To: kenneth.w.jucks@nasa.gov
From: Hank Revercomb
Date: 27 December 2012

Re: **Second Annual Report for CLARREO SCIENCE DEFINITION TEAM MEMBERSHIPS** (NASA Award Number, NNX11AE70G), University of Wisconsin-Madison, Space Science and Engineering Center

This is the second Annual Report for NASA Award Number NNX11AE70G, entitled CLARREO Science Definition Team (SDT) Memberships, with the overall objective of helping CLARREO become a successful climate benchmark mission by providing expert guidance to the CLARREO project in the wide range of areas.

This effort includes four SDT team memberships. The primary focus areas for each SDT member are (1) Revercomb: SI-traceable uncertainty analyses and Post-launch validation; (2) Knuteson: Infrared benchmark product development and model comparisons; (3) Smith: Climate trend detection and attribution, especially using special regression inversion techniques; and also including involvement in model comparisons and (4) Tobin: Use of CLARREO data as reference calibration for operational and research sensors.

Progress is reported for each team member in the four subsections to follow. Each identifies the general task areas in which contributions were made. The general task areas proposed included the following list:

1. Refining and prioritizing the goals of the mission, consistent with resource constraints
2. Refining the prioritizing the definition of required measurements
3. Refining and prioritizing measurement requirements
4. Developing calibration and validation plans
5. Defining geophysical products, data sets, and related processing algorithms
6. Identifying and performing prelaunch studies supporting mission goals
7. Developing science data processing system requirements and approach
8. Defining approaches for using CLARREO data for testing and improving climate projections
9. Science team telecons
10. Approximately three SDT Meetings per year.

Members participated in monthly team telecons and in the two SDT meetings held this year (10-12 April 2012 Hampton, VA and 16-18 October 2012 Boulder, CO).

1. Revercomb: SI-traceable uncertainty analyses and Post-launch validation

Results of analyses demonstrating the readiness of recent technological advancements to (1) meet the demanding CLARREO IR Earth radiance accuracy requirements (0.1 K 3-sigma brightness temperature calibration accuracy) and (2) allow this accuracy to be proven with on-orbit standards were refined and presented at two CLARREO SDT Meetings. The climate benchmark approach for CLARREO includes the use of (1) a calibrated Fourier Transform Spectrometer (FTS) that we refer to as the Absolute Radiance Interferometer (ARI) to measure Earth emitted radiance over much of the IR spectrum, and (2) an On-orbit Absolute Radiance Standard (OARS) that can be operated over a wide range of temperatures to verify the ARI accuracy on orbit. We also reported on our recent NASA Instrument Incubator Program test results that support this conclusion.

The latest results of the IR accuracy demonstration at Wisconsin were presented at the Fall 2012 American Geophysical Union (AGU) meeting supporting the conclusion that the expected performance of the OARS will meet the requirement of providing direct SI traceability to fundamental physical properties with better than 0.1 K 3-sigma radiance accuracy, traceable to on-orbit phase change standards. A list of references from the AGU meeting is given below:

A21E-0116. Observing Decadal Trends in Atmospheric Feedbacks and Climate Change with Zeus and CLARREO, Henry E. Revercomb; Fred A. Best; Robert O. Knuteson; David C. Tobin; Joe K. Taylor; P Jonathan Gero; Douglas P. Adler; Claire Pettersen; Mark Mulligan; David C. Tobin

A21E-0119. On-Orbit Absolute Radiance Standard for the Next Generation of IR Remote Sensing Instruments, Fred A. Best; Douglas P. Adler; Claire Pettersen; Henry E. Revercomb; P. J. Gero; Joe K. Taylor; Robert O. Knuteson; John H. Perepezko

A21E-0117. The University of Wisconsin Space Science and Engineering Center Absolute Radiance Interferometer (ARI): Predicted and Demonstrated Radiometric Performance, Joe K. Taylor; Henry E. Revercomb; Henry Buijs; Frederic Grandmont; P. J. Gero; Fred A. Best; David C. Tobin; Robert O. Knuteson

A21D-0087. The Heated Halo for Space-Based Blackbody Emissivity Measurement, P Jonathan Gero; Joe K. Taylor; Fred A. Best; Henry E. Revercomb; Raymond K. Garcia; Douglas P. Adler; Nick N. Ciganovich; Robert O. Knuteson; David C. Tobin

Contributions were made to general tasks 1-4, 9 and 10.

2. Knuteson: Infrared benchmark product development and model comparisons

Results of analyses identifying and performing prelaunch studies in the area of CLARREO benchmark products were presented at two CLARREO SDT Meetings. Details of the analysis performed during the reporting time period are given in the following paragraphs. Contributions were made to general project tasks 5-10.

A study conducted by graduate student Ms. Jacola Roman was performed that identified a methodology for the regional validation of Global Climate Model (GCM) moisture fields in the U.S. Great Plains and Midwest. Ms. Roman is pursuing a graduate degree in the University of Wisconsin-Madison Atmospheric and Oceanic Sciences department. Her research is partially supported by the NASA CLARREO mission through a research assistantship funded by this project within the UW Space Science and Engineering Center. The results of Ms. Roman's study were published in the Journal of Climate in 2012, the publication citation is given below;

Roman, Jacola A., Robert O. Knuteson, Steven A. Ackerman, David C. Tobin, Henry E. Revercomb, 2012: **Assessment of Regional Global Climate Model Water Vapor Bias and Trends Using Precipitable Water Vapor (PWV) Observations from a Network of Global Positioning Satellite (GPS) Receivers in the U.S. Great Plains and Midwest**. J. Climate, 25, 5471–5493. doi: http://dx.doi.org/10.1175/JCLI-D-11-00570.1

During the current year reporting period, Ms Roman presented a study at the April CLARREO science team meeting titled, *Estimating Column Water Vapor Time-To-Detect Using CLARREO-Proxy Retrievals*, the link to the presentation is provided below: (http://clarreo.larc.nasa.gov/2012CLARREO_SDT/Tuesday/Roman_Knuteson_clarreo_spring_2012_version5jar.pdf). Extracted from that presentation, Figure 1 illustrates the importance of assessing the CLARREO benchmark product on regional (15x30 deg) scales. For atmospheric total water vapor, the time to detect mid-latitude zonal trends can be greatly reduced by focusing on regions such as the Eastern U.S., India, and China. Implications for the societal impact of a CLARREO mission in the assessment of climate change are the subject of future work.

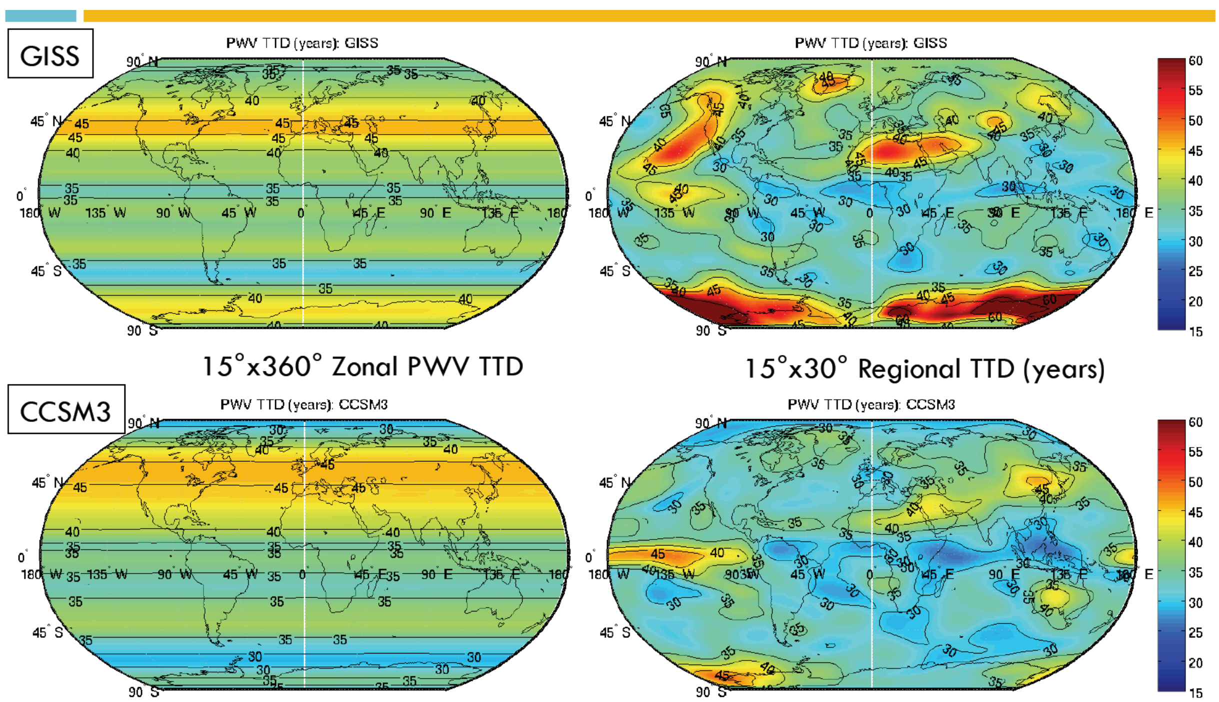

Figure 1. Comparison of two GCM models (from CMIP3) for the time to detect zonal and regional 100 year trends.

3. Smith: Climate trend detection and attribution, especially using special regression inversion techniques

During 2012 two major studies were undertaken to determine the feasibility of determining climate trends, and their accuracy, from satellite Dual Regression (DR) profile retrievals. The dual regression retrieval method is a cloud height classified linear all sky condition retrieval algorithm in which the result depends solely on satellite measured radiances (i.e., atmospheric profile trends will result solely from trends in the observed radiances). During the previous year

(2011), it was shown that the DR retrieval method when applied to Aqua AIRS data provided climate quality retrievals on a global basis. The agreement between the AIRS DR retrieved monthly mean profiles, and their annual trends for the 2003-2009 period, compared with Global Data Assimilation System (GDAS) analyses of operational profile data, was excellent over the radiosonde data-rich land areas of the globe. Thus it was concluded that DR retrievals from ultraspectral instruments, such as the AIRS, IASI, CrIS, and the CLARREO interferometer, possess the relative accuracy needed for climate trend determination.

HIRS Capability: The first 2012 study, whose results were reported at the April 2012 Science Definition Team meeting, investigated the use of the DR retrieval algorithm using High-resolution Infrared Radiation Sounder (HIRS) measurements. HIRS has a continuous record of radiance observations dating back to 1975. Although the HIRS record is long, it is not clear that the radiance observations can be useful for climate variable trend analysis because of their low vertical resolution resulting from the relatively low spectral resolution (4- 100 cm^{-1}) of the radiance measurements. Thus, the objective of this first study was *"to determine whether or not useful climate trend parameters can be obtained from the continuous record of HIRS data dating back to the Nimbus-6 HIRS of 1975"*.

The procedure used for accomplishing this objective was to determine the accuracy of HIRS monthly mean climate variables relative to the already established accuracy of AIRS monthly mean values. The procedure used involved:

(1) Simulating HIRS from IASI (IASI absolute calibration is comparable to AIRS) by spectral convoluting the continuous IASI radiance spectra using the HIRS channel spectral response functions.

(2) Retrieving global monthly mean climate variables, for 10-dgree latitude longitude grid areas, using the same DR retrieval algorithm used for CLARREO AIRS climate parameters

(3) Comparing differences of HIRS and AIRS with respect to GDAS profiles as a measure of relative accuracy (i.e., in order to account for diurnal sampling differences between Metop-HIRS (09:30 orbit) and Aqua-AIRS (13:30 orbit)

Figure 2 below shows the difference between AIRS and "HIRS" monthly mean temperature and humidity with the GDAS product for 500 hPa temperature and relative humidity. It can be seen that although the difference magnitudes and pattern for relative humidity are comparable, the magnitudes and difference patterns for atmospheric temperature are not comparable, often with magnitude differences in sign.

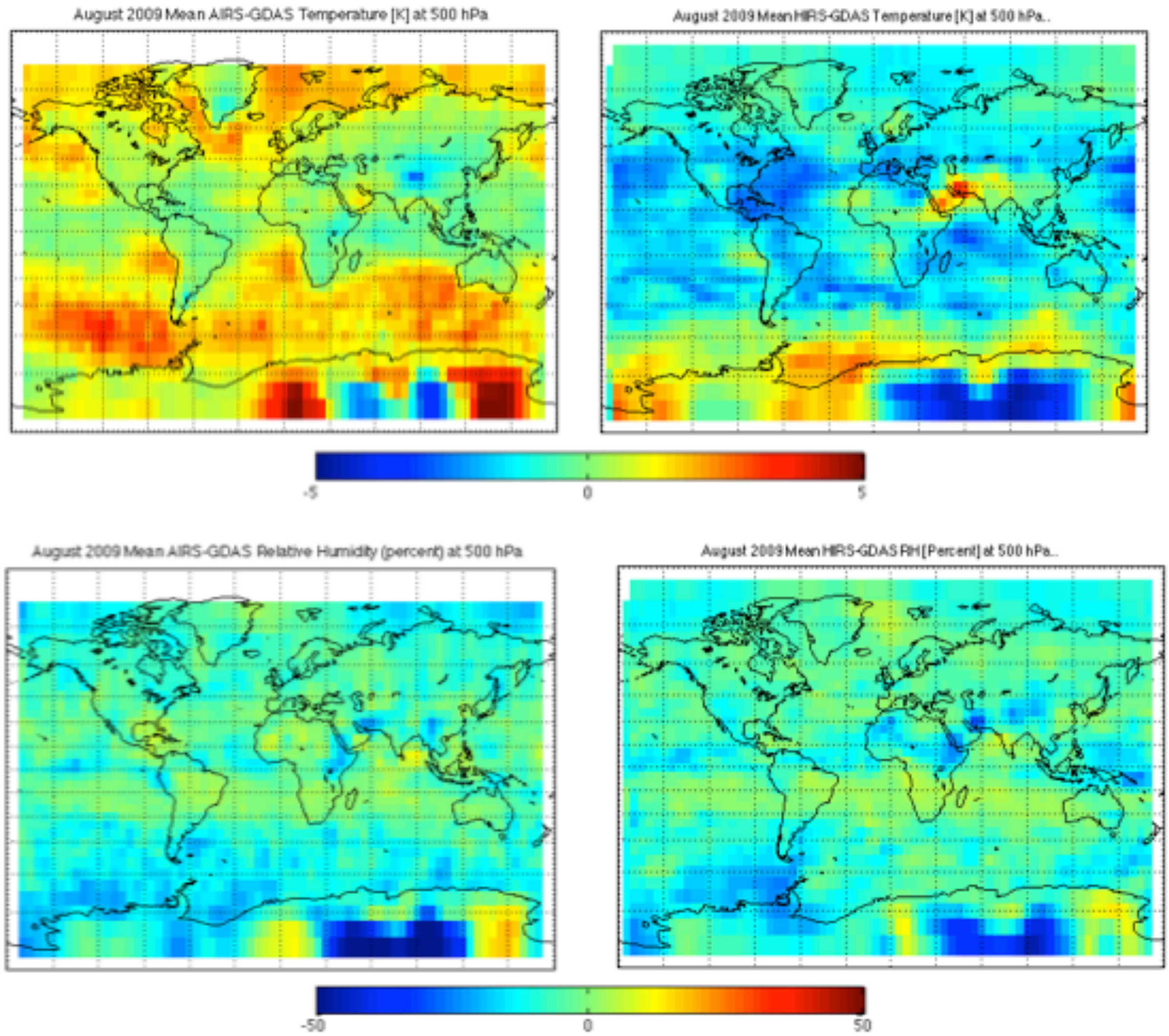

Figure 2. Comparison between AIRS and GDAS (Left hand panels) and "HIRS" and GDAS differences for August 2009 500 hPa temperature (upper panels) and relative humidity (lower panels).

Figure 3 shows the mean and standard deviation of the AIRS and GDAS differences and "HIRS" and GDAS differences computed for the entire globe (area weighted) for August 2009. Note that the abscissa for the "HIRS minus GDAS" plots is twice that of the "AIRS minus GDAS" plots. As can be seen the magnitude of the standard deviations are twice as great for HIRS as they are for AIRS, regardless of atmospheric level. This result is consistent with that expected from the difference in the vertical resolving power of the multi-channel HIRS and ultraspectral IASI measurement systems.

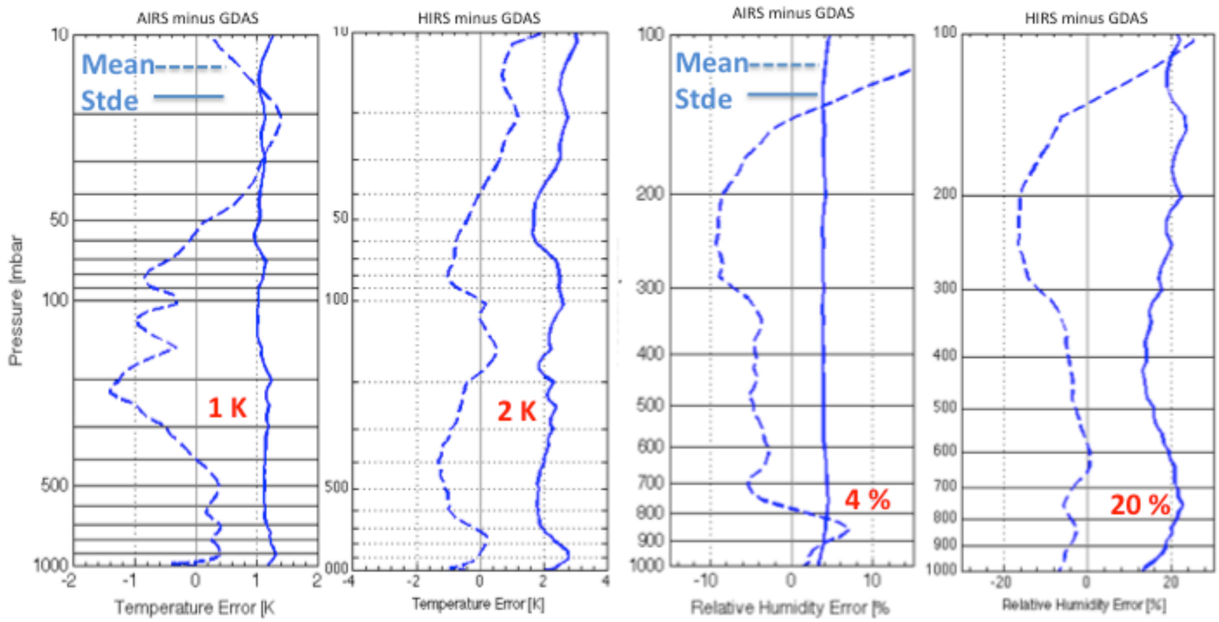

Figure 3. Global area weighted mean and standard deviation of retrieved and GDAS atmospheric temperature and humidity profiles for the entire month of August 2009.

Thus, the results of this study can be summarized as follows:

1. *The HIRS retrieval errors appear to be too large to provide climate accuracy measurements of atmospheric state for the early detection and specification of the magnitude of climate change*
2. *The results validate the need for satellite ultraspectral radiance measurement (e.g., from CLARREO) retrievals for providing atmospheric state measurements with suitable accuracy for the early detection and specification of the magnitude of climate change*

AIRS, IASI, CrIS Sounding Retrieval Differences: The second study focused on analyzing the source of differences observed between AIRS and CrIS retrievals and the implication of using these operational satellite sounding retrievals for climate monitoring. The retrieval method used was the DR algorithm, which has been shown to produce monthly mean average soundings for 10-degree latitude/longitude areas that are in excellent agreement with analyses of operational sounding data, particularly in radiosonde rich land areas of the globe. However, comparisons of soundings from AIRS and CrIS, which are very close in time and space, as a result of both satellites being in the same orbital plane, reveal small, but possibly significant, synoptic scale systematic differences between the two sets of sounding data. Since exactly the same retrieval algorithm and a similar set of spectral channels are used for the retrievals, it is concluded that these retrieval differences must be due to small synoptic scale differences in the radiances measured by the two satellite instruments. The AIRS is a grating spectrometer in which each spectral channel is observed with a separate detector element, whereas the CrIS is an interferometer spectrometer in which the radiance spectrum over three broad spectral bands is observed using a single detector for each spectral band.

In order to study the significance of the retrieval differences resulting from these two different types of instruments, computer software was prepared to obtain space and time co-located radiance spectra and sounding retrievals from the Aqua and Suomi-NPP satellites. Also, software based on an algorithm developed by team member Dave Tobin was developed to simulate AIRS spectral channel radiances from CrIS quasi-continuous radiance spectra. These tools were then used to analyze granules of Aqua AIRS and Soumi-NPP CrIS data for various geographical locations and times.

Figure 4 shows statistics that imply that, for a relatively large geographical region (25-60 N, 60-100 W) over a half-monthly period (16-30 April, 2012), the errors in the AIRS, CrIS, and IASI retrievals are comparable. The two left hand panels show that there is little difference in the mean and standard deviations of the errors of the retrievals from each instrument, assuming the GDAS analyses are a good measure of "Truth". However, the right hand panels show that the retrievals are not the same when measured at the same location and time and that there are significant systematic differences between the three sets of sounding retrievals, particularly for atmospheric temperature. For climate analyses using a combination of these satellite retrievals, such systematic differences must be eliminated in order to eliminate false climate signals resulting from the diurnal sampling characteristics of each satellite system.

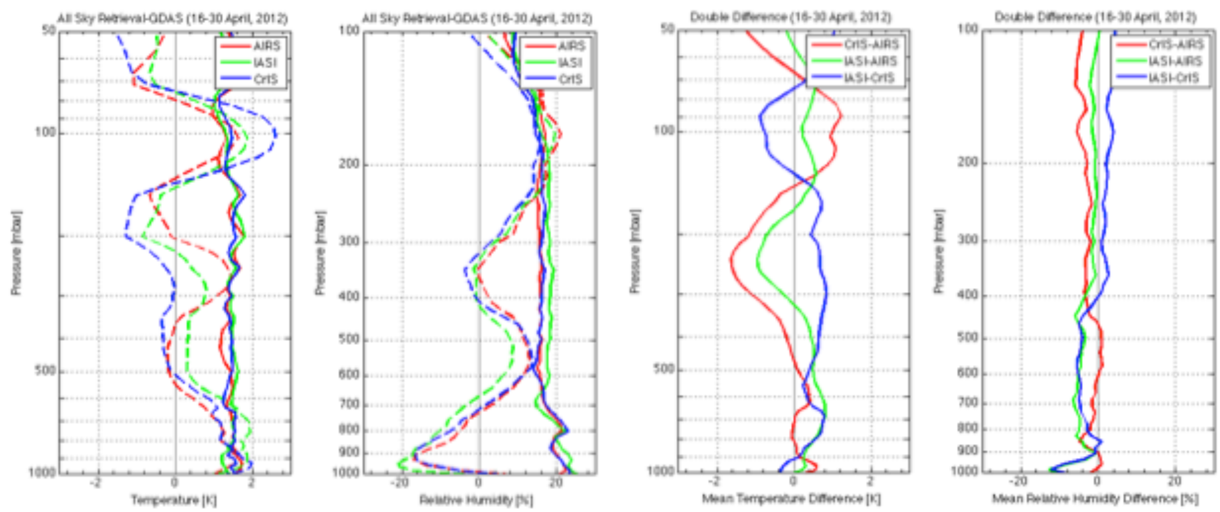

Figure 4. Mean (dashed curves) and standard deviations (solid curves) between AIRS, CrIS, and IASI profile retrievals and co-located GDAS analyses of operational temperature and relative humidity sounding data (left hand panels) within the radiosonde data rich geographical area 26-60 N, 60-100W for all orbits within the 16 – 30 April 2012 time frame. Also shown is the mean of the differences between individual pairs of the retrievals (right hand panels) used to obtain the statistics shown in the left hand panels.

Figure 5 below is an example, April 27, 2012, which shows the geographical dependence of the retrieval differences for AIRS and CrIS on the brightness temperatures averaged over 20 cm-1 spectral intervals observed at 0717 UTC and 0712 UTC for the two instruments, respectively. The very large differences (dark regions) in the brightness temperature difference images are the result of clouds that are sampled differently as a result of field of view response differences between the two instruments. However, one can see that away from clouds the brightness temperature differences are small (< 1 K) but not random noise. The synoptic scale patterns of these small radiance differences can be seen to cause significant differences in the retrieved atmospheric relative humidity and temperature as large as 20 % and 2 K, respectively. Thus, it is important to be able to cross-calibrate the radiances from the various sounding instruments in order to eliminate erroneous instrument dependent retrieval sampling errors in climate analyses of multiple satellite sounding data. One very notable feature is the influence of radiance measurement differences for the great lakes that are reflected in the 500 hPa retrieved temperature analysis. These differences are most likely a result of instrument hardware differences, such as the different scan mirror coatings and their sensitivities to polarized scene radiance, although they could also be due to angular differences in the reflectivity of water for the two different local zenith angles of the two satellite measurements. In either case, this radiance measurement difference results in an erroneous artifact results in the retrieved 500-mb temperature field.

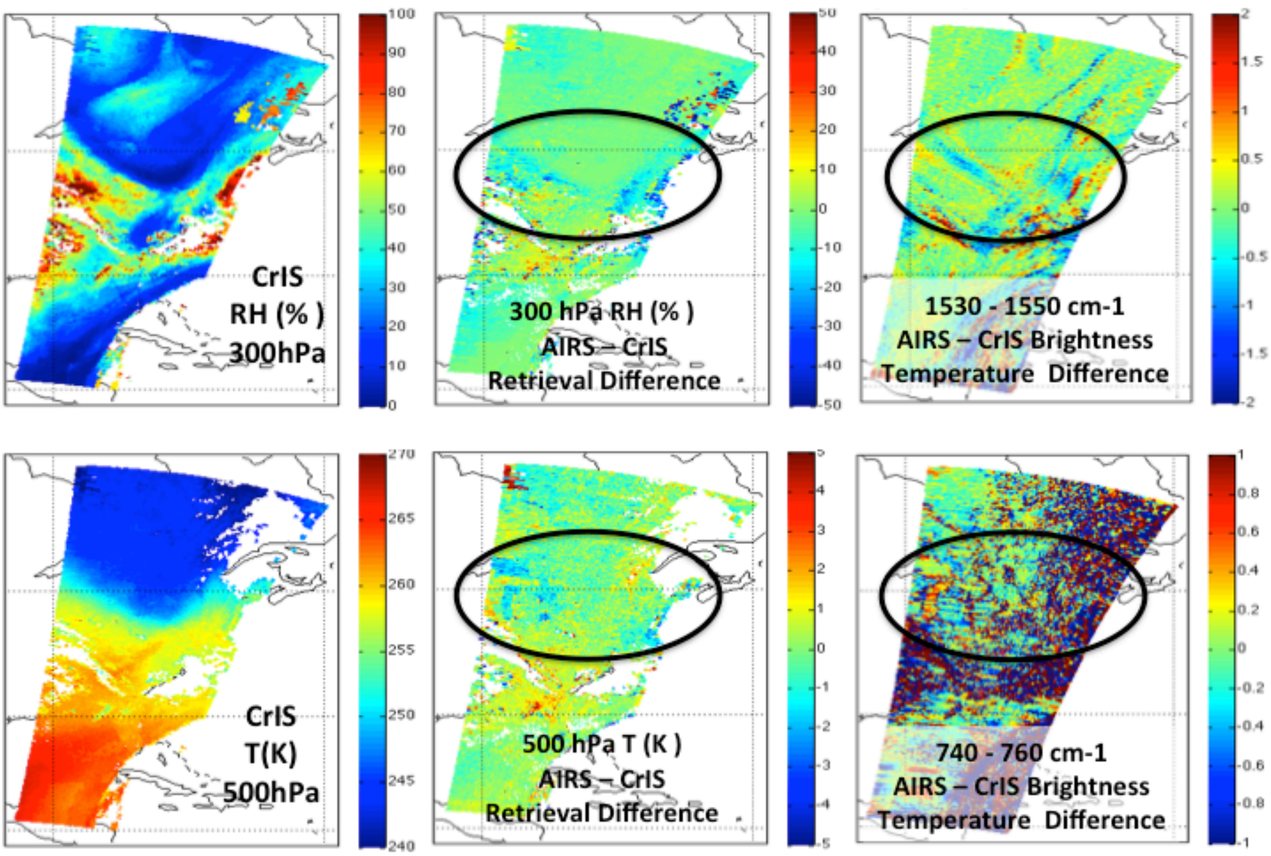

Figure 5. An example (April 27, 2012) showing the dependence of AIRS (07:17 UTC) and CrIS (07:12 UTC) retrievals on the difference of the radiances, expressed in brightness temperatures, measured by the two instruments.

The analysis of AIRS and CrIS retrieval differences was supported by a satellite validation flight conducted using the NASA Global Hawk (GH) Unmanned Airborne Vehicle (UAV) during "The Hurricane and Severe Storm Sentinel (HS3) Mission". The flight was coordinated to be under the Aqua and Suomi-NPP satellite overpasses of the western Atlantic ocean (25-35 N, 70-75 W) around 20 UTC on October 6, 2012. The GH carried the Scanning High-resolution

Interferometer Sounder (SHIS) that observed radiance spectra from which atmospheric retrievals could be obtained with 2-km spatial resolution within the AIRS and CrIS data granules. The SHIS is known to have very high absolute accuracy with its calibration sources referenced to the NIST standard. Also, as many as thirty-six 2-km resolution SHIS soundings can be averaged within the 14-km footprints of the AIRS and CrIS sensors. Thus, by using exactly the same CrIS/AIRS/IASI DR retrieval algorithm to process the SHIS radiance data enabled the SHIS soundings to be a very low noise absolute accuracy airborne estimate of "retrieval truth" for validating the satellite-retrieved soundings.

Figure 6 shows the mean and standard deviations between AIRS, CrIS, and SHIS retrieved profiles with co-located profiles extracted from GDAS analyses of operational sounding data. Also shown are the mean and standard deviation of the retrieval differences for the three instrument pairs. The results indicate CrIS and SHIS provide the most accurate and comparable sounding retrievals as compared to AIRS, at least for the mid-low troposphere. This result may be due to the fact that the effective noise levels for both the SHIS and CrIS radiances are nearly six times smaller than that for the AIRS.

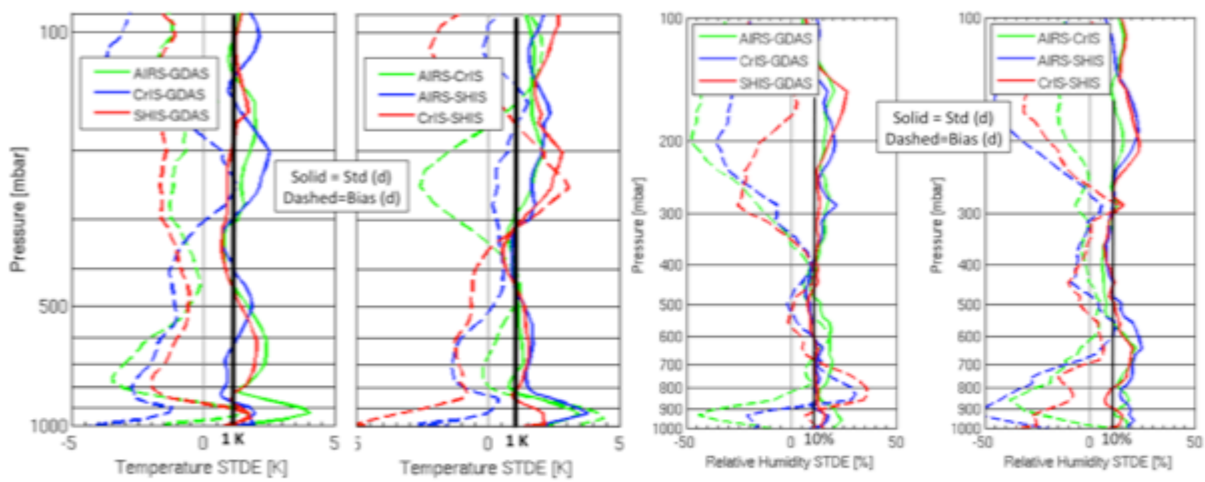

Figure 6. Mean (dashed curves) and standard deviations (solid curves) between AIRS, CrIS, and SHIS profile retrievals and co-located GDAS analyses of operational temperature and relative humidity sounding data (left hand and right hand panels, respectively) and the mean and standard deviation of the individual retrieval pairs within the geographical area 25-35 N, 65-75 W for October 6, 2012.

Thus, the results of this second study can be summarized as follows:

1. *Synoptic scale patterns of AIRS/CrIS retrieval differences result from small synoptic scale differences in the radiance observations.*
2. *Although relatively small, these differences could be significant for regional climate change studies if they were to persist in monthly averaged data.*
3. *Given the magnitude of ultraspectral sounders in orbit today (AIRS, CrIS, IASI-A, IASI-B), these biases should be able to be eliminated through cross calibration of the radiances obtained by the various sensors*

4. *The next step is to compute regional monthly mean averages of sounding variables from the various ultraspectral sensors in orbit in order to determine the accuracy to which regional climate change can be assessed through the analysis of operational satellite atmospheric profile retrievals*

Contributions were made to general tasks 5-10.

4. Tobin: Use of CLARREO data as reference calibration for operational and research sensors

Efforts this past year have focused on showing the benefits of a CLARREO mission for intercalibration objectives. Material below summarizes a) the demonstration of the CLARREO intercalibration technique as applied to CrIS/AIRS radiance intercomparisons, b) Simulations of the intercalibration accuracy for the proposed Zeus missions, and c) progress on documenting the CLARREO intercalibration technique and capabilities.

A) Demonstration of the CLARREO intercalibration technique as applied to CrIS/AIRS radiance intercomparisons

With the launch of Suomi-NPP in October 2011 and first data from the Cross-track Infrared Sounder (CrIS) in January 2012, we have participated in various Cal/Val studies for CrIS this year. This includes radiance intercomparisons with both AIRS and IASI via the "big circle" SNO technique, which is the same comparison technique that has been proposed for CLARREO intercalibration. Sample results for CrIS/AIRS intercomparisons are shown here, further demonstrating the validity and accuracy of the intercomparison technique and capability proposed for CLARREO.

Figure 7. below includes example information regarding the "big circle" intercomparison approach, showing a sample Simultaneous Nadir Overpass (SNO) of AIRS and CrIS, and for a large ensemble of SNOs the Gaussian behavior of the differences due to spatial non-uniformity. Figure 8 then shows comparisons of CrIS and AIRS for three wavelength regions. As with our previous simulation studies, these types of comparisons using real data demonstrate that the biases between two sensors can be determined with very low uncertainty using the CLARREO intercomparison principles.

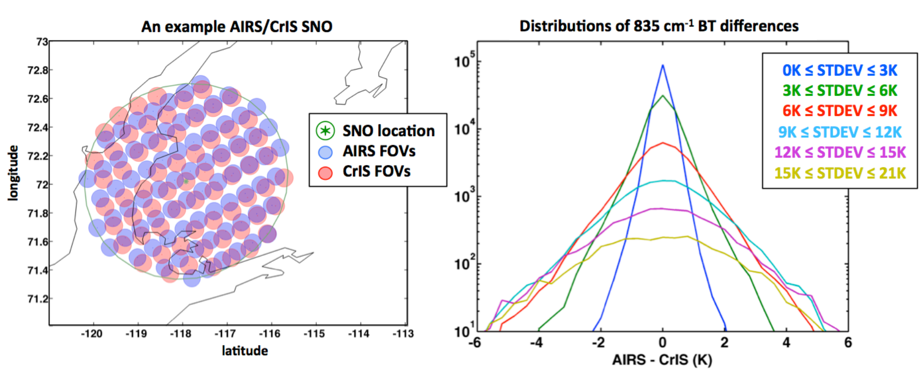

Figure 7. Locations of AIRS and CrIS footprints within a ~100km "big circle" centered on an example SNO location (left) and distributions of AIRS minus CrIS 835 cm^{-1} brightness temperatures for different ranges of spatial non-uniformity from a large ensemble of SNOs (right).

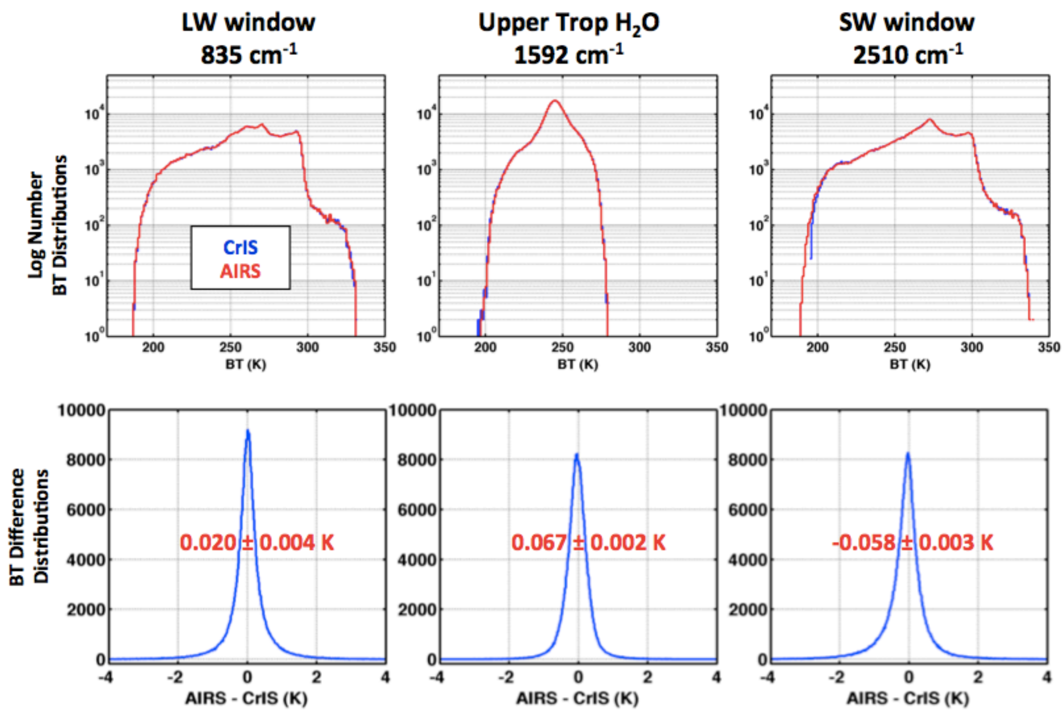

Figure 8. Example comparisons of AIRS and CrIS brightness temperature observations for three wavelength regions. The top panels show distributions of all-sky observations over ~8 months of co-located observations. The bottom panels show the distribution of differences, with the mean difference and uncertainty listed in red text.

B) Assessment of Zeus EV-2 and Zeus EV-I (ISS) Intercalibration capabilities

As part of our "Zeus" proposals to the NASA EV-2 and EV-I missions this year, the ability to perform intercalibration of operational hyperspectral sounders (AIRS, IASI, CrIS) with Zeus was assessed. Figure 9 shows example results from our simulations, for Zeus EV-2 (one 90° polar orbiting satellite) and for Zeus EV-I (on the ISS). The simulated intercalibration accuracy is shown as a function of mission time, and depends on the Zeus footprint size, noise performance, on the number of SNO coincidences obtained from each orbit, and on the wavelength region of interest. In both cases, the simulations show that an intercalibration accuracy of 0.1K 3-sigma is obtained within a few months of mission start.

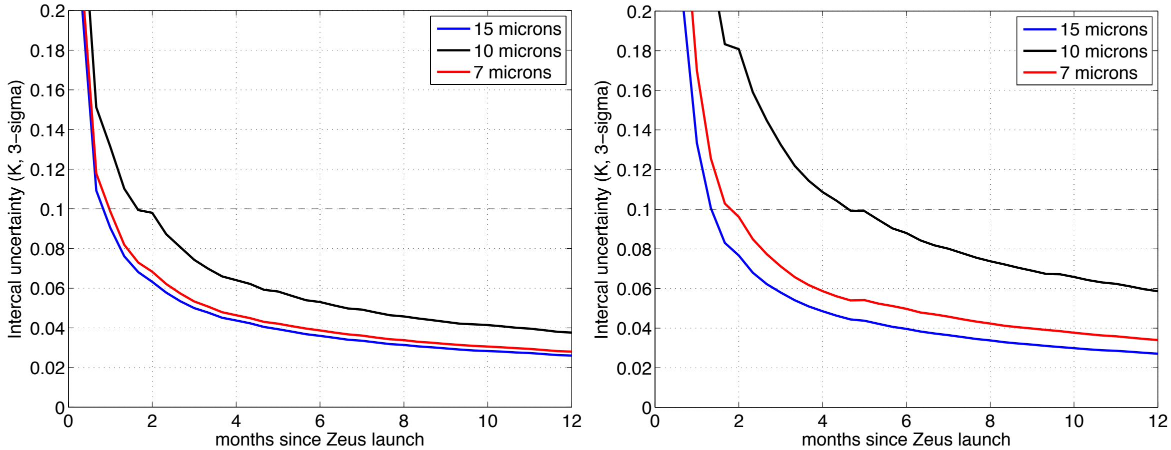

Figure 9. Operational sounder (e.g. AIRS, IASI, CrIS) intercalibration accuracy as a function of months since mission start for EV-2 Zeus (left, one 90° polar orbiting satellite) and for EV-I Zeus (right, on the ISS).

C) CLARREO IR Intercalibration paper

Despite various demonstrations of the intercalibration technique proposed for CLARREO in peer-reviewed and gray literature, there is a need for a dedicated peer-reviewed paper on the subject. "CLARREO as a Reference for Infrared Satellite Intercalibration" by Tobin, D. C., R. E. Holz et al. is currently in preparation for submission to J. Atmos. Oceanic Technol. or Geoscience and Remote Sensing Letters. This paper will describe the CLARREO IR intercalibration technique and provide information on how accurate the intercalibration can be performed.

Contributions were made to tasks 1, 2, 3, 5, 6, 7, 9, and 10.