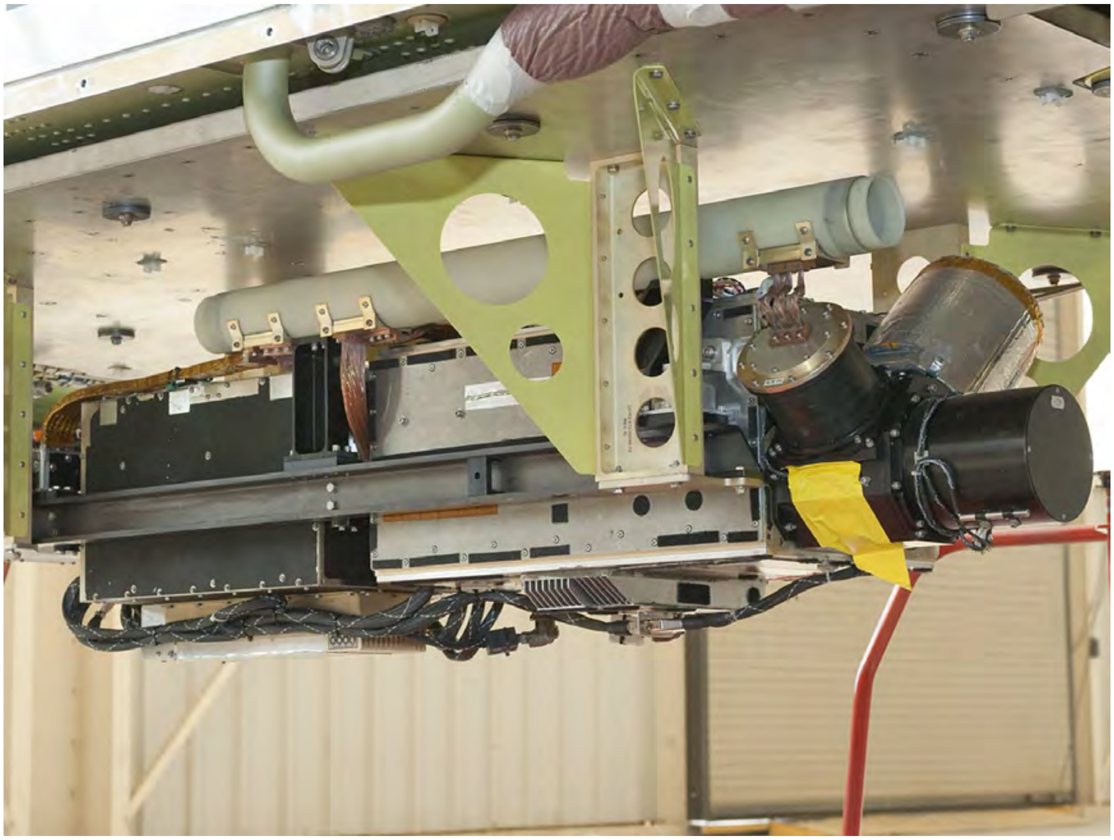

Figure 8: The S-HIS integrated to the Global Hawk with the heat straps (4 of 5 are visible) in place and connected to the rigid segment of the outside air flow tube.

1.3 2012 Range, Transit, and Science Flights

In 2012, the UW S-HIS team supported S-HIS and HS3 mission operations of the NASA AV-6 Global Hawk from the NASA Dryden flight facility in Southern California and the NASA Wallops Flight Facility in Virginia.

One range flight was completed on 2012-08-28 with the AV-6 HS3 payload (S-HIS hyperspectral infrared sounder, AVAPS dropsonde system, and the Cloud Physics Lidar). The S-HIS instrument successfully collected high quality data from take-off to landing for the range test flight and the optimization of the S-HIS Zone 25 thermal environment was verified.

The DFRC to WFF transit flight and Leslie over-flight was completed 2012-09-06, with return transit from WFF to DFRC on 2012-10-12. The S-HIS instrument successfully collected high quality data for the full duration of both transit flights.

AV-6 science flights were conducted from the NASA Wallops Flight Facility on 2012-09-11, 2012-09-14, 2012-09-19, 2012-09-22, 2012-09-26, and 2012-10-06.

- 2012-09-11: Tropical Storm Nadine flight #1
- 2012-09-14: Tropical Storm Nadine flight #2
- 2012-09-19: Tropical Storm Nadine flight #3
- 2012-09-22: Tropical Storm Nadine flight #4

- 2012-09-26: Tropical Storm Nadine flight #5
- 2012-10-06: SNPP/Aqua under-flight

The S-HIS instrument successfully collected high quality data from takeoff to landing for all science flights.

Representative examples of S-HIS retrieval products from the 2012 mission are provided in Figure 9 through Figure 11.

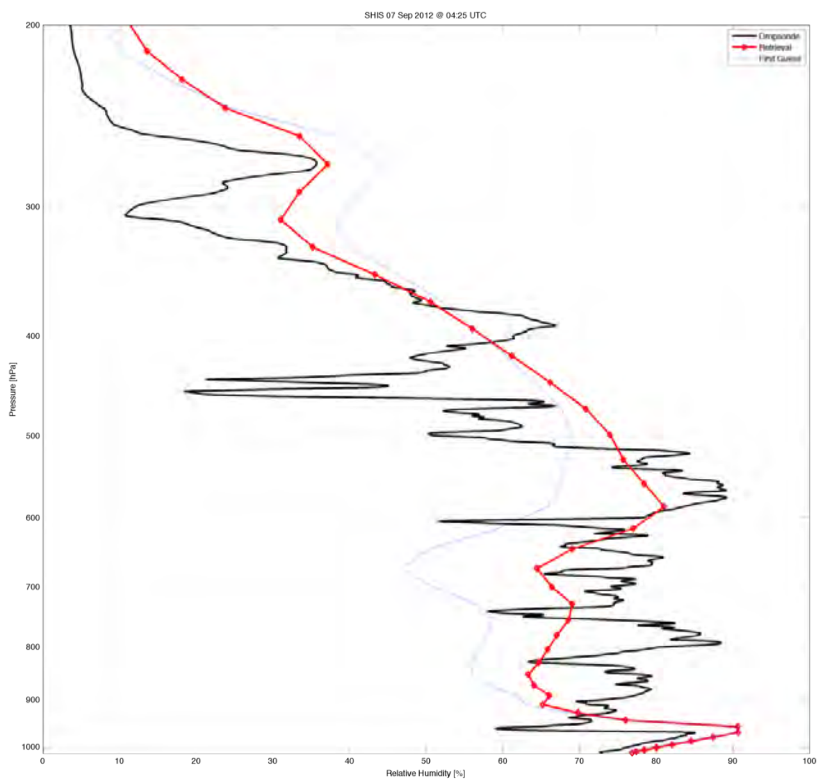

Figure 9: Sample RH Profile from Optimal Estimation with UWPhysRet compared to Dropsonde; 07 Sept 2012, 04:25

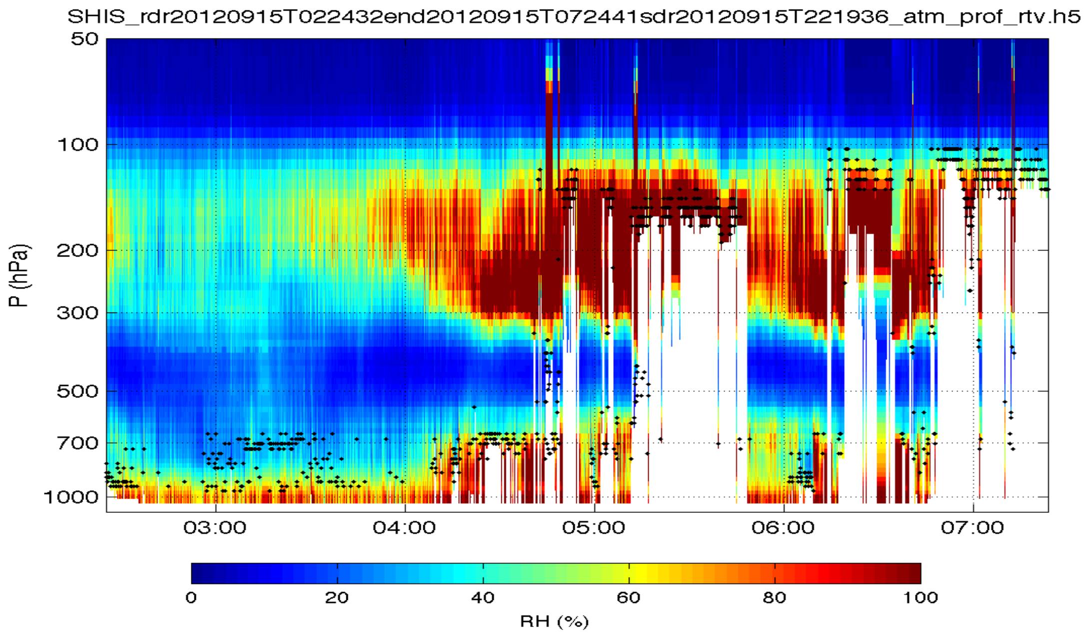

Figure 10: Relative Humidity cross-section; Dual Regression (DR) retrieval, 2012-09-15. The black dots indicate retrieved cloud tops.

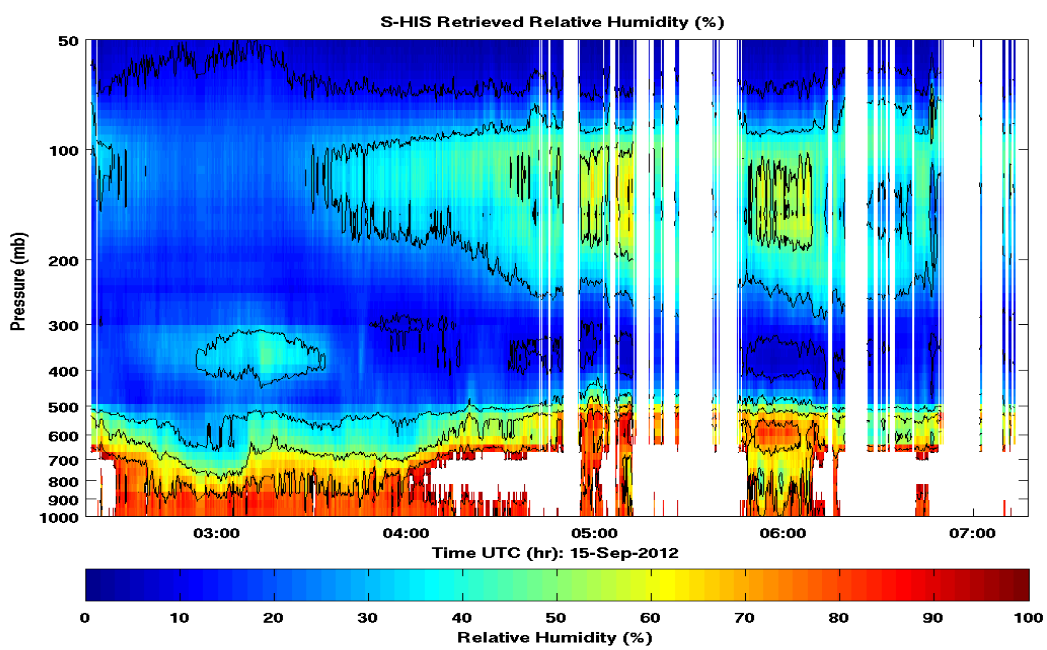

Figure 11: Relative Humidity cross-section; Optimal Estimation UWPHYSRET retrieval, 2012-09-15.

1.4 2013 Range, Transit, and Science Flights

In 2013, the UW S-HIS team supported S-HIS and HS3 mission operations of the NASA AV-6 Global Hawk from the NASA Dryden flight facility in Southern California and the NASA Wallops Flight Facility in Virginia.

One range flight was conducted from NASA Dryden on 2013-08-01 with the AV-6 HS3 payload (S-HIS hyperspectral infrared sounder, AVAPS dropsonde system, and the Cloud Physics Lidar). The S-HIS instrument successfully collected high quality data from take-off to landing for the range test flight.

The DFRC to WFF transit flight was completed 2013-08-06, with return transit from WFF to DFRC on 2012-09-26. The S-HIS instrument successfully collected high quality data for the full duration of both transit flights.

AV-6 science flights were conducted on 2013-08-20, 2013-08-24, 2013-08-29, 2013-09-04, 2013-09-07, 2013-09-16, and 2013-09-19.

- 2013-08-20: Former Tropical Storm Erin, Saharan Air Layer
- 2013-08-24: Saharan Air Layer
- 2013-08-29: Pre-Gabrielle, Saharan Air Layer
- 2013-09-04: Tropical Storm Gabrielle
- 2013-09-07: Tropical Storm Gabrielle
- 2013-09-16: Tropical Storm Humberto
- 2013-09-19: Pouch 37, Invest 95

The S-HIS instrument successfully collected high quality data from takeoff to landing for all science flights, with the exception of an instrument power cycle required during the 2013-09-04 flight. The power cycle resulted in a loss of S-HIS data for approximately 40 minutes, and the on-duty Mission Scientist was consulted such that the timing of the power cycle did not impact critical science data.

Representative examples of S-HIS retrieval and brightness temperature products for the 2013 flights are provided in Figure 12 through Figure 15.

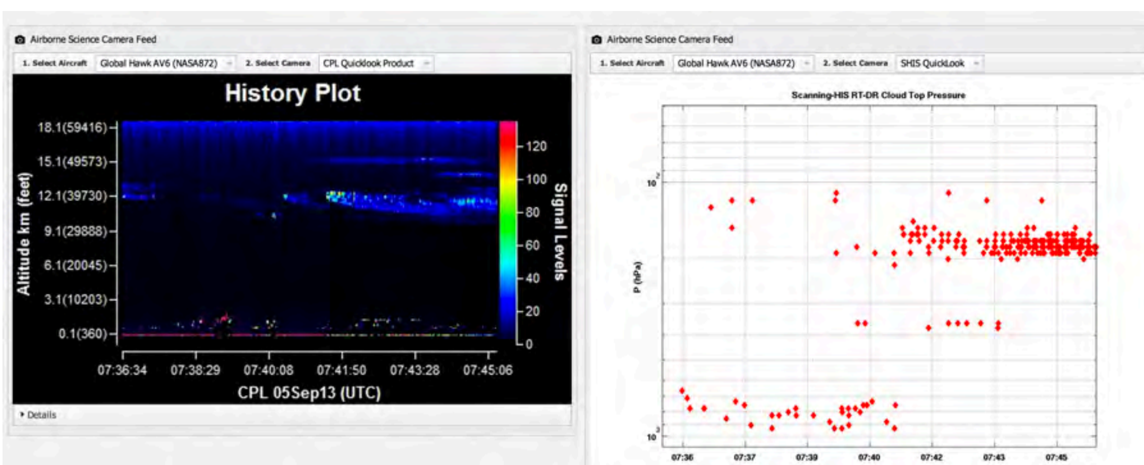

Figure 12: Comparison of CPL and S-HIS cloud top height real-time products (2014-09-04) delivered via NASA MTS.

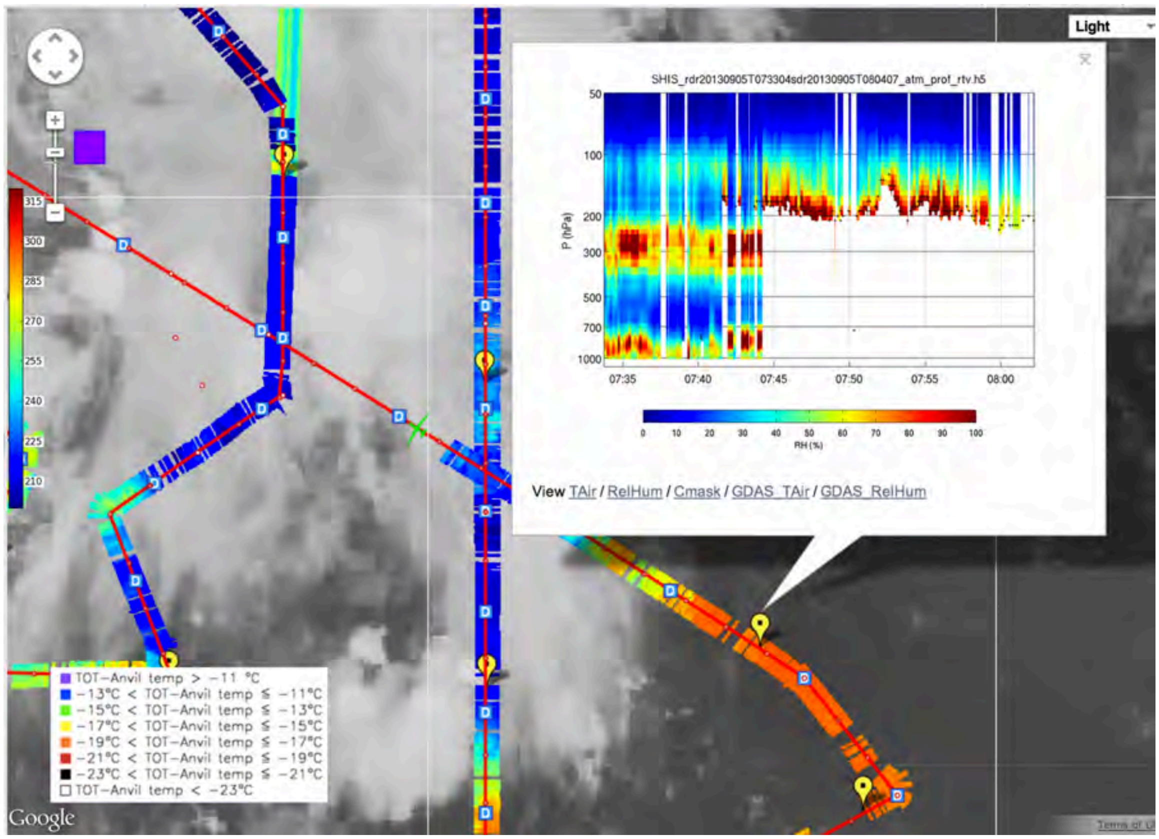

Figure 13: Corresponding 30 minute DR retrieval RH summary plot (2014-09-04) displayed in MTS.

Figure 14: A new data display showing time series of realtime S-HIS brightness temperatures was tested. 895-905 cm^{-1} (blue) and 690-700 cm^{-1} (red) channels are shown above (2013-09-16).

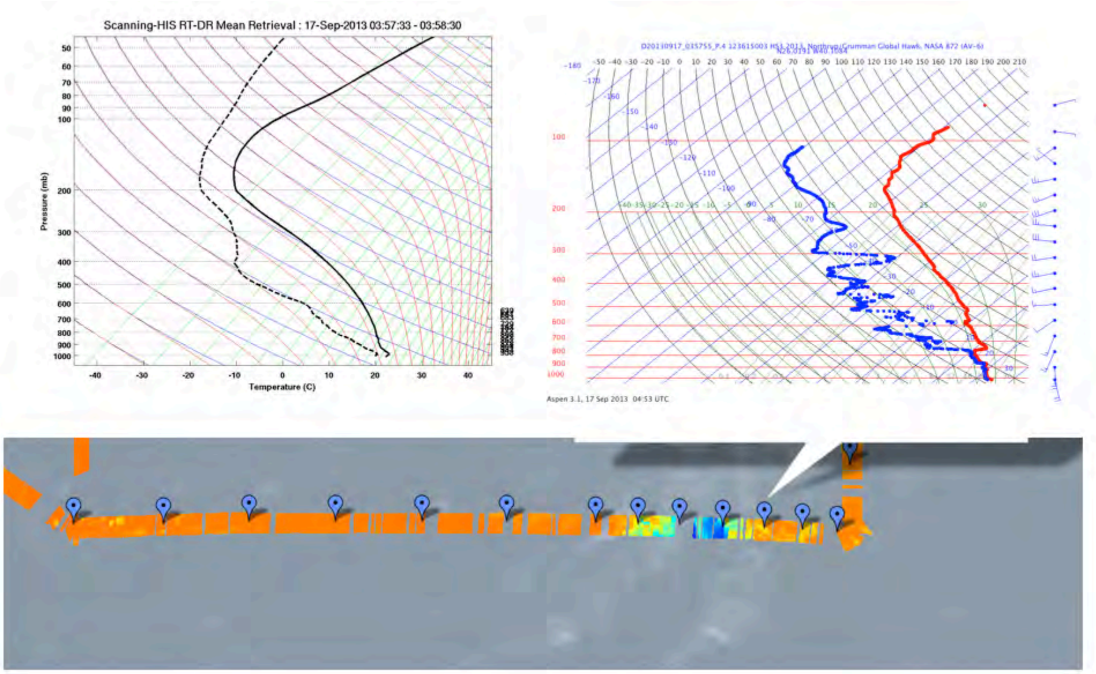

Figure 15: Relatively good agreement between SHIS temperature and moisture structure (left) with the dropsonde profiles (right). This comparison is in the SE corner of the flight where the SAL was encountered (2013-09-16).

1.5 2014 Range, Transit, and Science Flights

In 2014, the UW S-HIS team supported S-HIS and HS3 mission operations of the NASA AV-6 Global Hawk from the NASA Dryden flight facility in Southern California and the NASA Wallops Flight Facility in Virginia.

One range flight was conducted from NASA Dryden on 2014-08-06 with the AV-6 HS3 payload (S-HIS hyperspectral infrared sounder, AVAPS dropsonde system, and the Cloud Physics Lidar). The S-HIS instrument successfully collected high quality data from take-off to landing for the range test flight.

The DFRC to WFF transit flight was completed 2014-08-26, with return transit from WFF to DFRC on 2014-09-30. Both flights were combined science and transit flights. The S-HIS instrument successfully collected high quality data from takeoff to landing for all science flights and transit flights, with the exception of planned instrument power cycles 45 – 60 minutes prior to science waypoint 1 during the 2014-08-28, 2014-09-05, 2014-09-11, 2014-09-14, 2014-09-16, and 2014-09-22 flights. The power cycle was implemented to address concerns with S-HIS Stirling Cooler behavior, and resulted in no loss of science data.

- 2014-08-26: Combined transit / science flight
- 2014-08-28: Hurricane Cristobal
- 2014-09-02: Tropical Storm Dolly

- 2014-09-05: Invest 90, Pouch 27
- 2014-09-11: Tropical Storm Edouard
- 2014-09-14: Hurricane Edouard
- 2014-09-16: Hurricane Edouard
- 2014-09-18: Tropical Storm Edouard
- 2014-09-22: MDR flight #1 (SAL)
- 2014-09-28: MDR flight #2 (Pouch 41, Pouch 42, SAL)
- 2014-09-30: NOAA G-IV intercomparison over the Gulf of Mexico

Representative examples of S-HIS retrieval and brightness temperature products for the 2014 flights are provided in Figure 16 through Figure 20.

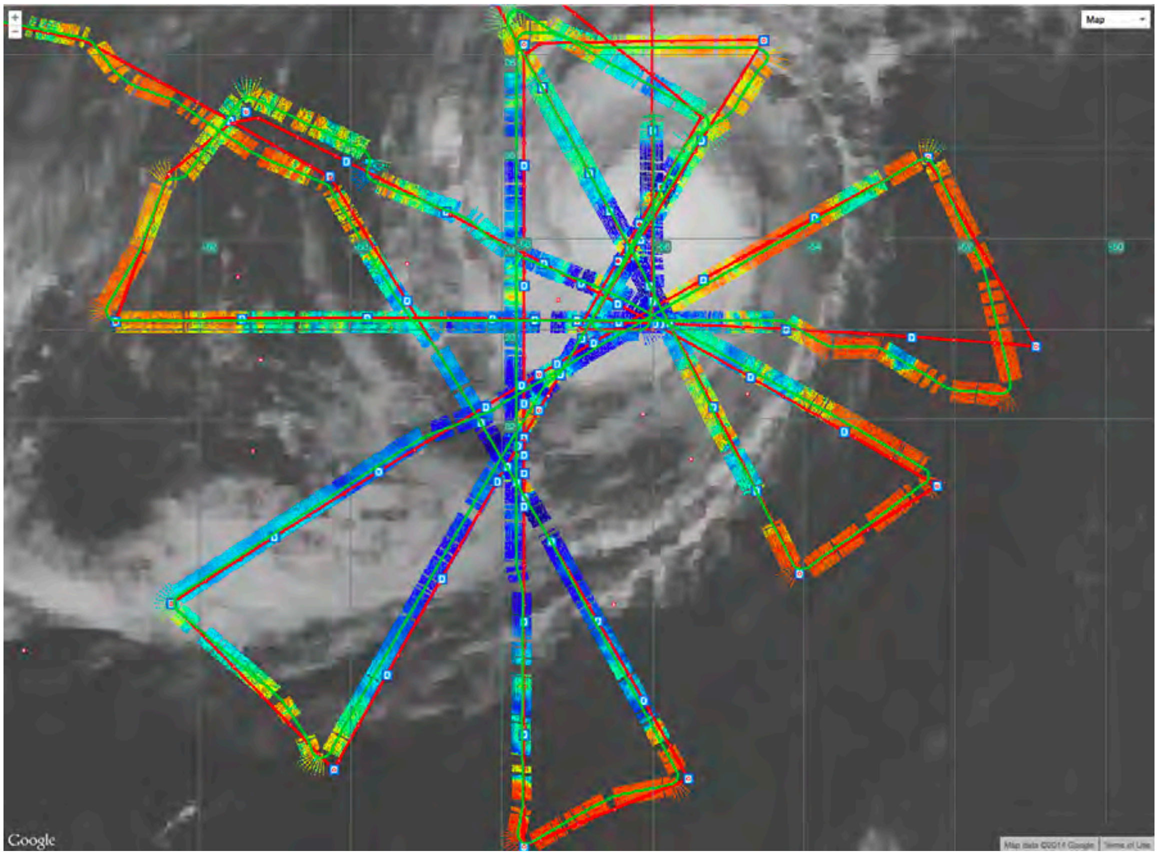

Figure 16: S-HIS 895-900 cm^{-1} Brightness Temperature image overlaid on GOES IR in MTS showing multiple overpasses of the eye of Hurricane Edouard (2014-09-16).

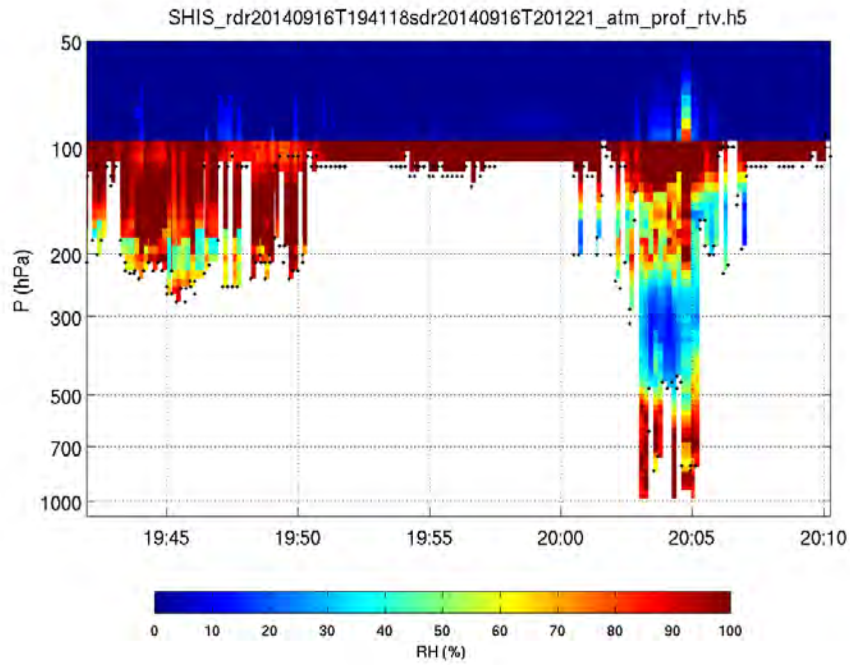

Figure 17: S-HIS relative humidity profile retrieval during the third eye transect of Hurricane Edouard (2014-09-16).

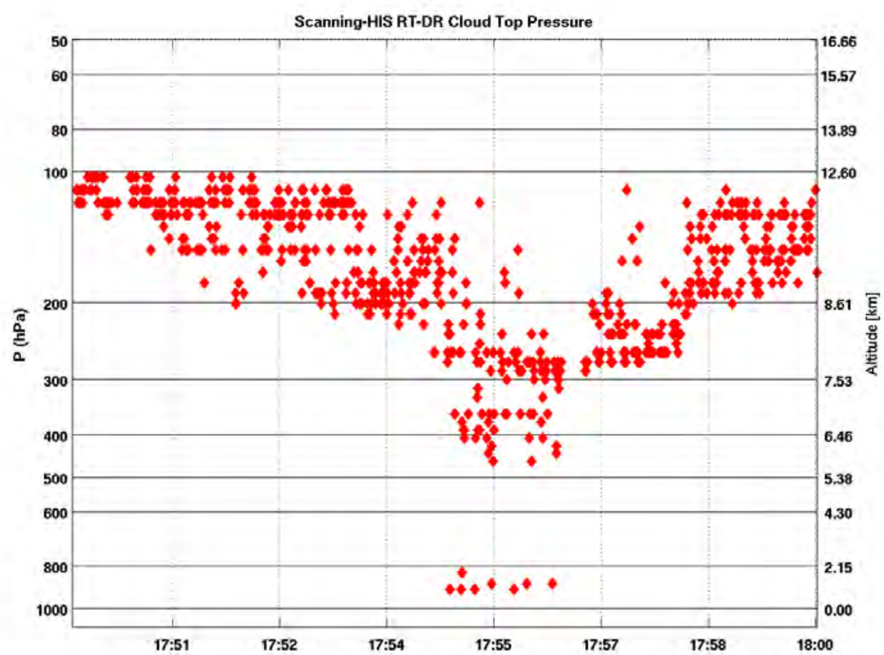

Figure 18: 10 minute history of S-HIS retrieved CTP during the second eye transect of Hurricane Edouard (2014-09-16).

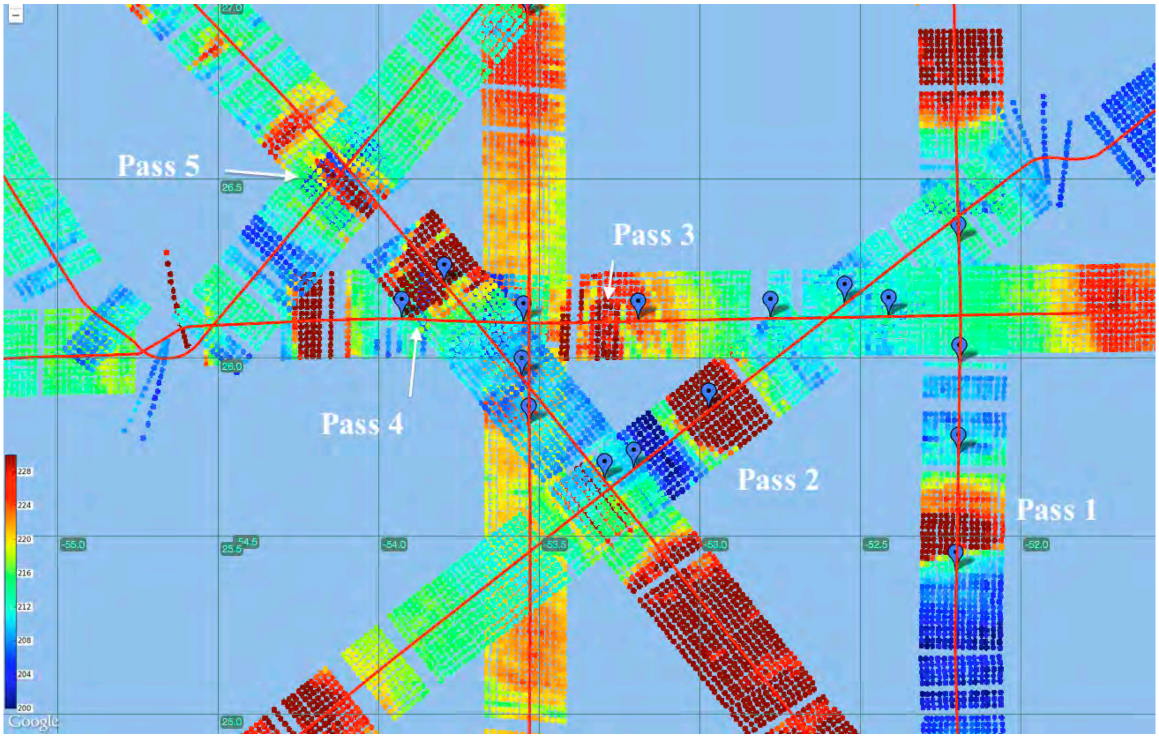

Figure 19: S-HIS 895-900 cm^{-1} Brightness Temperature image in MTS showing multiple overpasses of the eye of Hurricane Edouard (2014-09-14).

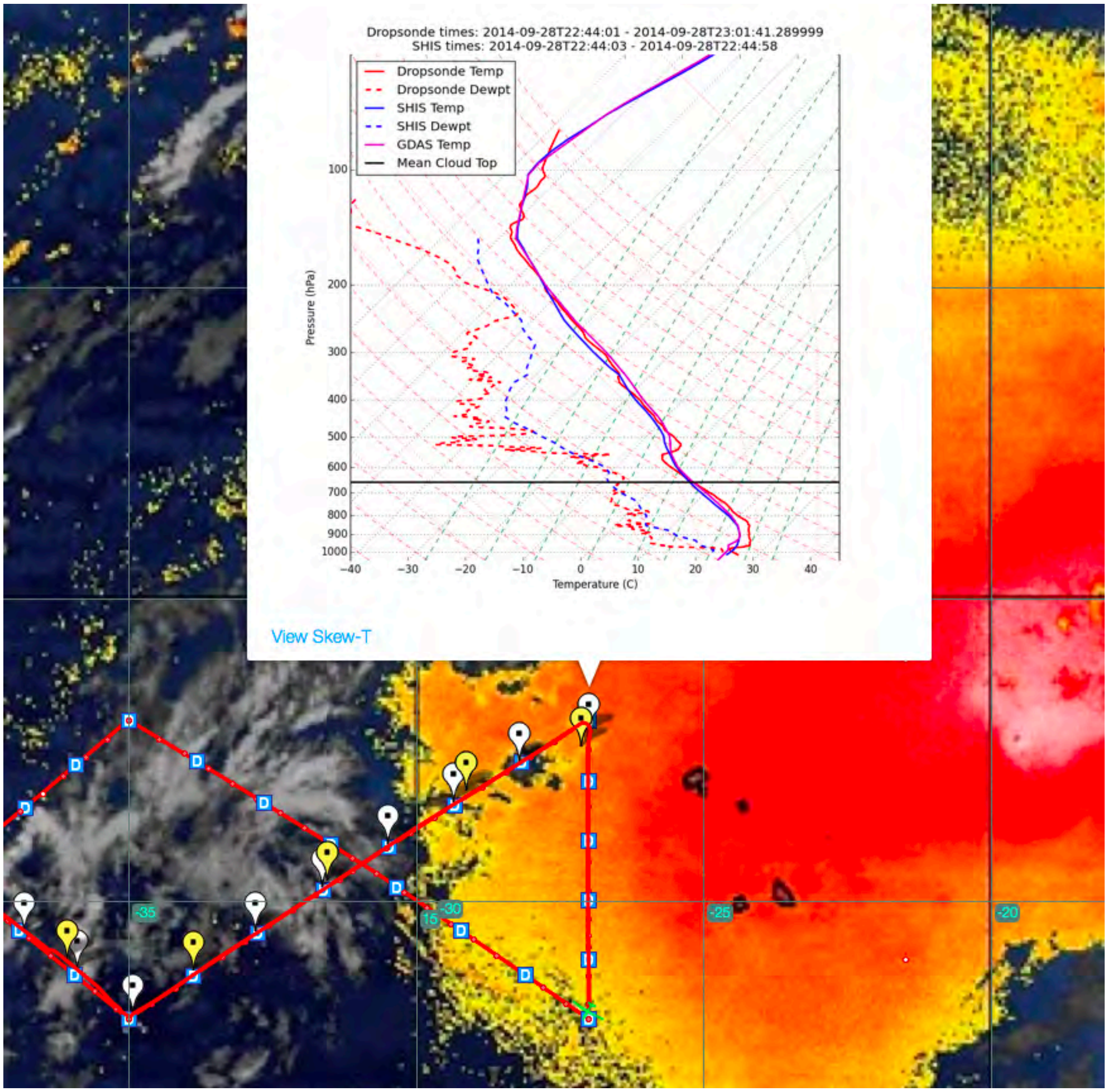

Figure 20: S-HIS and AVAPS skew-T comparison plot for 2244 UTC (2014-09-28). This sounding was noted in the #HS3 room to be a classic ENATL SAL sounding with a dry slot from ~955-550 mbar, and 20-30% RH at 600-900 mbar.

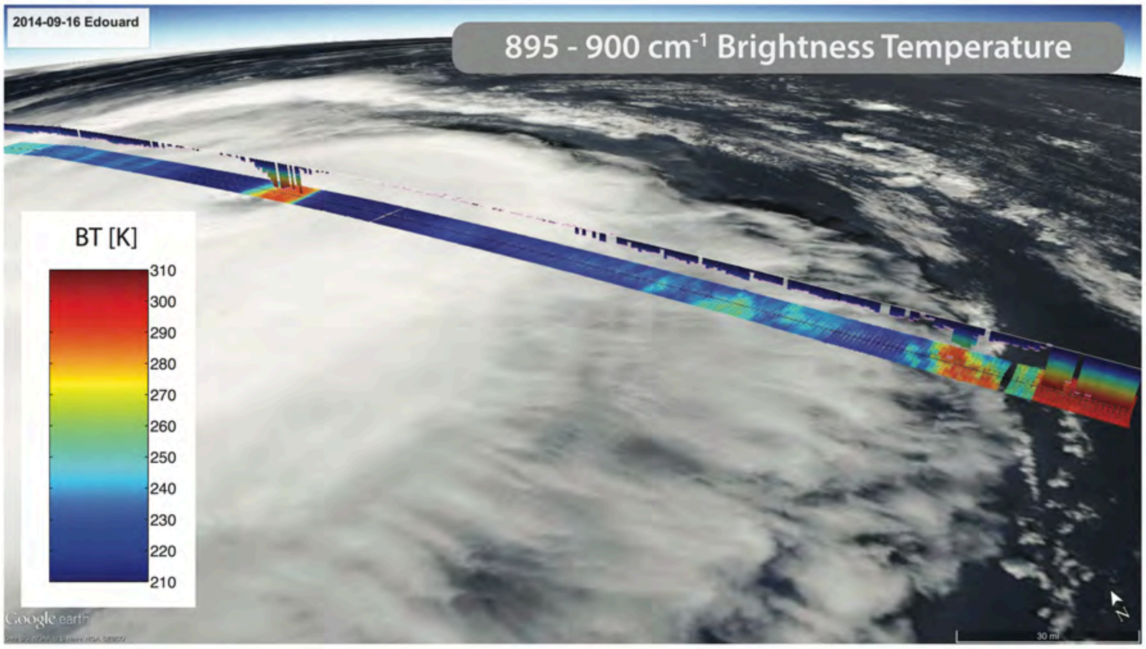

Figure 21: S-HIS footprints, colored by BT (895 – 900 cm^{-1}), and Dual Regression retrieved nadir temperature profile overlaid on VIIRS true color imagery (VIIRS images produced using polar2grid) during an overpass of Hurricane Edouard on 2014-09-16. The eye of Hurricane Edouard is evident.

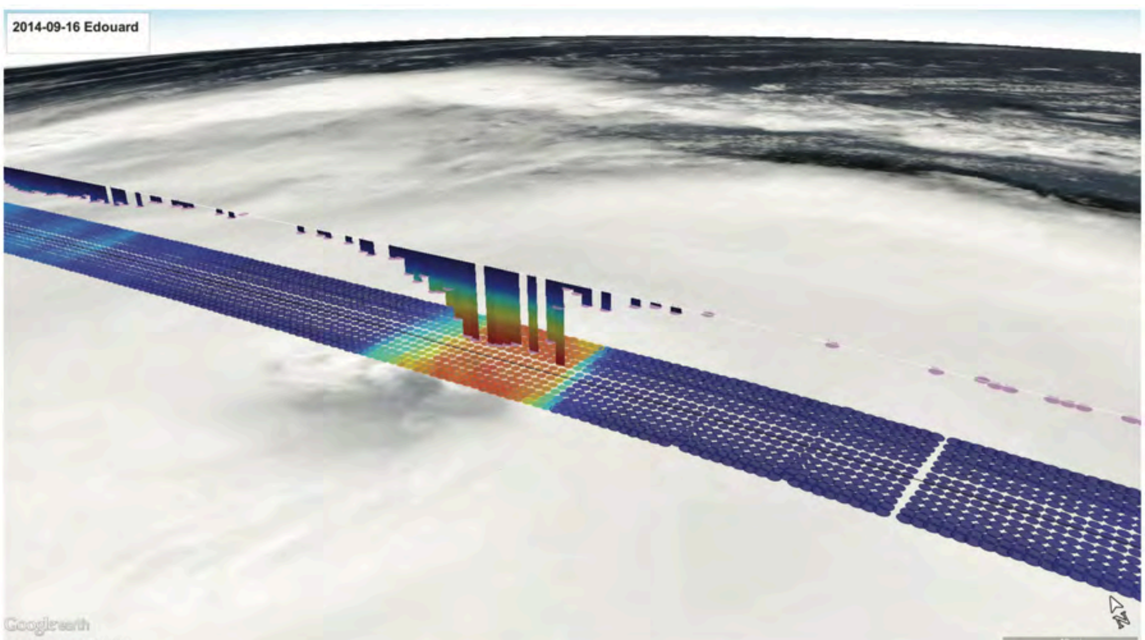

Figure 22: Close-up view of Figure 21 near the eye of Edouard (2014-09-16).

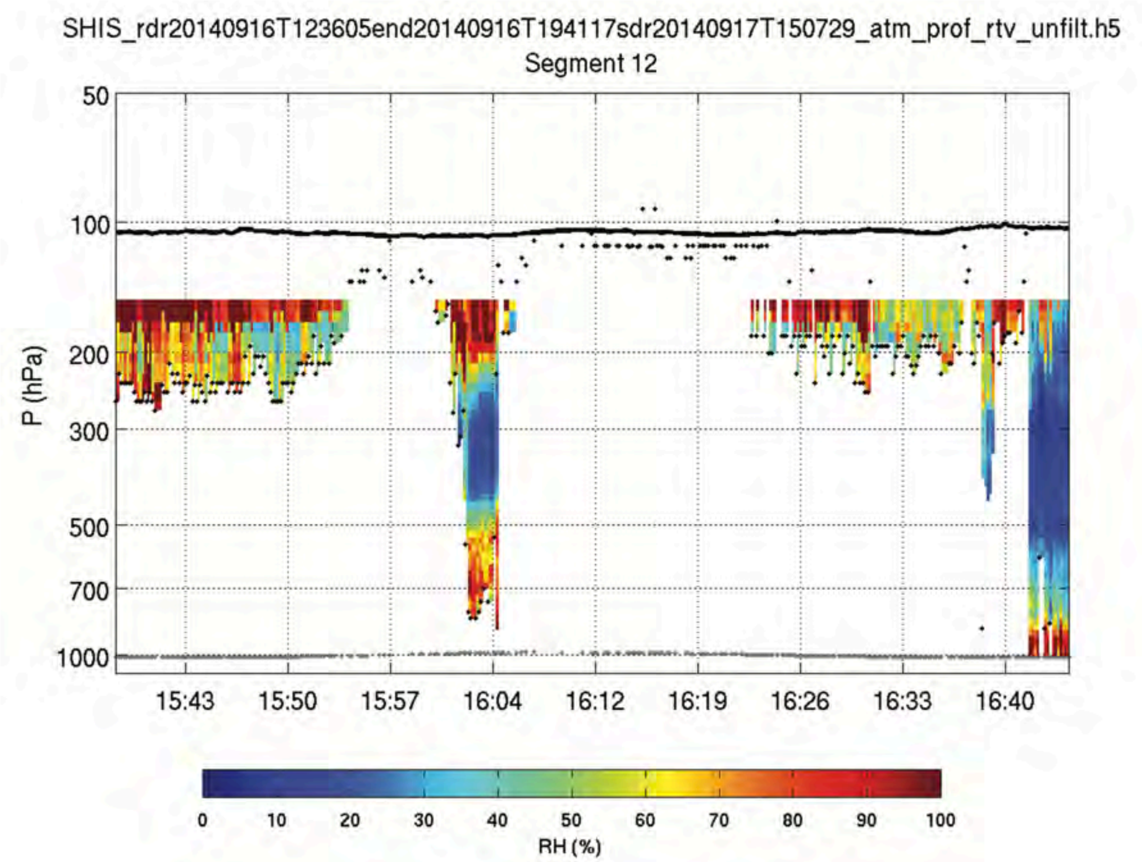

Figure 23: Dual regression retrieved RH curtain during an overpass of the eye of Hurricane Edouard on 2014-09-16. Quick-look delivered post-flight via S-HIS webpage.

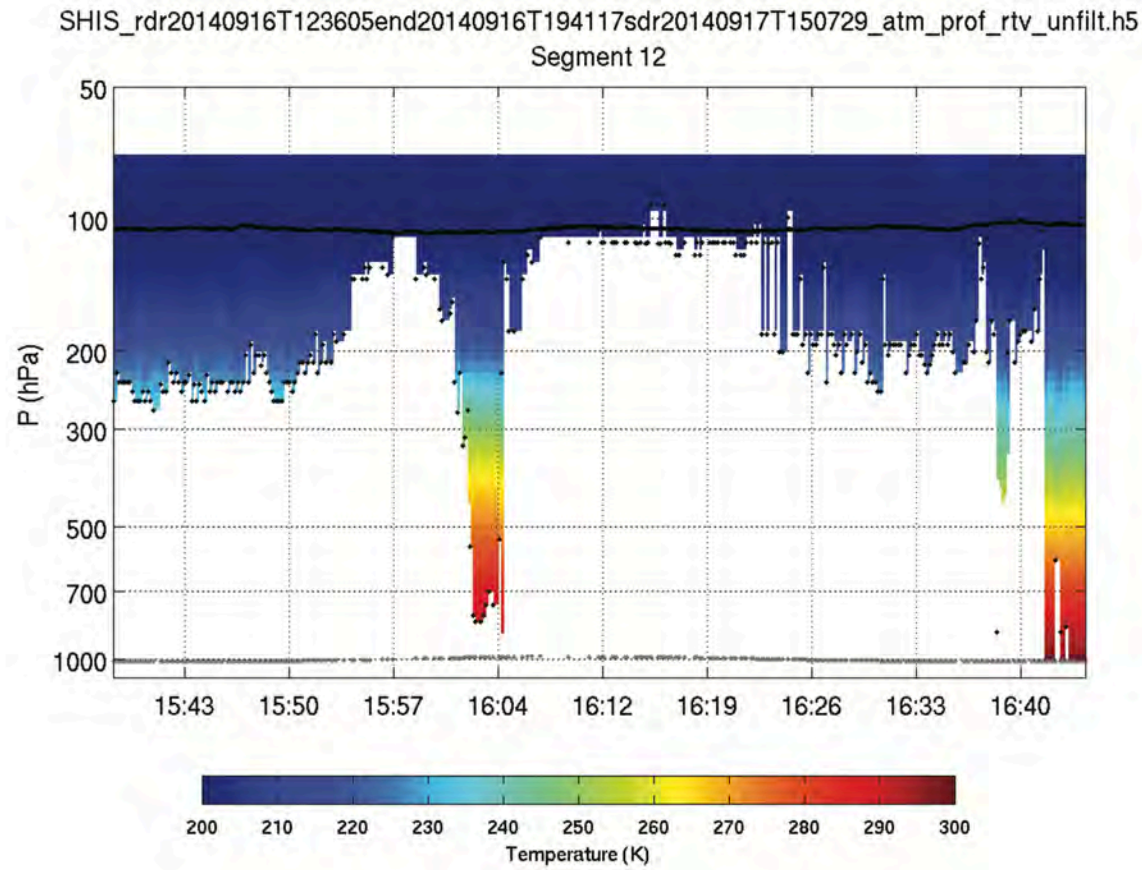

Figure 24: Dual regression retrieved Temperature curtain during an overpass of the eye of Hurricane Edouard on 2014-09-16. Quick-look delivered post-flight via S-HIS webpage.

1.6 Data Products

Quick-look product images, comparison plots, SDR and EDR data products, and Matlab readers for the data products were produced and delivered via the SSEC ftp server during each mission year. New users are required to register with an email address for contact information such that a distribution list can be easily maintained for product announcements and updates.

The S-HIS team coordinated with the GHRC DAAC to ensure the S-HIS data products were compliant with file format standards. After final reprocessing of the complete S-HIS HS3 dataset was completed, the final data product and associated readers and documentation were submitted to the NASA GHRC DAAC.

2 Pre-campaign and post-campaign testing of S-HIS performance

There are four major phases of S-HIS radiometric calibration:

(1) Pre-Integration at Subsystem Level
(2) Pre-Deployment Calibration Verification
(3) Post-Deployment Calibration Verification
(4) Instrument Calibration During Flight Using On-Board Calibration Blackbodies

Step one is typically completed on the order of every 5 years and was completed in 2012. Steps 2 and 3 are completed pre- and post-mission, respectively, and were completed in 2011, 2012, 2013, and 2014 for the annual HS3 missions. Step 4 describes the in-flight calibration scheme.

2.1 Pre-Integration at Subsystem Level

The S-HIS thermistor readout electronics are calibrated using a series of 6 fixed resistance standards, that are each calibrated to an accuracy of better than 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.

Results from the blackbody calibration conducted in the spring of 2012 are shown in Figure 9 compared with the results from the last major blackbody calibration (2001).

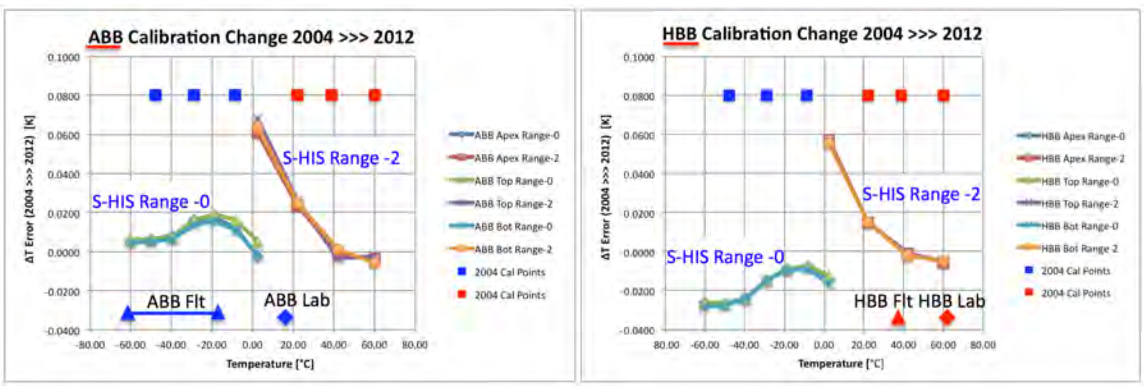

Figure 25: Blackbody calibration results compared with results from the last major calibration of 2004, show insignificant change in the key temperature ranges used – less than 25 mK change for the ABB, and less than 5 mK for the HBB.

The change in ABB calibration over the range it is used in S-HIS Current Range-0 and Range-2 is less than 25 mK, an excellent result. The large difference at 0 °C (Range-2) is most likely due to extrapolation error from the 2004 calibration where the lowest temperature used in the Range-2 calibration was at 21 °C.

The change in HBB calibration over the range it is used in S-HIS Current Range-2 is less than 5 mK, an excellent result. The large difference at 0 °C is most likely due to extrapolation error from the 2004 calibration where the lowest temperature used in the Range-2 calibration was at 21 °C.

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.

The overall blackbody temperature uncertainty budget is 53.3 mK (3-sigma), compared with the requirement of 100 mK. This uncertainty budget reflects the current state of the art for the S-HIS blackbody temperature calibration and captures the best methods, procedures, and techniques developed at UW-SSEC for blackbody calibration. Details of the blackbody temperature uncertainty budget are provided in Table 3.

Table 3: Blackbody Temperature Uncertainty Budget.

Resistance	Uncertainty	[mK] (3-sigma)
Calibration Resistor Measurement Uncertainty (ΔT equiv)	0.5	Measured with UW-SSEC, Fluke 8508A
S-HIS Readout Electronics Measured Error (ΔT equiv)	10.0	Includes long-term stability - values represent readings in the "as-received" condition (8 years since last cal)
S-HIS Readout Electronics Temperture Error (ΔT equiv)	5.0	2 x (that measured with board from 24 to 36°C in lab), to account for mear vacuum
Self Heat Correction uncertainty (ΔT equiv)	3.3	30% of the correction
Subtotal (RSS)	11.7	
Thermistor		
Temperature Calibration Probe uncertainty	5.0	Custom made Thermometrics SP-60 Probe, read with Hart 2563 Thermistor Module. Probe with electronics calibrated end-to-end at Hart. Checked at TPW at SSEC and found to be within 2 ± 2 mK
Gradient between temp probe and cavity thermistors uncertainty	10.0	inludes gradients within the cavity and calibration plug; as well as includes probe stem error / wire lead heat leaks thermistor wire heat leaks
Calbiration Fit Equation Residuals	2.0	4-term Steinhart-Hart fitting equation
Long-term stability	10.0	Over the last 8 years, the HBB changed less than 5 mK, except where we know there was an exprapolation error from last time at 20C. The ABB is within 25 mK of last time; but this is within the old probe tolerance of 30 mK
Subtotal (RSS)	15.1	
Cavity Assembly, In-Use, Integrated to Instrument		
Cavity to thermistor gradient uncertainty	25.0	
Thermistor lead heat leak temperature bias uncertainty	25.0	Needs refiement
Paint gradient uncertainty	18.0	Full expeted gradient (needs refinement)
Monte-Carlo Ray Trace model uncertainty in determining Teff	30.0	
Subtotal (RSS)	49.7	
Total (RSS)	53.3	

2.2 Pre-Deployment Calibration Verification

Prior to each field campaign end-to-end calibration verification is performed using a variable temperature blackbody in the zenith view and an ice-bath blackbody in the nadir view. The radiances measured by the S-HIS instrument are compared to those calculated for the verification blackbodies, using 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. These blackbodies have had their emissivity measured at NIST 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 S-HIS instrument has undergone a side-by-side radiance intercomparison test with the NIST TXR, using an AERI blackbody as a transfer standard. The mean difference at 10 microns between these instruments was 38 mK - well less than the propagated 3-sigma uncertainties.

As noted, the S-HIS pre-mission end-to-end calibration verification was conducted immediately prior to each annual HS3 field deployment (2011 through 2014). The test configuration for pre- and post-deployment end-to-end calibration verification is shown in Figure 26.

After instrument and source set-up and stabilization are completed and verified, 30 minute datasets are collected at three external blackbody temperatures (Ambient, 318K, 333K). The external blackbody temperature is allowed to stabilize before each data collection, and Ice Bath Blackbody data is collected for the duration of the test (approximately 135 minutes).

For all pre-deployment end-to-end calibration verification tests, the ambient, 318K, 333K, and ice-bath blackbody data showed agreement within the established calibration and validation uncertainty (3-sigma). Results are shown in Figure 27 through Figure 34. While all results are within the established uncertainties, the mid-wave band result for the ice-bath blackbody is not ideal. This behavior is consistent with historical results for ice-bath blackbody tests conducted in the laboratory environment. The nonlinearity correction parameters for the long-wave and mid-wave band are optimized for flight conditions, and the mid-wave result is likely due to non-optimal nonlinearity correction in the laboratory thermal environment.

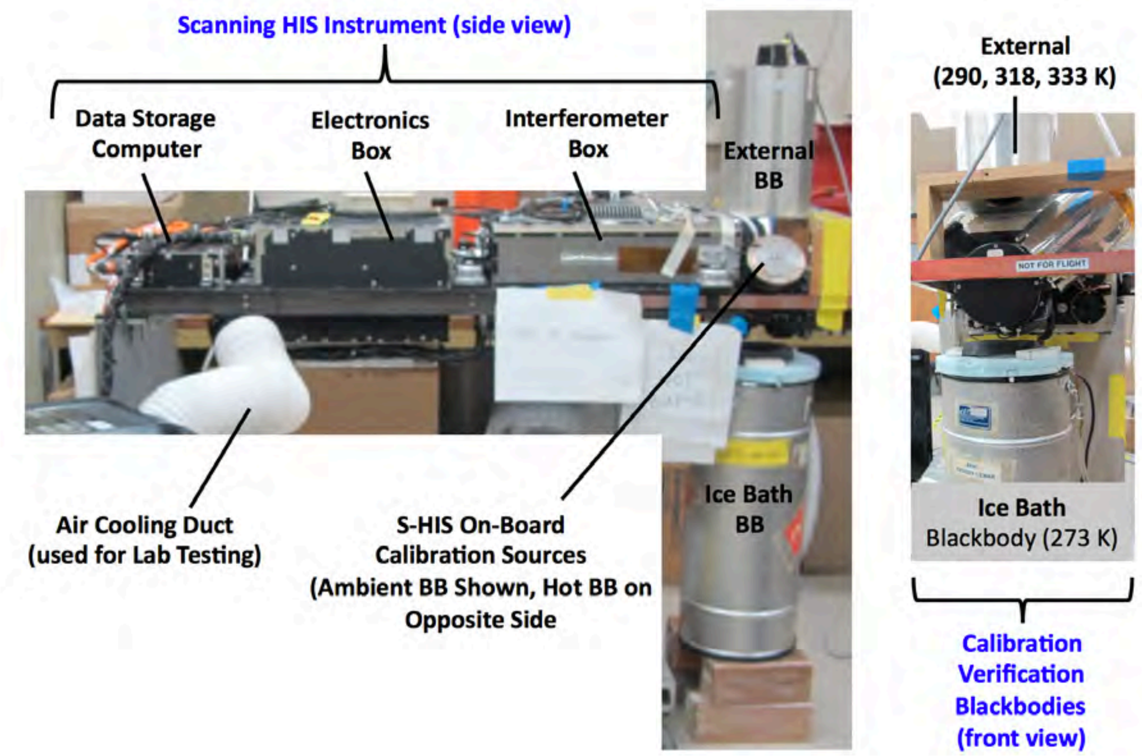

Figure 26: S-HIS radiometric calibration verification configuration.

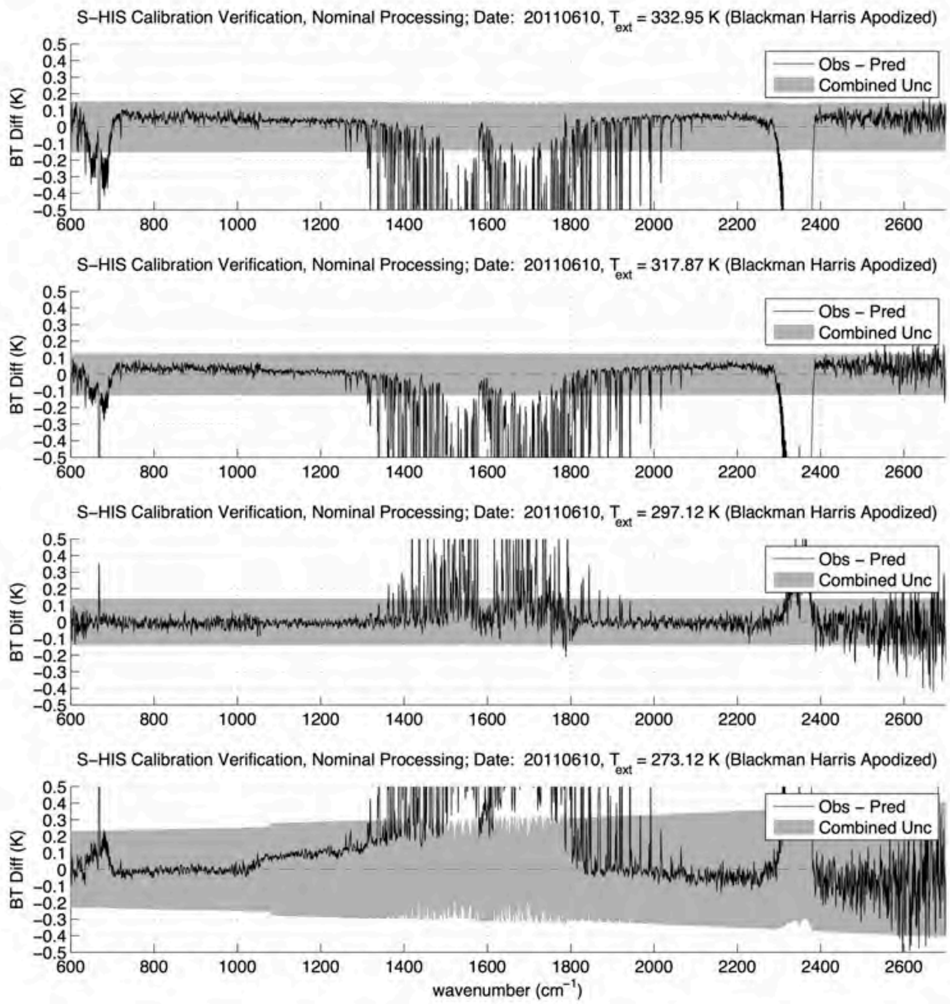

Figure 27: 2011 Pre-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 332.95K, 317.87K, 297.12K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

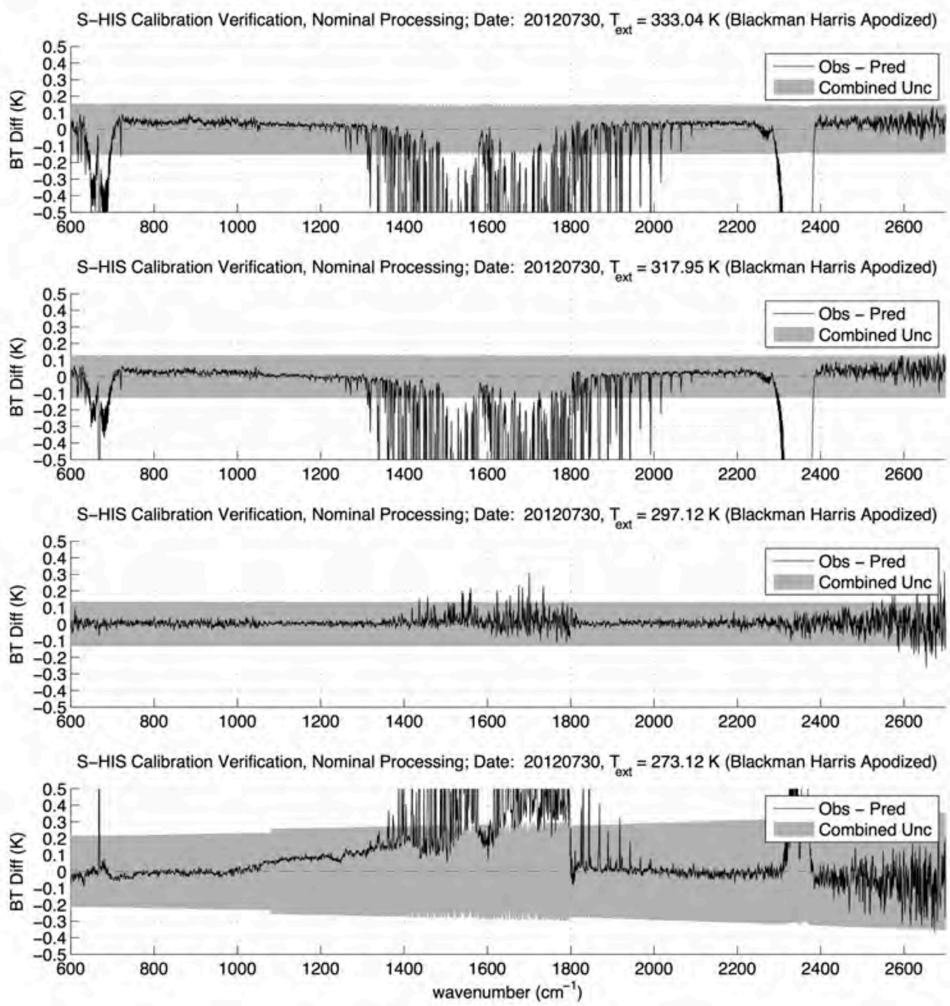

Figure 28: 2012 Pre-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 333.04K, 317.95K, 297.12K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

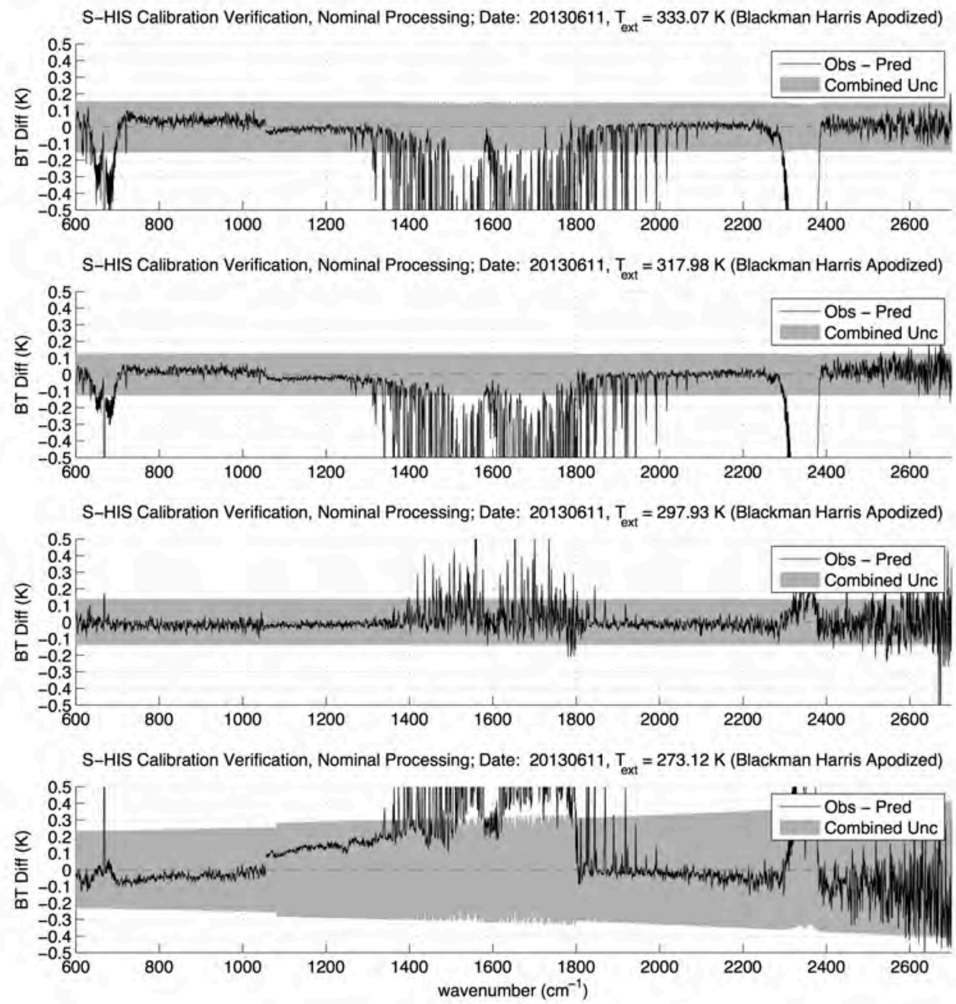

Figure 29: 2013 Pre-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 333.07K, 317.98K, 297.93K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

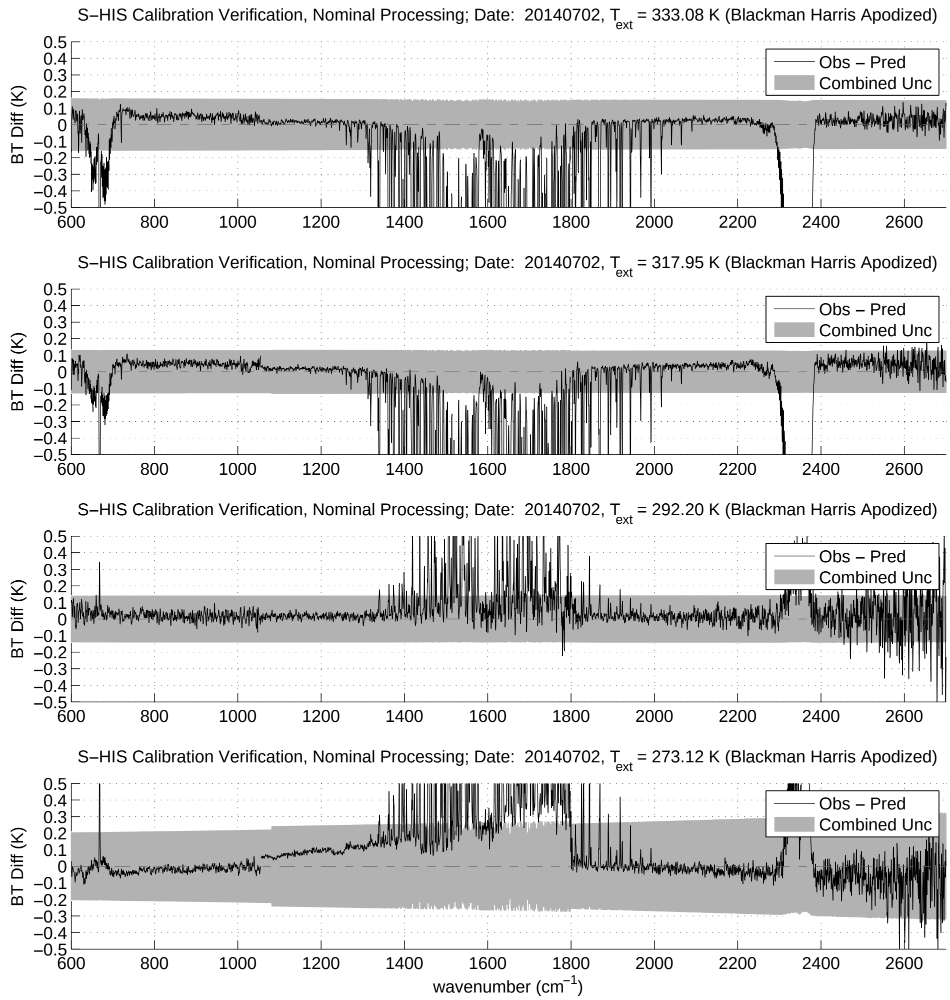

Figure 30: 2014 Pre-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 333.08K, 317.95K, 292.20K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

2.3 Post-Deployment Calibration Verification

Following each field campaign, the pre-deployment end-to-end calibration verification procedure is repeated. Details of the test and analyses are provided in the preceding section.

For all post-deployment end-to-end calibration verification tests, the ambient, 318K, 333K, and ice-bath blackbody data showed agreement within the established calibration and validation uncertainty (3-sigma). Results are shown in Figure 31 through Figure 34. Again, it is important to note that while the results are within the established uncertainties, the mid-wave band result for the ice-bath blackbody is not ideal. This behavior is consistent with historical results for ice-bath blackbody tests conducted in the laboratory environment. The nonlinearity correction parameters for the long-wave and mid-wave band are optimized for flight conditions, and the mid-wave result is likely due to non-optimal nonlinearity correction in the laboratory thermal environment.

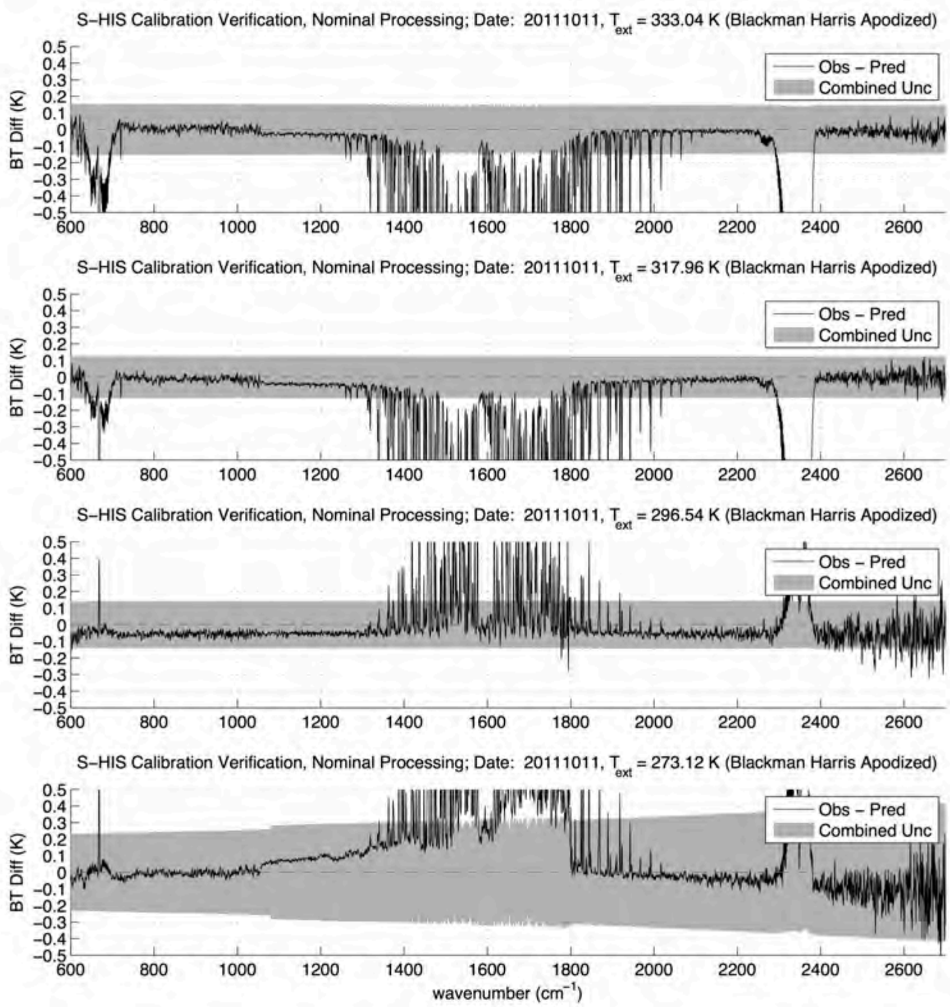

Figure 31: 2011 post-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 333.04K, 317.96K, 296.54K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

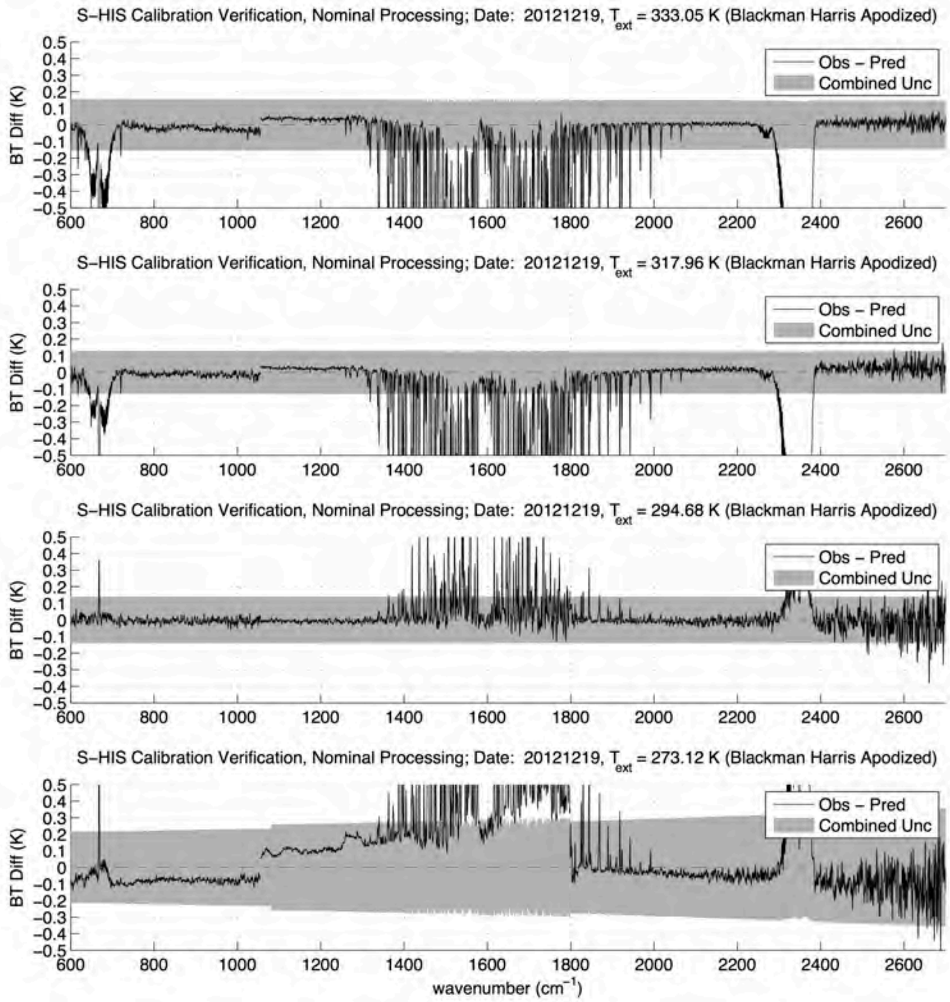

Figure 32: 2012 post-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 333.05K, 317.96K, 294.68K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

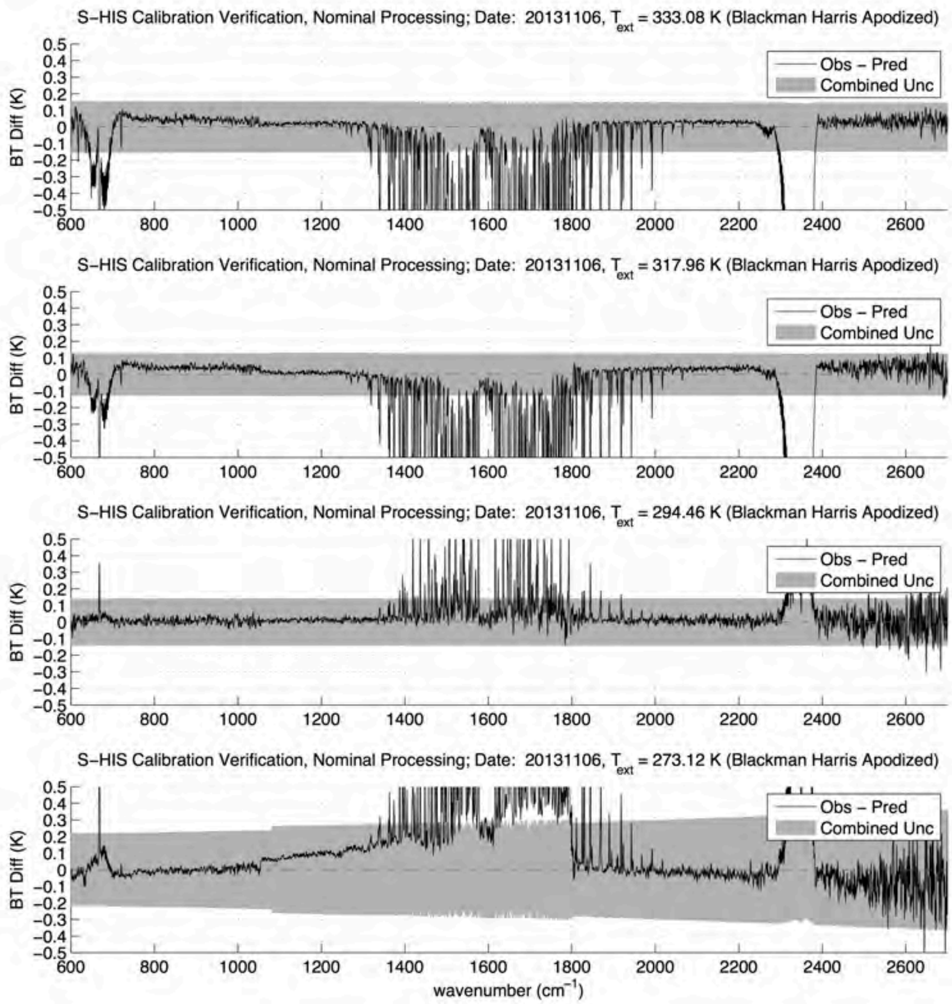

Figure 33: 2013 post-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 333.06K, 317.96K, 294.46K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

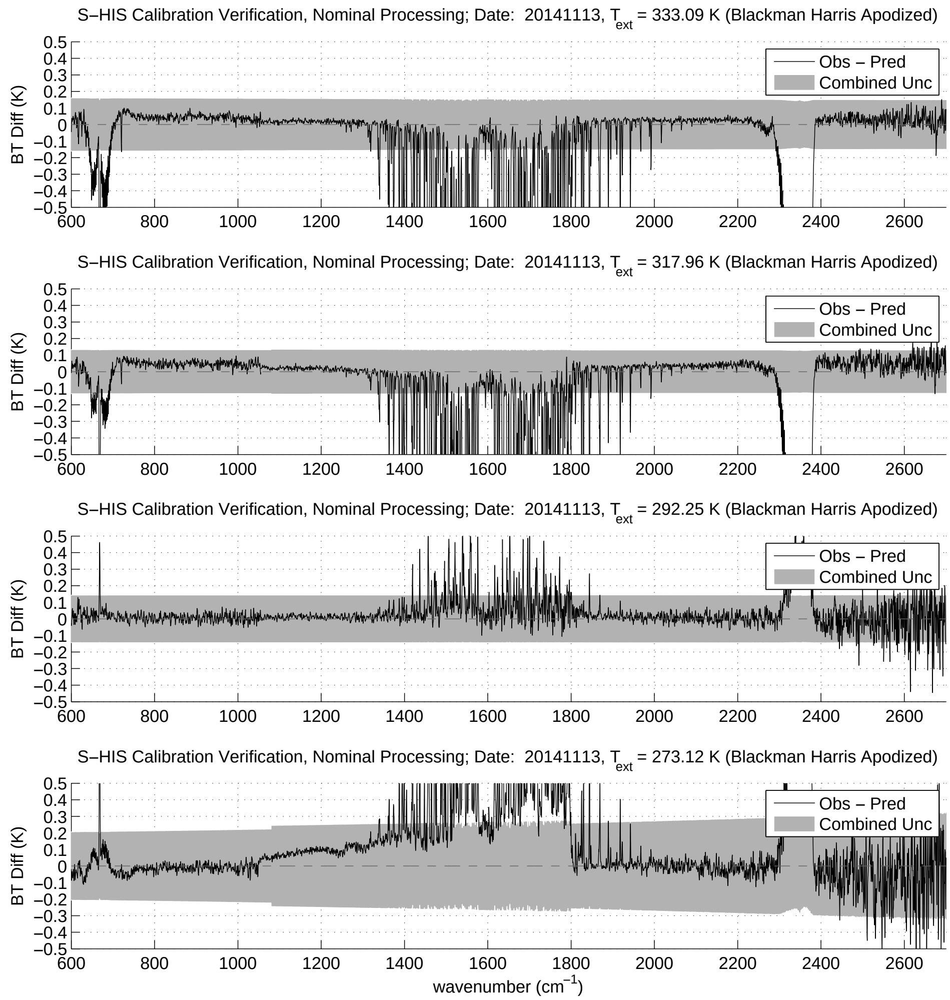

Figure 34: 2014 post-deployment radiometric calibration verification brightness temperature residuals (measured – predicted difference, with combined uncertainty). The 4 panels represent different external blackbody temperatures, top to bottom: 333.09K, 317.96K, 292.25K (ambient), and 273.12K (ice bath blackbody). Atmospheric absorption and emission are not included in the predicted brightness temperatures (no line by line radiative transfer model utilized). All uncertainties are 3-sigma.

2.4 Instrument Calibration During Flight Using On-Board Calibration Blackbodies

During flight, the S-HIS Earth scene radiance measurements are calibrated several times a minute using its two On-Board Calibration Blackbodies (Ambient Blackbody, ABB; Hot Blackbody, HBB). The Ambient Blackbody runs at the pod ambient temperature (between -25 and -55°C, depending on the local ambient environment); and the Hot Blackbody runs at 27°C.

3 Ongoing development and optimization of architecture and software to implement real-time, near real-time, and long term data handling, processing, and display for long duration Global Hawk flights.

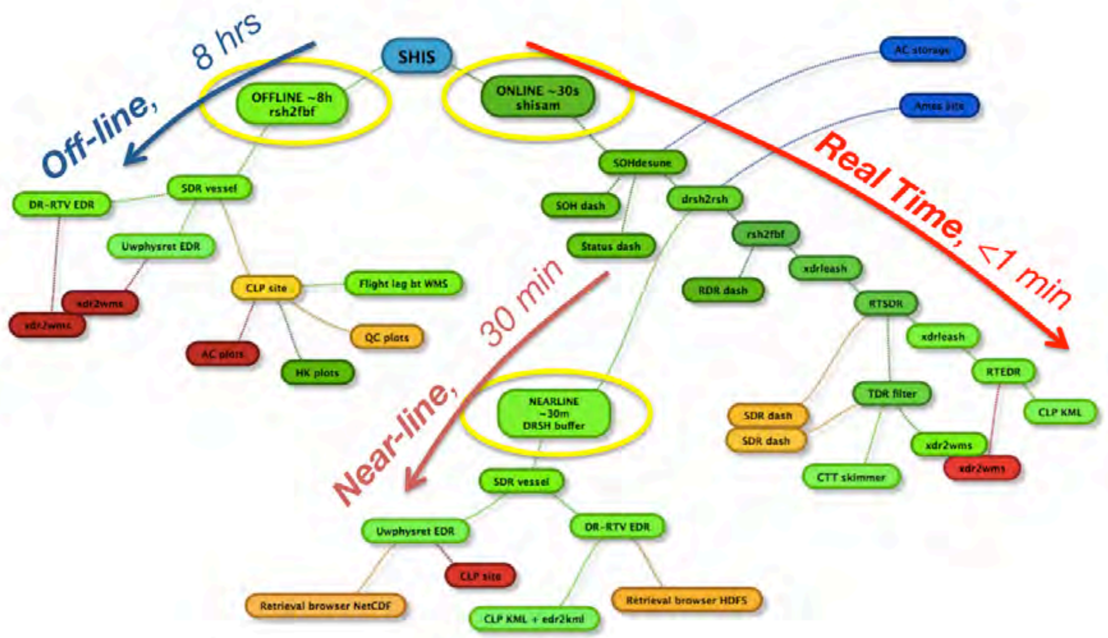

Figure 35: S-HIS HS3 data processing paths.

S-HIS offers three levels of data products, raw data records (RDR), scientific data records (SDR), and environmental data records (EDR). Raw data records are provided directly from the instrument and include housekeeping temperatures and measurements, blackbody temperatures, and raw observed interferograms. Through radiometric calibration using reference blackbody spectra, RDRs are used to create calibrated absolute radiance spectra SDRs that can in turn be represented as brightness temperature spectra. Through a second, longer, software processing step, SDRs are used to create EDR atmospheric profiles. The SDR and EDR data are operationally produced and distributed.

There are three S-HIS HS3 data processing paths: (1) Offline batch post processing, (2) near-line processing (30 minute latency), and (3) real-time processing (~45 second latency). These data processing paths are illustrated in Figure 35 and are summarized in the following sub-sections.

3.1 Post-processing of Radiance Calibration and Atmospheric Retrieval

Following each flight the UW team downloads the complete raw dataset collected onboard the S-HIS instrument and subsequently uploads the dataset to the SSEC at University of Wisconsin-Madison for post-processing. This post-processing consists of a sequence of batch scripts, which execute custom calibration software for the conversion of interferograms to radiances. A GH flight of 24 hours can be processed in about 4 hours of wall clock time on a dedicated computer at the UW-SSEC. The processing of raw data to radiances is fully tested and automated. Once the radiances are available, the UW team has custom software for the retrieval of temperature and water vapor profiles and cloud heights. Two independent retrieval algorithms have been developed, a Dual Regression (DR) algorithm that is a statistical eigenvector regression method, and provides retrievals under clear and cloudy conditions; and UWPhysRet that is a clear sky algorithm. The retrievals for temperature, water vapor retrieval, and clouds are compared with collocated dropsonde (AVAPS) and lidar (CPL) data. The DR retrieval algorithm is fully automated.

3.2 Real-time and Near-line Radiance Calibration and Atmospheric Retrieval

The S-HIS instrument data downlink methodology has evolved over time with the technology available and new aircraft platforms. Initially, S-HIS data was primarily retrieved from internal storage on the instrument after landing and processed post-flight. In some cases, a small amount of data was provided via status packets or state of health (SOH) packets. These packets hold a minimal amount of information to verify that the instrument is operating as expected and can't be used for high level scientific analysis. For lab or "fly-along" DC-8 airborne lab use, when direct connections to the instrument are possible and not bandwidth limited, a scientist uses a direct TCP network connection to subscribe to data in real-time.

The HS3 mission on the Global Hawk marks the first time that real-time S-HIS science data is downlinked, processed, and made available to scientists on the ground within 1 minute of observation. The ability to view real-time S-HIS observations allows scientists to quickly analyze the storm formation, and allows real-time mission planning, inclement flight weather avoidance as well as tracking the instrument state of health. For the HS3 mission, a new method was developed named DRSH (Datagram Raw Scanning-HIS). A datagram or UDP connection is an unordered, connectionless protocol for sending data. This means that the software must handle the potential for out of order and even missing data, and also that data connections are unidirectional and use less bandwidth than a RSH TCP connection. A connectionless protocol like UDP is important when operating on the Global Hawk because of the possibility of satellite communication outages for extended periods of time, and to permit security guarantees to the aircraft by operating as an egress-only data relay.

S-HIS data goes through a series of connections to push data from the Global Hawk to processing machines on the ground. Starting as a DRSH packet sequence from the instrument, the data goes through the aircraft network and is sent over a KU band satellite connection to routing computers on the ground. The routing computers are configured by NASA's IT team to forward S-HIS's DRSH packets from the aircraft payload network to a processing computer in the Payload Mobile Operations Facility (PMOF) at the Wallops Flight Facility (WFF) and a server at the UW-SSEC. The path to the SSEC is made longer by a required detour to Dryden Flight Research Center. Once these machines receive the data, software validates packets and reassembles the RSH data stream, handling any missing or out of order pieces of information. The data is then processed, and radiances and retrieved temperature and water vapor products are made available via GUI software and web services used by the Global Hawk Mission Tool Suite.

The state of health of the S-HIS instrument is monitored in real-time in the PMOF at NASA WFF using graphical displays. Once data packets reach the processing machine in the PMOF, raw data record processing is performed and then displayed in a graphical user interface known as the S-HIS Dashboard. The Dashboard provides time series of temperatures and spectra for the last 200 measurements (approximately 100 seconds). It also displays the values of various instrument housekeeping sensors, and whether they are within their acceptable operating ranges. Further displays are available for Status and State-of-Health

(SOH) packets (delivered via Iridium), for use in the case of a Ku communication outage or if the full datagram (DSRH) data is otherwise not available.

Furthermore, collaborating scientists can view the real-time downlinked S-HIS data products through the NASA Mission Tools Suite website or the SSEC S-HIS website during flight, from anywhere in the world. Data and images are provided to both of these services via a server at the UW-SSEC.

For each SDR record that is produced, the brightness temperature data is added to Web Map Service (WMS) layers, represented as GeoTIFF image fragments with metadata. WMS layers can be viewed in NASA Mission Tools or Google Earth to see geo-located real-time measurements made by S-HIS. Additionally, various quick-look images of the calibrated brightness temperatures and retrieved atmospheric profiles are produced at regular intervals in near real-time. The quick-looks are made available on the SSEC S-HIS website as geo-located PNG images and as dynamic KML markers that can be viewed in Mission Tools or Google Earth. KML markers are clickable icons on a map that open a separate window for viewing the quick-look images.

The algorithms used in the real-time calibrated radiance and Dual Regression retrieval processing are fast enough to produce values within seconds of reception. Near-line processing utilizes the full batch processing including quality control; applied to KU downlinked data separated into 30-minute data segments.

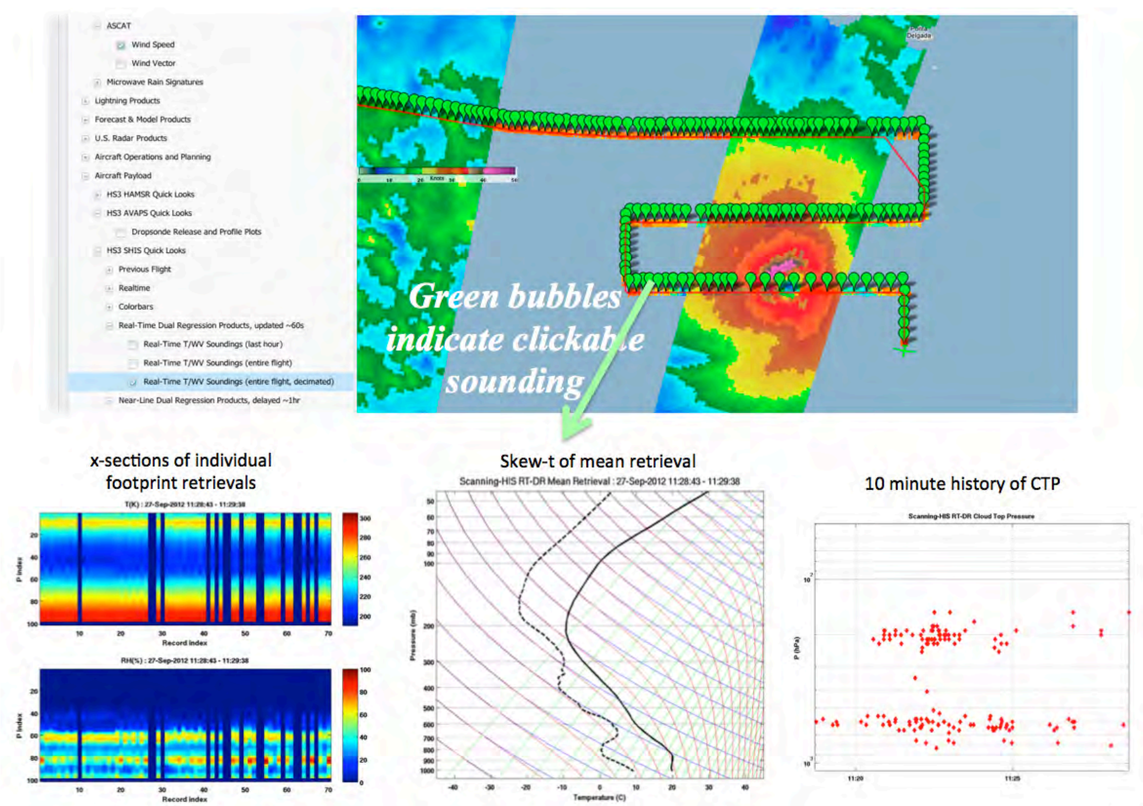

Figure 36: Example of S-HIS Real-time Dual Regression retrieval products.

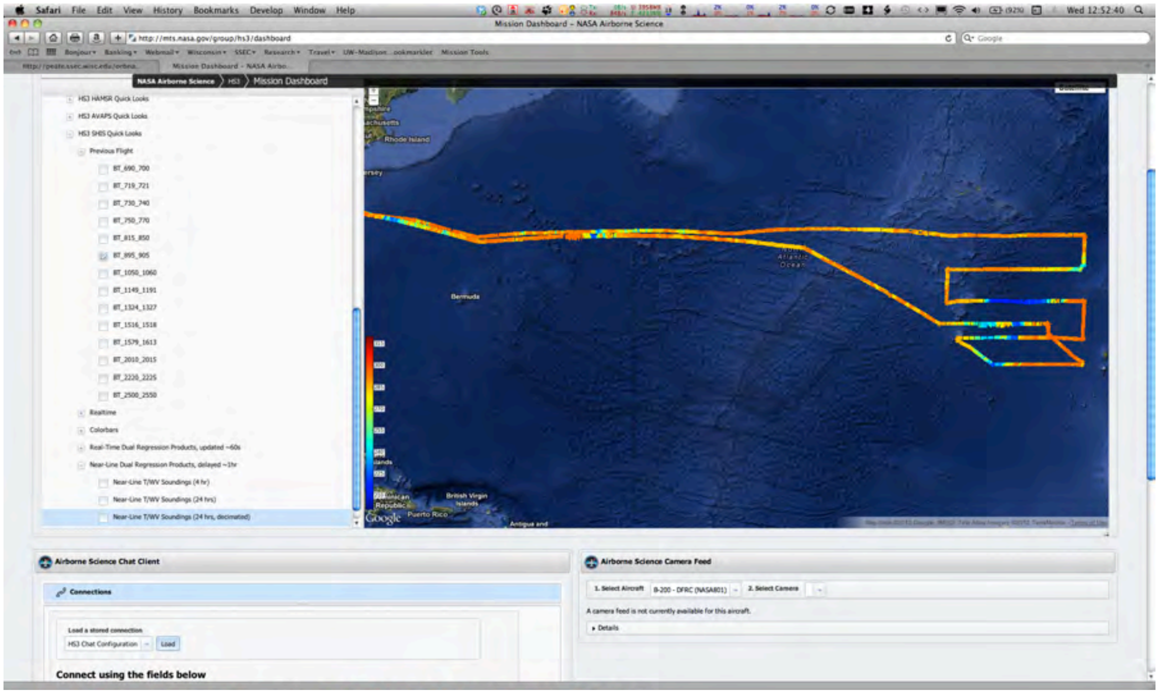

Figure 37: Example S-HIS WMS layer in NASA MTS (S-HIS 900cm^{-1} Brightness Temperature).

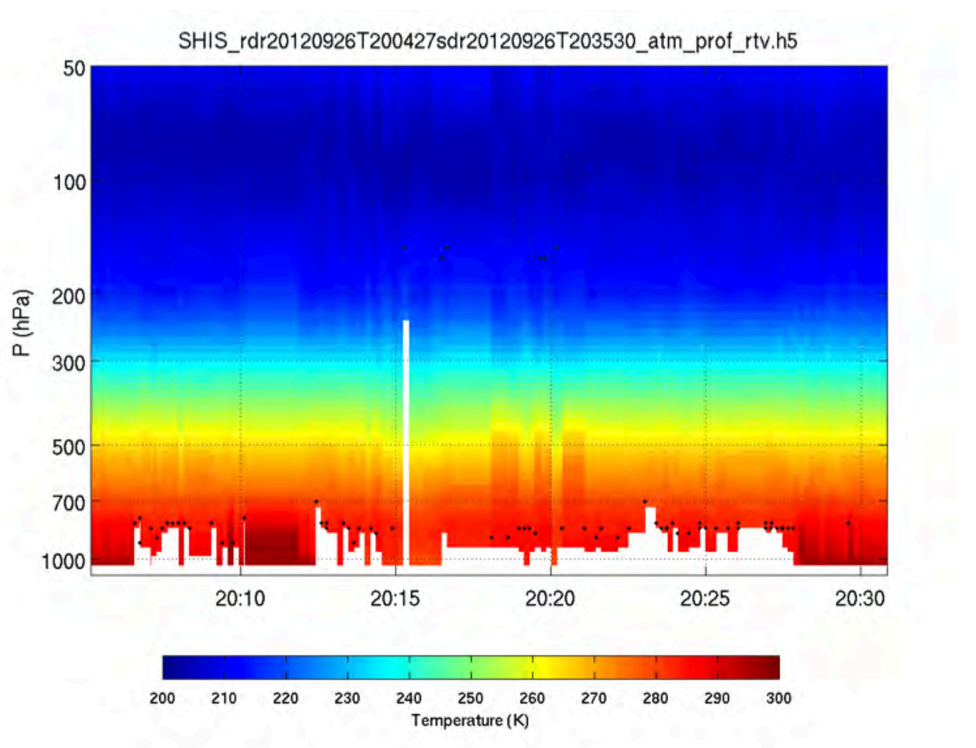

Figure 38: Example real-time temperature profile retrieval delivered via S-HIS website.

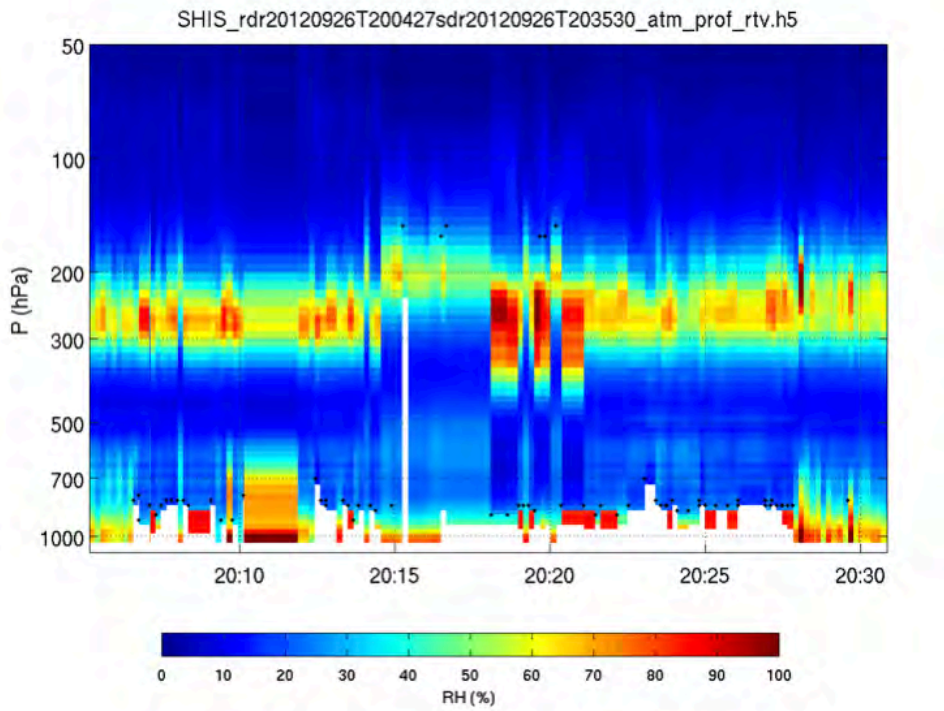

Figure 39: Example real-time relative humidity profile retrieval delivered via S-HIS website.

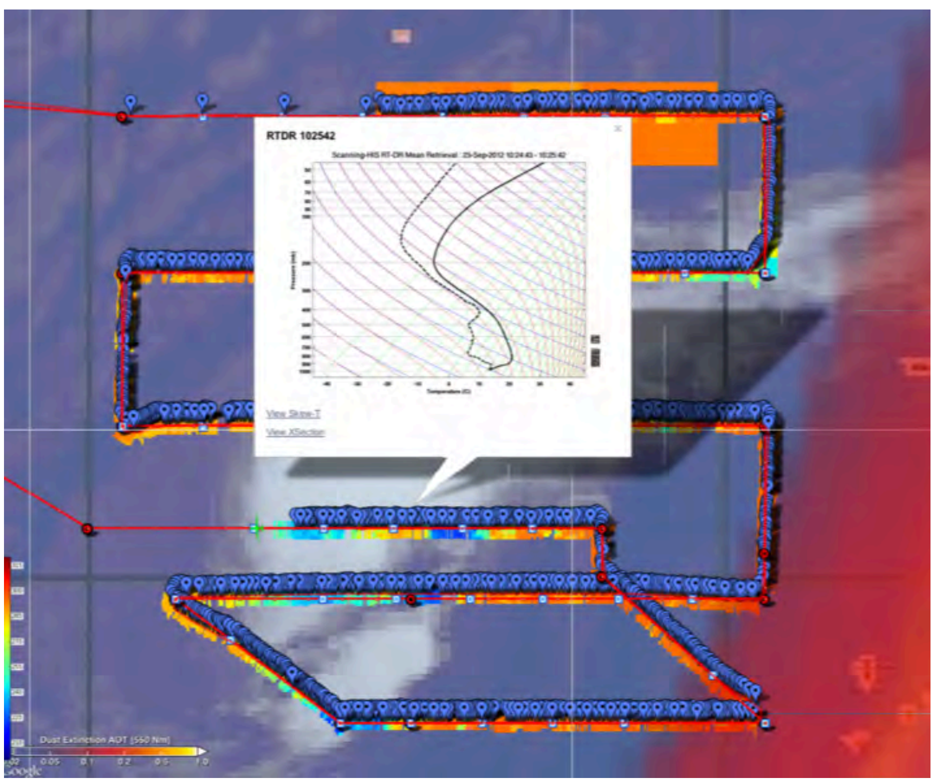

Figure 40: Example Skew T profile delivered in real-time via kml markers in NASA MTS.

For the 2014 HS3 season, beginning with the 2014-09-12 flight, SHIS/AVAPS comparison skew-T plots were added to MTS. Initially, an average of S-HIS retrievals from data collected during the sonde drop was used in the comparison, with a simple outlier rejection applied to the S-HIS retrievals (Figure 41). By the 2014-09-22 flight a refined field of view averaging and selection algorithm was developed and applied to the S-HIS retrievals used in the AVAPS comparison plots. This resulted in improved temperature and dewpoint agreement between the two instruments. Two comparison plots from the 2014-09-22 flight are provided in Figure 42 and Figure 43. These profiles were taken east of a convective complex during the eastward track, with the later S-HIS retrieval average (Figure 43) more fully capturing the mid-level dry slot.

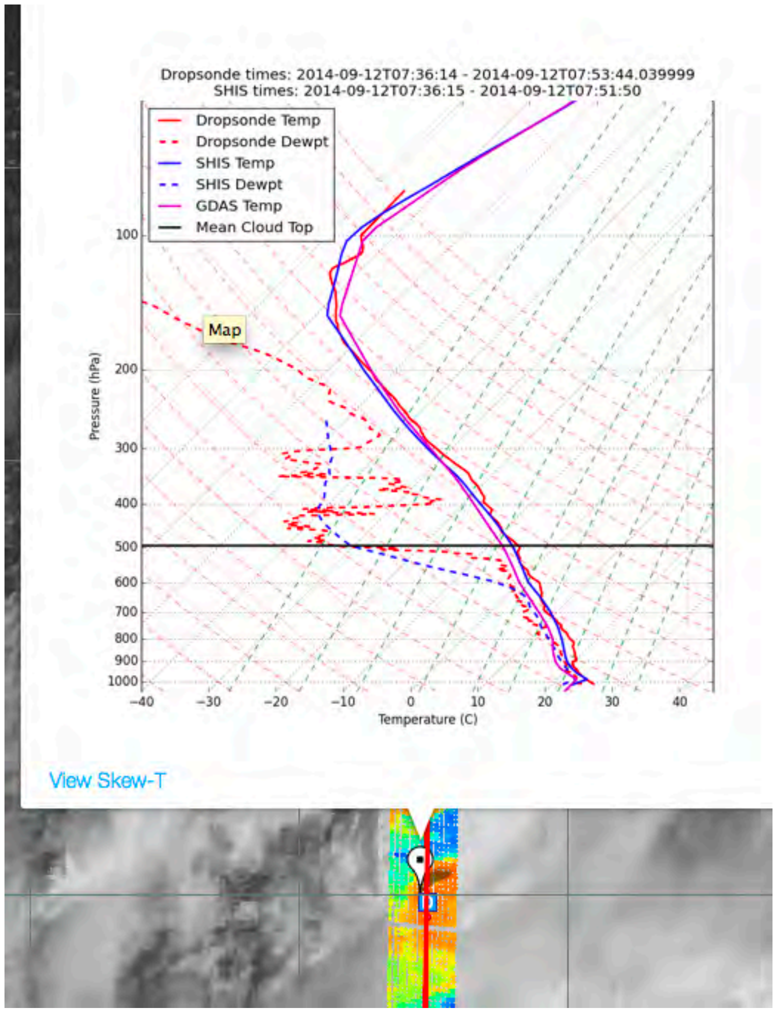

Figure 41: S-HIS / AVAPS comparison skew-T plot delivered via MTS (2014-09-12 flight, initial implementation).

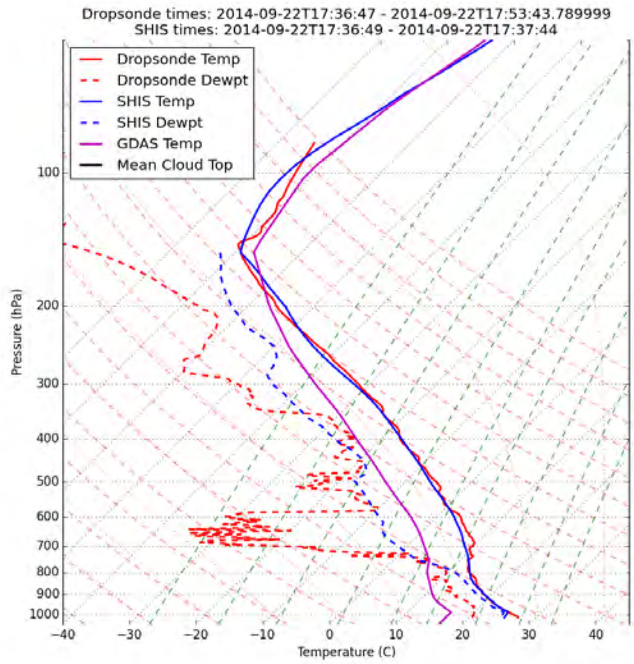

Figure 42: Example S-HIS / AVAPS comparison skew-T plot delivered via MTS for the 2014-09-22 flight. The S-HIS retrieval average does not resolve the mid-level dry slot for this sounding.

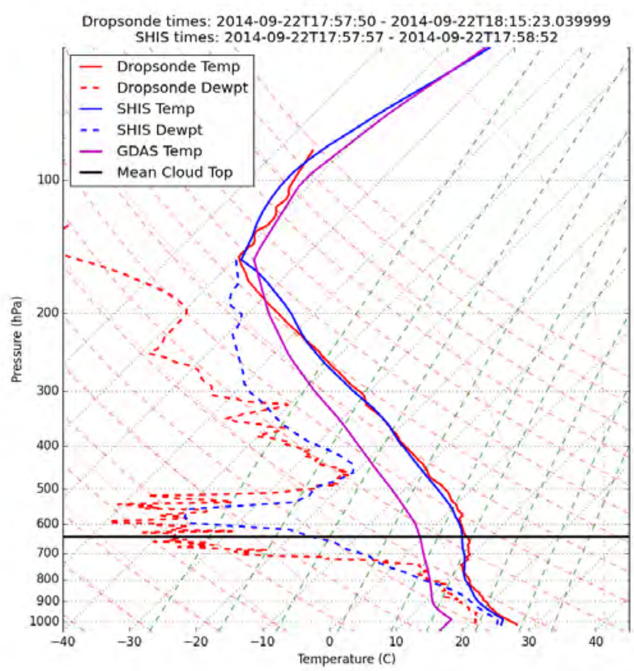

Figure 43: Example S-HIS / AVAPS comparison skew-T plot delivered via MTS for the 2014-09-22 flight. The S-HIS retrieval average more fully captures the mid-level dry slot in this case.

4 Optimization and implementation of improved temperature, water vapor, and cloud retrieval capabilities

4.1 S-HIS Dual Regression Retrieval

Development and optimization of the S-HIS Dual Regression Retrieval algorithm continued throughout the HS3 mission. All HS3 datasets (2011, 2012, 2013, 2014) have been reprocessed using the updated algorithm for the final submission to the HS3 data repository. The largest Dual Regression Retrieval advancement completed during the final flight year (2014) was the implementation of a statistical bias correction. The Dual Regression retrieval method uses a statistical training data set, and imperfect skill due to lack of vertical resolution in radiances, leads to statistical bias. The statistical bias can be identified and corrected for by calculating model radiances from the forecast profile and performing the Dual Regression retrieval on the simulated radiances. The resulting retrieval error in the simulated retrieval is the statistical bias.

To provide atmospheric retrievals under all-sky conditions, the "Dual Regression" retrieval algorithm has been adapted for the S-HIS on the Global Hawk. This retrieval approach has been used previously for other high spectral resolution IR satellite sensors including AIRS, IASI, and CrIS, and provides retrievals of temperature and water vapor profiles, various cloud parameters, column ozone and carbon dioxide, and surface pressure and temperature (Smith et al. 2012). This work was performed primarily by Dr. Elisabeth Weisz and Dr. William Smith, with coordination provided by Dr. David Tobin.

The S-HIS DR retrieved temperature and water vapor results were compared with collocated AVAPS profiles. A two-minute mean of S-HIS DR temperature and water vapor profiles were plotted on a skew-T diagram for each AVAPS dropsonde during the HS3 campaign. An example from the 2013 season is provided in Figure 44.

Daily-mean, four-panel images representing S-HIS DR retrievals relative to AVAPS dropsondes were also created for each HS3 flight. Data were compiled with respect to relative humidity (RH) and water mass mixing ratio (H2OMMR). Data were also filtered based on DR retrieved cloud top pressure limited to 700 mb. An example four-panel image is provided in Figure 45;

A radiative closure study to further characterize and confirm the observed AVAPS dry bias was completed. Once again, data were compiled with respect to relative humidity (RH) and water mass mixing ratio (H2OMMR), and were filtered based on DR retrieved cloud top pressure limited to 700 mb. The AVAPS and dual-regression retrieved profiles were used to compute upwelling radiance at the Global Hawk altitude and compared to the S-HIS measured radiances. An example of this comparison was presented at the 2015 HS3 Science Team Meeting (Figure 46). The strong negative bias for AVAPS between 1200 and 2000 cm^{-1} is indicative of an upper tropospheric water vapor deficiency (dry bias). The S-HIS measured radiances (converted to equivalent brightness temperature) are expected to be accurate to approximately 0.25K or better for this wavenumber region and scene brightness temperature.

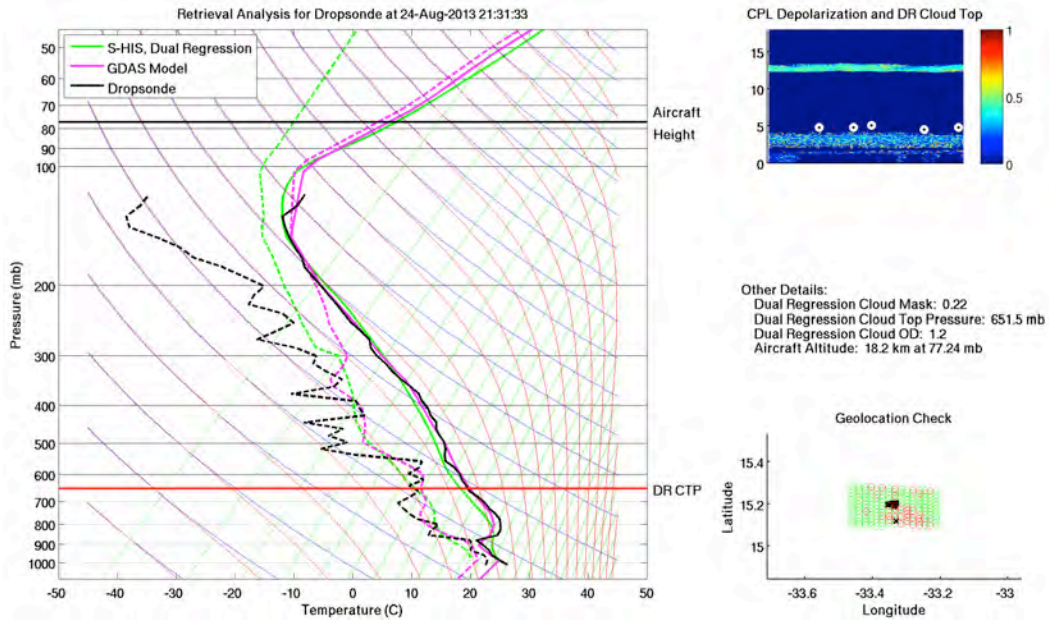

Figure 44: Sample DR Profile comparison to Dropsonde & GDAS; 24 August 2013. This example shows a good retrieval quality, despite upper level thin cirrus and lower level aerosol layers. The left panel shows a skew-T diagram that includes the dropsonde (black), S-HIS DR mean retrieval (green) and GDAS model (magenta) profiles; where dashed-lines represent dewpoint temperature and solid lines indicate temperature. The top right image shows the CPL depolarization for a two-minute window centered on the dropsonde time, used to illustrate the nadir cloud conditions for the given dropsonde. A geolocation sanity check is provided in the lower right. This image shows the S-HIS surface projected points (circles; green suggests no cloud while red specifies a positive cloud retrieval) and the dropsonde position during its descent (black x).

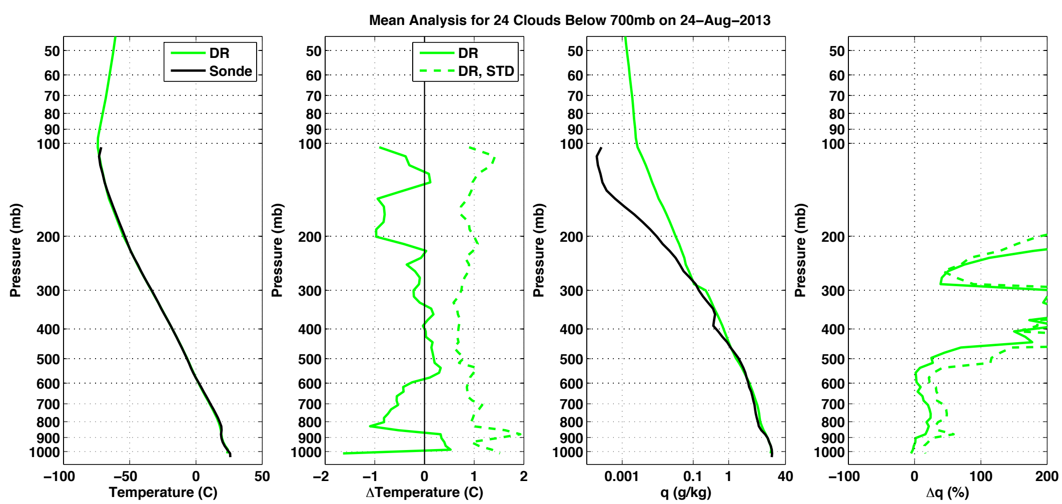

Figure 45: A daily-mean, four-panel image representing S-HIS DR retrievals relative to AVAPS dropsondes is created for each HS3 mission sortie. The dry bias of the dropsonde above 400 mb is a consistent feature. Data are compiled with respect to relative humidity (RH) and water mass mixing ratio (H2OMMR). Data are also filtered based on DR retrieved cloud top pressure limited to 700 mb. The first panel shows the mean daily temperature profile for each dropsonde (black) and corresponding two-minute mean S-HIS DR retrieval (green); panel 2 shows the difference from mean (T_{DR} – T_{AVAPS}) and its standard deviation; panel 3 shows the same as panel 1, but for relative humidity (note the significant dry bias in the dropsonde

above 400 mb); and panel 4 shows the difference from mean for RH, along with its standard deviation (RH_{DR} – RH_{AVAPS}).

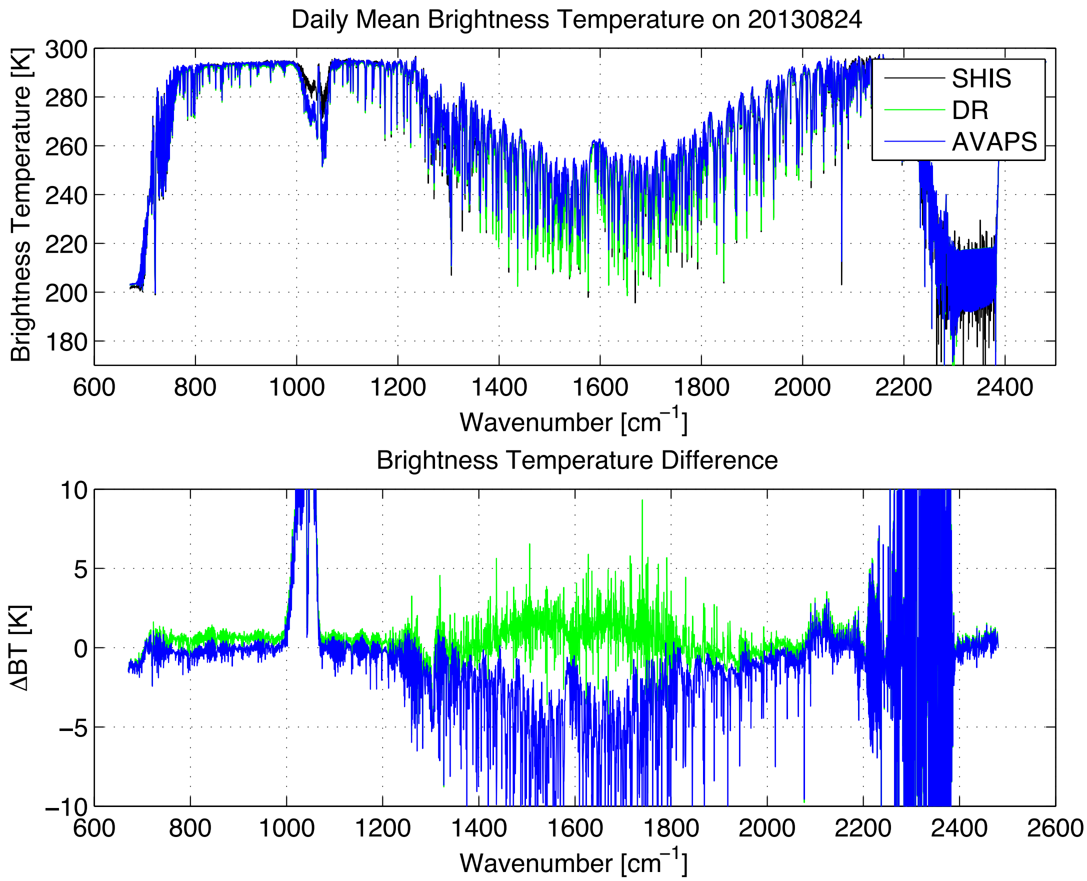

Figure 46: Radiance closure study results for 24 August 2013 flight. The AVAPS and dual regression profiles were used to compute upwelling radiance at the Global Hawk altitude and compared to the S-HIS measured radiance. Results are indicated in brightness temperature units. The strong negative bias for AVAPS between 1200 and 2000 cm^{-1} is indicative of an upper tropospheric water vapor deficiency (dry bias).

Nadir S-HIS DR retrieved cloud top pressure and optical depth are compared to collocated Cloud Physics Lidar (CPL) measurements for all flights, on both an individual flight, annual, and full-mission basis. An example of the comparison for the 2013-08-28 flight is shown in Figure 47. The top panel shows the CPL log-extinction as a function of time for the entire flight. The DR cloud top pressure was overlaid upon the CPL image with a black dot for each collocated DR cloud top that was retrieved. The bottom left image shows the collocated flight track for the given sortie, where black indicates high cloud and white indicates low cloud (or clear sky). The adjacent image is a density scatterplot showing the collocated DR cloud top heights relative to CPL. Data are filtered to exclude non-uniform scenes (i.e., CPL Z STD < 2 km). The bottom right-most image provides a summary classification of all collocated S-HIS DR and CPL measurements for the flight, and the neighboring panel to the left shows a histogram of the collocated S-HIS DR – CPL cloud top height differences, applying the same non-uniform scene filter used for the density scatterplot.

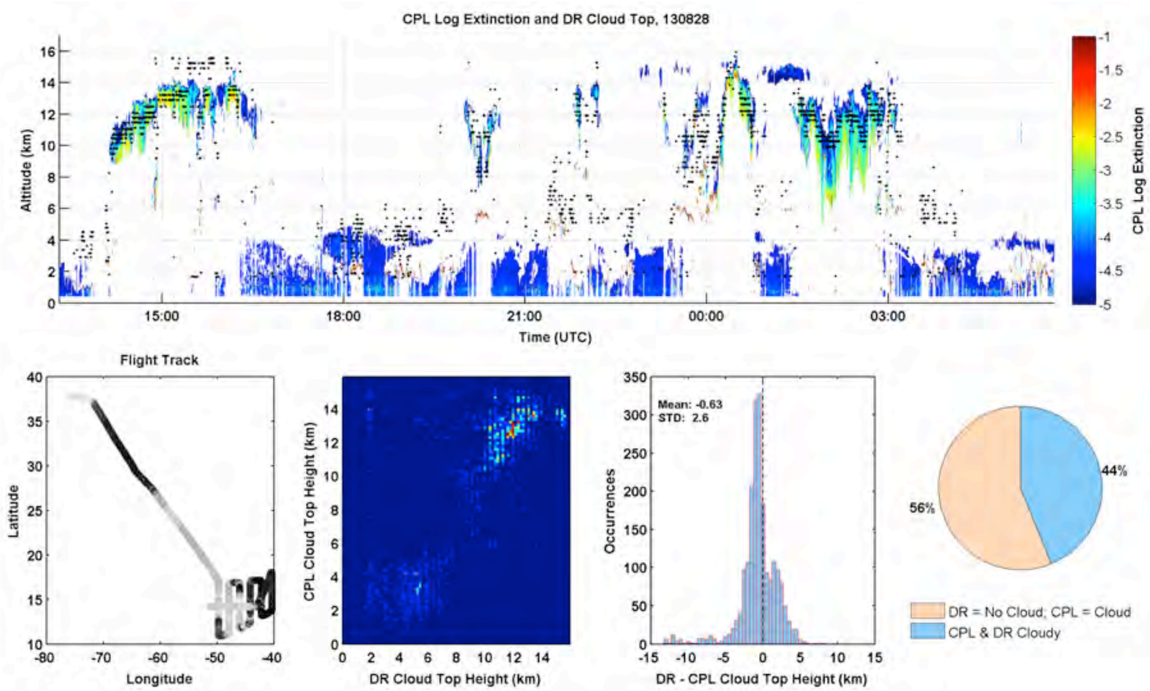

Figure 47: Example comparison of S-HIS DR retrieved cloud top pressure and optical depth and collocated Cloud Physics Lidar (CPL) measurements.

An example of an annual statistical comparison of S-HIS DR retrieved cloud top pressure and optical depth and collocated CPL measurements for the 2013 mission is shown in Figure 48. The analysis was extended to determine the effects of cloud optical depth for cases where the S-HIS DR did not discern the presence of cloud. Data was further broken down to clouds above (or below) 5 km. Mean collocated CPL data were used for both OD and cloud top height in this analysis.

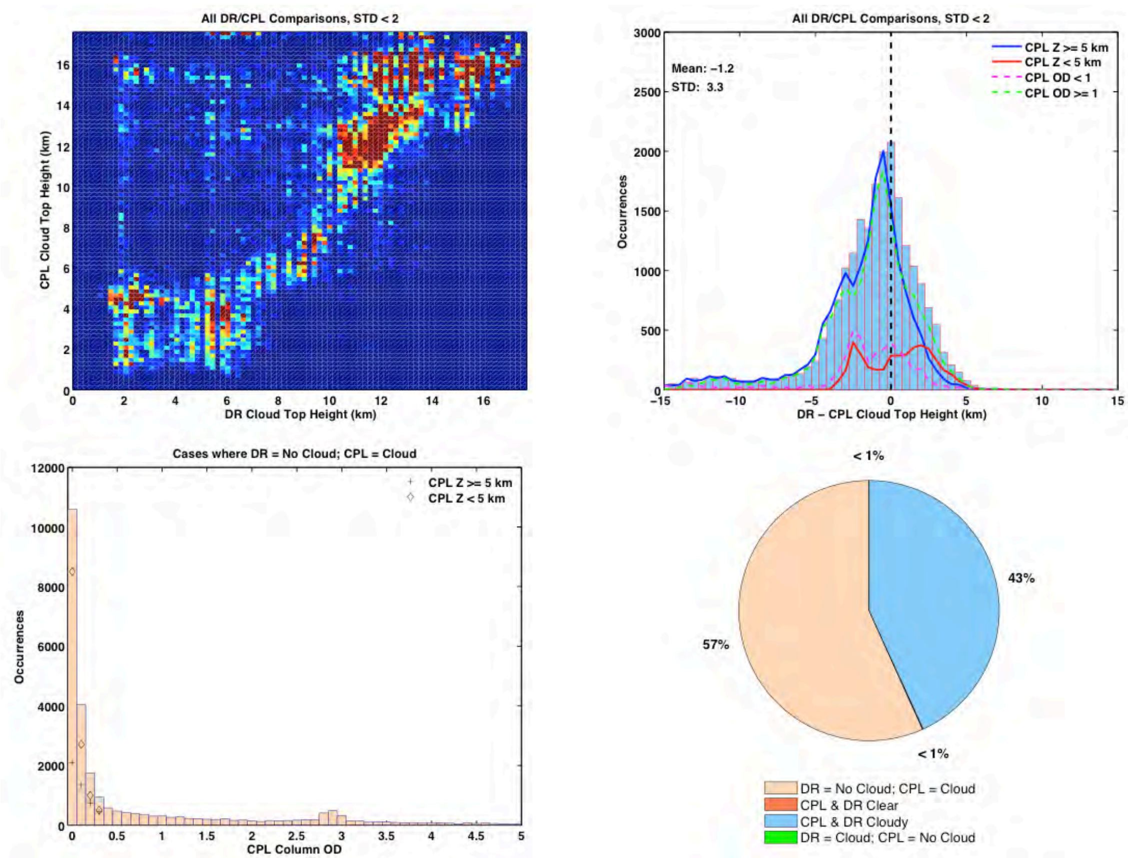

Figure 48: Statistical comparison of S-HIS DR retrieved cloud top pressure and optical depth and collocated CPL measurements for 2013 mission.

Smith, William L. Sr.; Weisz, Elisabeth; Kireev, Stanislav V.; Zhou, Daniel K.; Li, Zhenglong and Borbas, Eva E. ***Dual-regression retrieval algorithm for real-time processing of satellite ultraspectral radiances.*** *Journal of Applied Meteorology and Climatology, Volume 51, Issue 8, 2012, 1455–1476. Reprint #6809.*

4.2 UWPHYSRET Physical Retrieval Algorithm

A research algorithm developed at the University of Wisconsin for use with satellite data has been implemented for processing S-HIS data during the HS3 mission. This method is based on the Rodgers (2000) methodology of maximum a posteriori probability (MAP) estimation, also known colloquially as Optimal Estimation. The software package developed at the UW-SSEC is called UWPHYSRET. The initial implementation of this algorithm used the LBLRTM line-by-line model from AER, Inc. as the forward operator. The UWPHSRET methodology was used to produce the S-HIS nadir cross-sections presented at the May 2012 science team meeting. This method allows UW experts to carefully evaluate the diagnostic properties of the retrieval for selected case studies. This method also provides uncertainty estimates along with the estimate of profile temperature and water vapor values.

During HS3 mission, this retrieval scheme was modified to run much faster by using the OSS forward model that was tuned by AER to accurately agree with LBLRTM. It is now practical to explore a larger set of case studies. UWPHYSRET also provides uncertainty estimates along with the estimate of profile temperature and water vapor values.

5 Support of Science Team

The S-HIS team supported all Science Team telecons and Science Team Meetings (2010, 2012, 2013, 2014, and 2015). The following posters and talks were presented by members of the S-HIS team at the Science Team Meetings:

- 2010: Overview of the S-HIS Instrument. Hank Revercomb et al (presentation);
- 2012: S-HIS Status and Performance on the Global Hawk Demonstration Flights. Joe Taylor et al (presentation);
- 2012: S-HIS Retrieval Results; Comparisons to GDAS, IR Satellite, HAMSR, and Dropsondes. Bob Knuteson et al (presentation);
- 2013: Summary of S-HIS Status and Results. Hank Revercomb et al (presentation);
- 2013: S-HIS Real-time Processing and Data Transport. David Hoese et al (poster);
- 2013: S-HIS Radiometric Calibration and Performance. Joe Taylor et al (poster);
- 2014: Summary of S-HIS status, Real-time Data Collection and Processing. Dan DeSlover et al (presentation)
- 2014: S-HIS Dual Regression Analysis for the 2012 and 2013 Campaigns Relative to AVAPS and CPL measurements. Dan DeSlover et al (poster).
- 2014: Scanning High-resolution Interferometer Sounder (S-HIS) Radiometric Calibration and Performance Summary (HS3 2013). Joe Taylor et al (poster).

6 UW HS3 Summary of Accomplishments

The University of Wisconsin Space Science and Engineering Center team in support of the S-HIS instrument successfully provided real-time, and quality controlled final radiance and retrieval products for the NASA HS3 mission. Final products have been made available for distribution and have been archived to the HS3 data repository at the NASA GHRC DAAC. Major accomplishments include:

- Improvements to the Global Hawk Zone 25 thermal environment to enhance S-HIS calibration accuracy and reduce operational risks from high electronics temperatures were implemented and verified.
- Successful operation of the S-HIS on long duration Global Hawk flights has been demonstrated, with greater than 99% up-time from takeoff to landing,
- Accurate radiance spectra from all science flights have been processed and temperature/water vapor profile products show reasonable agreement with dropsonde, CPL, and HAMSR microwave results,
- S-HIS calibration reference accuracy has been verified,
- S-HIS data handing and processing for real-time and near real-time processing was developed and were operational for all science flights, with products displayed in NASA MTS and via webpage quick-looks,
- Improved retrieval capabilities have been implemented, including a physical retrieval for clear sky (UWPhysRet) and a Dual Regression capability for clear and cloudy skies,
- Quick-look product images, comparison plots, and final data products were made available during each reporting period. Final products and Matlab readers for the data products were delivered via the SSEC ftp server. All datasets were reprocessed using the 2015 data processing algorithms, and re-distributed and archived to the HS3 project data repository
- Active participation in the annual science team meetings and in team telecons.