Title of Grant / Cooperative Agreement:	NRA / Research Opportunities in Space and Earth Sciences-2010
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Name of Principal Investigator:	Hank Revercomb
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Name and Address of recipient's institution:	UNIVERSITY OF WISCONSIN SYSTEM 21 N PARK ST STE 6401 MADISON WI 53715-1218
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Reference 14 CFR § 1260.28 Patent Rights *(abbreviated below)*
The Recipient shall include a list of any Subject Inventions required to be disclosed during the preceding year in the performance report, technical report, or renewal proposal. A complete list (or a negative statement) for the entire award period shall be included in the summary of research.

Subject inventions include any new process, machine, manufacture, or composition of matter, including software, and improvements to, or new applications of, existing processes, machines, manufactures, and compositions of matter, including software.

Have any Subject Inventions / New Technology Items resulted from work performed under this Grant / Cooperative Agreement?	No ○	Yes ◉
If yes a complete listing should be provided here: Details can be provided in the body of the Summary of Research report.		

Reference 14 CFR § 1260.27 Equipment and Other Property (abbreviated below)
A Final Inventory Report of Federally Owned Property, including equipment where title was taken by the Government, will be submitted by the Recipient no later than 60 days after the expiration date of the grant. Negative responses for Final Inventory Reports are required.

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Attach the Summary of Research text behind this cover sheet.

Reference 14 CFR § 1260.22 Technical publications and reports (December 2003)
Reports shall be in the English language, informal in nature, and ordinarily not exceed three pages (not counting bibliographies, abstracts, and lists of other media).

A Summary of Research (or Educational Activity Report in the case of Education Grants) is due within 90 days after the expiration date of the grant, regardless of whether or not support is continued under another grant. This report shall be a comprehensive summary of significant accomplishments during the duration of the grant.

To: Hal Maring
From: Hank Revercomb (PI), Dave Tobin (CoI), Bob Knuteson (CoI), Fred Best (CoI), Chris Moeller (CoI), Dan Laporte (CoI), and Larrabee Strow (Collaborator)
Date: 16 September 2015
Re: **NPP Science Team Grant (NNXAK21G) Final Report**

This is the final report for The University of Wisconsin-Madison, Space Science and Engineering Center grant entitled "***Assessment and Optimization of IR Radiance Measurements and Products for Climate, Assimilation, and Remote Sensing Applications: Continued NPP Science Team Participation***".

Following the completion of the assessment of the NOAA CrIS system to serve NASA as a source for climate quality products, we were given guidance to begin scoping out efforts required to provide algorithms to produce climate quality CrIS L1B radiance products for NASA. This marked the completion of the work under this (NNXAK21G) grant, and the remainder of this report includes summary material of our assessements. Progress of the L1B work is reported separately under a contract with NASA though JCET/UMBC (contract number 0000015021).

Because this project was focused on overall assessment reports from each Science Team (Sounder and Atmosphere), this final report consists of two parts, Part A addressing our overall evaluations of the CrIS sensor, algorithms, and data records; and Part B addressing our work on VIIRS Sensor evaluation. Very brief introductions to each part follows below.

(Part A) Our inputs on CrIS to the Sounder Team Assessment Report (page 2)—**Please read at least the first page, the Executive Summary**, consisting of bottom line recommendations. The report is organized as suggested by Jim Gleason. The Executive Summary, Section I, is followed by an Introduction and Background (Section II) and the main body is divided into Sections; (III) Sensor Characterization, (IV) Algorithms (including ATBDs and Software implementation), (V) Sensor Data Records from IDPS, (VI) Environmental Data Records from IDPS, and finally (VII) Recommendations for Improvements and New Products.

It should be noted that we are extremely pleased with the excellent performance of the CrIS instrument. It has been proven to display extremely stable and well understood spectral properties (annual changes are smaller than AIRS orbital changes), low noise (substantially better than both AIRS and IASI), and high accuracy (better than 0.2 K 3-σ brightness temperature for all wavelengths and scene temperatures, except for spectrally localized ringing that for many applications can be largely removed by apodization). CrIS is certainly capable of continuing the AIRS climate record with equal or better accuracy and spectral resolution, while requiring significantly fewer spacecraft resources.

(Part B) VIIRS Radiometric performance Studies (page 24)
This section details our year-2 contributions to resolution of the Reflective Solar Band degradations and comparisons of the VIIRS IR bands to CrIS that demonstrates the generally excellent calibration of VIIRS using the high spectral resolution standard of CrIS.

Support from the NPP Atmosphere PEATE has been especially important for both our CrIS and VIIRS work.

Part A. UW-SSEC Suomi NPP CrIS Product Assessment Report

(input to Sounder Team Report)

I. EXECUTIVE SUMMARY

Our current assessment of CrIS SDR and EDR algorithms and data are given below:

a. **Generally, Suomi NPP cal/val** has shown that CrIS observations are fully capable of successfully continuing the high accuracy and information content of the EOS Aqua AIRS climate record.
b. **The IDPS algorithm for CrIS SDR radiance** calibration meets the accuracy and latency requirements for weather applications, but the implementation is unnecessarily complex, expensive to modify, and sub-optimal for climate applications.
c. **The CrIS SDR data** produced by IDPS are meeting initial expectations, although subtle refinements are needed to improve data continuity and quality.
d. **The IDPS algorithm for CrIS EDR products** should be adequate for climate process studies, but alternative algorithms are needed to understand climate trend assessment.
e. **The assessment of the climate quality of CrIS EDR data** is currently in progress and no final conclusions can yet been drawn regarding the product performance.
f. **Alternative "Science" code** is a necessary tool for thorough evaluation of the vendor supplied IDPS code for each CrIS product, including SDRs, EDRs, IPs, and Level 3 gridded products.

The following recommendations are suggested for the next NPP solicitation for proposals:

1. **Elevate the priority and involvement for the development of CrIS SDR radiance gridded and PDF climate products** to more fully exploit the information content and absolute accuracy of the IR spectral radiances.
2. Encourage the development of **a satellite climatology of temperature and water vapor derived from CrIS EDRs** produced by IDPS **and several alternative algorithms** applicable to hyperspectral IR sensors.

3. Solicit the **development of additional products from NPP to continue and enhance the EOS AIRS record**, in particular the distribution of atmospheric greenhouse gases (CO_2, CH_4, CO, and O_3), clouds, and dust aerosols along with land/ice/ocean surface properties in the thermal infrared at high spectral resolution.
4. Solicit the development of product-centric algorithms and data to refine some sensor-centric algorithms and products, **specifically including the combination of CrIS, VIIRS, and ATMS for cloud and thermodynamic products.**
5. **Devote more resources to research involving CrIS to properly reflect its high value for climate applications, deriving from its high accuracy, stability and information content.**

II. INTRODUCTION AND BACKGROUND

The Cross-track Infrared Sounder (CrIS) is a high spectral resolution sounding instrument that is the operational counterpart to the Atmospheric Infrared Sounder (AIRS) on the EOS Aqua Platform. As such, it has very similar spectral resolution/coverage and spatial sampling properties to AIRS and the same wide range of potential applications. While specified primarily as a temperature and water vapor profiling instrument for weather forecasting, its powerful potential for climate applications has long been recognized and has been reinforced by the activities supporting the CLimate Absolute Radiance and Refractivity Observatory (CLARREO) Decadal Survey mission as a Tier 1 NASA priority. The *climate process studies* and diverse range of *climate product examples* developed by the AIRS Science Team and others, along with the potential to serve as part of a *climate benchmarking system* for decadal trend characterization a la CLARREO represent the diverse range of important climate applications of CrIS.

This report is the first assessment by the Suomi NPP Science Team of the overall quality for climate applications of the CrIS sounding measurements and products with recommendations for improvements. The overall question to be addressed is often summarized as "*Can Suomi NPP continue the EOS climate record*?" To illustrate the nuances of this question, we offer a few short answers here that will be developed further in the body of the report:

1. The basic sensor characteristics and measurement quality of CrIS are definitely capable of successfully continuing the high accuracy and information content data record of AIRS (see Section III).
2. The operational SDR algorithms and processing are working reasonably after a year with many modifications, but will not serve the climate community well for performing required quality refinement and reprocessing (see Section IV). Code that is more transparent to developers, like the joint UW/UMBC CrIS Calibration Algorithm and Sensor Testbed (CCAST) is needed (see Section V). It is important to realize that products based directly on measured radiances and brightness temperatures are fundamental climate records in their own right. It is also important to recognize that the existing AIRS L1B radiance record is not considered climate quality for many studies, and improvements such as the planned AIRS L1C code/products are still needed.

3. The IDPS CrIMSS EDR products are limited to profiles of temperature, water vapor, and pressure performed after cloud clearing with a specialized physical retrieval algorithm. Therefore, while IDPS EDR products are not yet validated for climate applications, they are inherently incomplete for representing the full climate potential of CrIS. Further, discontinuities are to be expected when joined to the AIRS record (see Section VI). A common, high spectral resolution retrieval algorithm, specifically chosen for creating an unbiased climate record is needed to produce refined climate products from the 1330 orbit starting in 2002. Options are presented (see Section IV).
4. To fully represent the potential of the infrared sounders on EOS and Suomi NPP, in addition to advanced sounder type high vertical resolution temperature and water vapor profiling, CrIS/AIRS climate products should include cloud properties, dust optical depth, trace gas distributions, and surface emissivity. Again, common algorithms for CrIS, IASI and AIRS are needed (see Section VII).
5. Given the absence of IR absorbing channels on the Suomi NPP imager, VIIRS, coordination between CrIS and VIIRS teams are needed to produce the best cloud products (see Section VII).

The basic climate products ultimately expected from CrIS can be characterized as level 3 means, higher moments, and probability distribution functions from (1) Spectral Radiances and Brightness Temperatures (SDR-like reprocessed products), (2) Temperature and Water Vapor Profiles (EDR-like reprocessed products), and (3) Other key products, including cloud properties, dust optical depth, trace gas distributions, and surface emissivity.

III. SENSOR CHARACTERIZATION

1. CrIS Radiometric Accuracy and Stability

The CrIS radiometric accuracy has proven to be excellent and substantially exceeds the Suomi NPP program requirements that were established primarily for weather applications. As we summarize here, this instrument is very well suited to continue, and in several ways to improve on, the accuracy offered for establishing a valuable climate record from high resolution IR spectra began by the AIRS instrument on the NASA EOS Aqua platform. Much of the substantial calibration accuracy improvement of these spectrometers over lower resolution radiometers stems from the huge improvement in knowledge of the spectral response functions.

For easy reference, the spectral coverage and resolution of CrIS is illustrated by comparison to AIRS and IASI in Figure 1 and figure 2 shows its excellent noise performance.

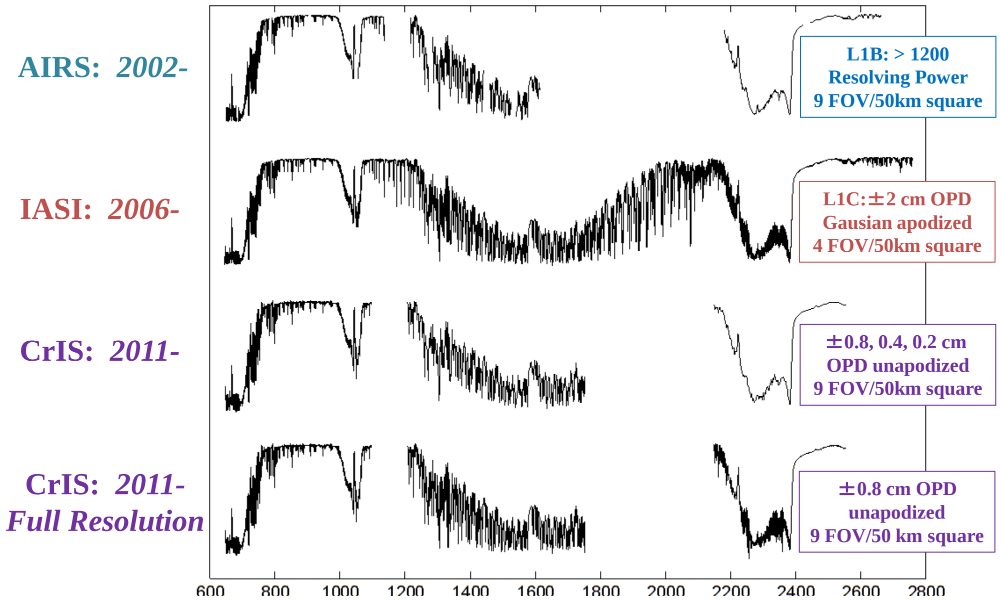


Figure 1. Comparison of brightness temperature spectra from CrIS to AIRS and IASI. These spectra calculated using LBLRTM accurately represent the actual spectral coverage and resolution of each instrument. The AIRS resolution has approximately a constant resolving power (ν/Δν), while the resolution for both IASI and the full-resolution CrIS are approximately independent of wavenumber. Therefore, after mid-2013 when the full resolution capability of CrIS will be routinely downlinked, the resolution of the newer instruments will be substantially higher than the legacy EOS AIRS for the shorter wavelength regions of the spectra.

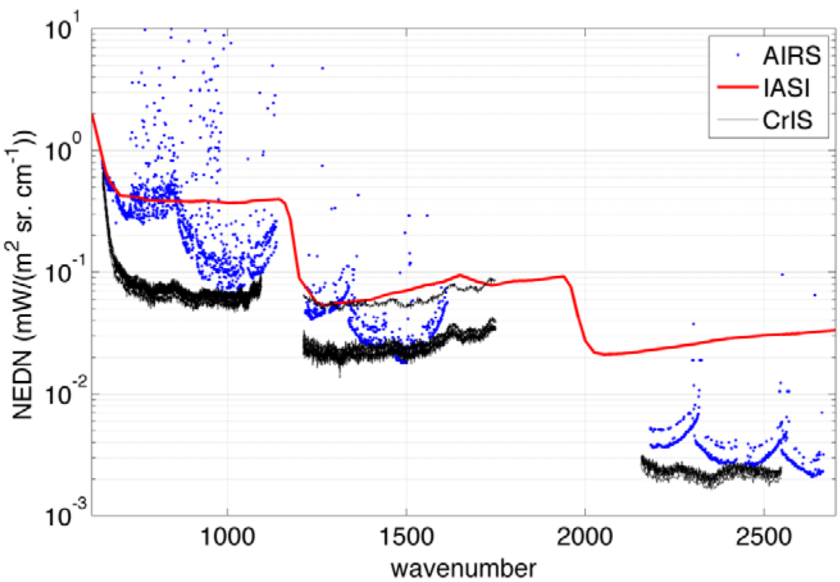


Figure 2. Comparison of CrIS radiance noise (NEDN) to that for AIRS and IASI. Note that in the important 15 micron band region, CrIS noise is about 4 time smaller than both AIRS and IASI. Also noteworthy is the excellent performance even in the shortwave band (2150 to 2600 cm^{-1}). This comparison is made for warm scenes, but even for cold scenes the shortwave noise performance is comparable to that of AIRS.

The preflight expectations for CrIS performance are summarized in figure 3, which shows estimates of 3-sigma brightness temperature uncertainty as a function of scene temperature. Note that after on-orbit refinements are completed our expectation that "not-to-exceed" uncertainties are expected to be less than 0.2 K.

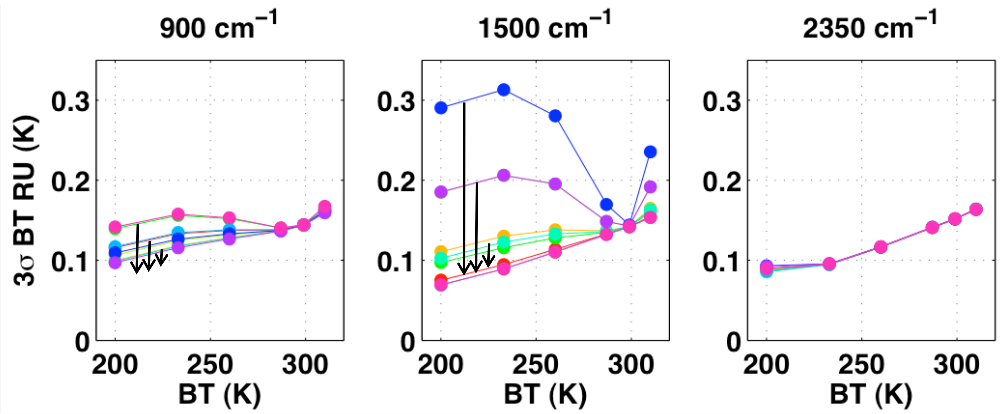


Figure 3. Preflight radiometric uncertainty estimates for blackbody sources in terms of 3-sigma brightness temperature as a function of scene brightness temperature for the center wavelength of each band (left to right: LW, MW, SW). The colored dots identify the field-of-view (FOV) of each element of the CrIS 3x3 detector array defining simultaneous field of regard (FOR) measurements covering 50x50 km at nadir. The wide range of uncertainty in the Midwave and smaller range in the Longwave are caused by FOV non-linearity differences. The black arrows indicate that these differences have been greatly reduced by on-orbit calibration/validation activities as demonstrated in Figure 7 to follow.

The on-orbit agreement between the nine CrIS FOVs after completion of "provisional" level analyses is shown in Figure 4.

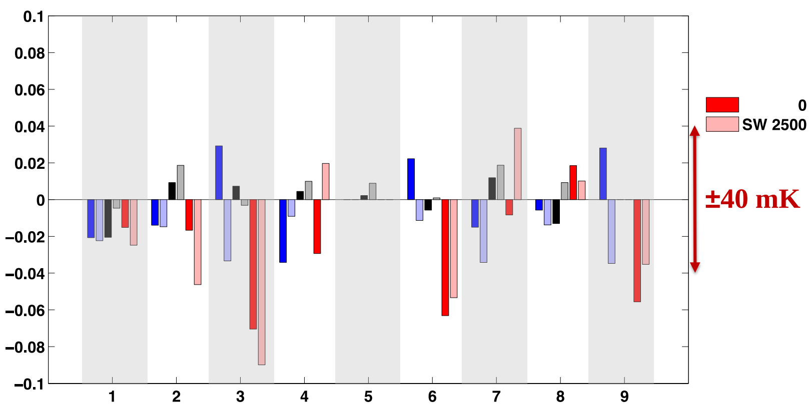


Figure 4. On-orbit brightness temperature comparisons among CrIS nine individual FOVs composing each 50x50 km FOR for six sample wavenumbers. Note that most differences are less than ±20 mK. The exception are SW pixels 3, 6, and 9, an anomaly that is still being studied. In general, these relative comparisons that inherently include some errors from the on-orbit comparison process are excellent and consistent with the expectations of Figure 3.

On-orbit comparisons have also been made to both AIRS and IASI as illustrated for the longwave band in Figure 5.

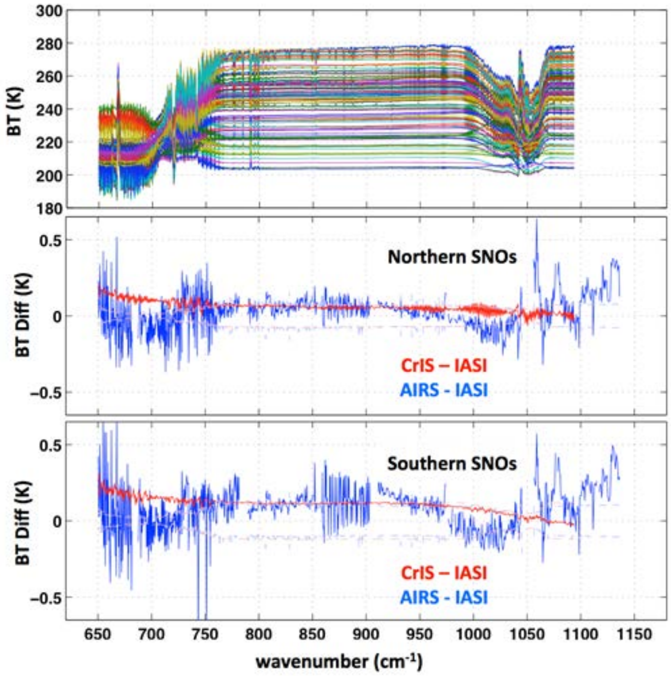


Figure 5. Summary of on-orbit comparison between CrIS brightness temperature spectra and both AIRS and IASI. All data from February-November 2012 that meets intercomparison criteria (within 20 minutes, and 3° degrees viewing angle, with viewing angle <30° for AIRS and near nadir for IASI) is used. The dashed curves are error estimates indicating that most of these differences are significant. While these results will be the subject of detailed studies for considerable time, it is clear that the agreement is very good, especially between CrIS and IASI.

The temporal stability of the comparison between CrIS and AIRS is illustrated in Figure 6.

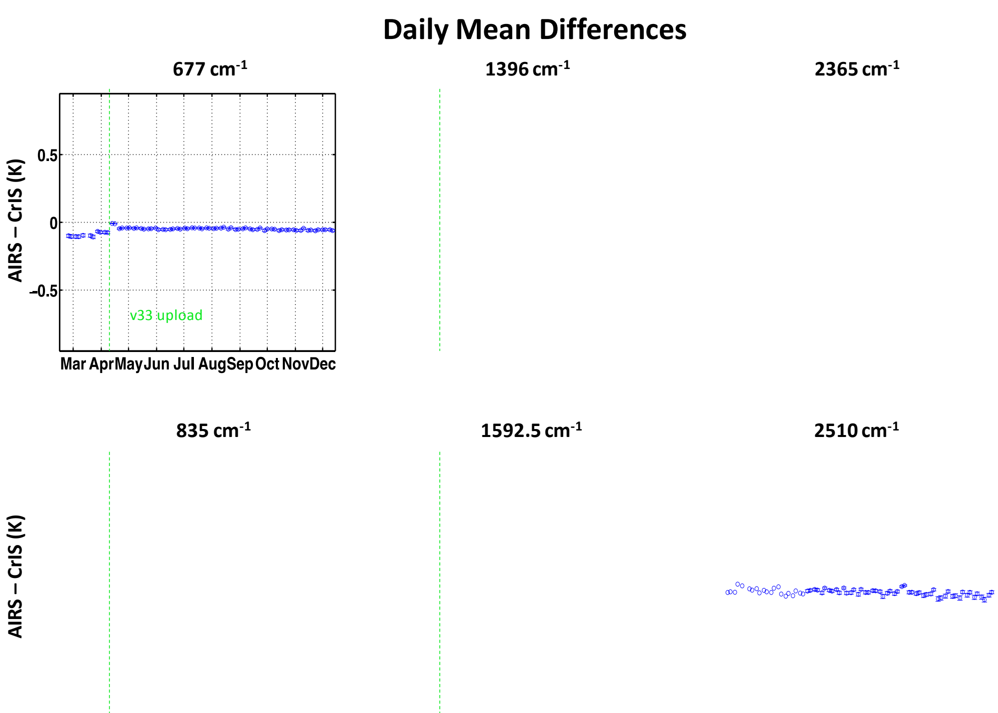


Figure 6. Temporal stability of AIRS minus CrIS differences for six sample wavenumbers. The small jog in April was caused by an upload of new calibration parameters for CrIS. Note that the differences are usually significantly less than ±0.2 K.

Drawing on the sensor characterization results to date, a preliminary estimate of the CrIS SDR in-flight Radiometric Uncertainty (RU) is shown in Figure 7. Opposed to the pre-flight RU estimates showing Thermal Vaccuum blackbody views in Figure 3, the in-flight RU can vary depending on the magnitude and shape of the observed spectrum; this example is for an 8-minute granule from 24 February 2012 with a reasonable sample of clear sky spectra. It applies to all nine CrIS FOVs, because of the FOV-to-FOV intercomparison techniques applied for reducing non-linearity uncertainties on-orbit.

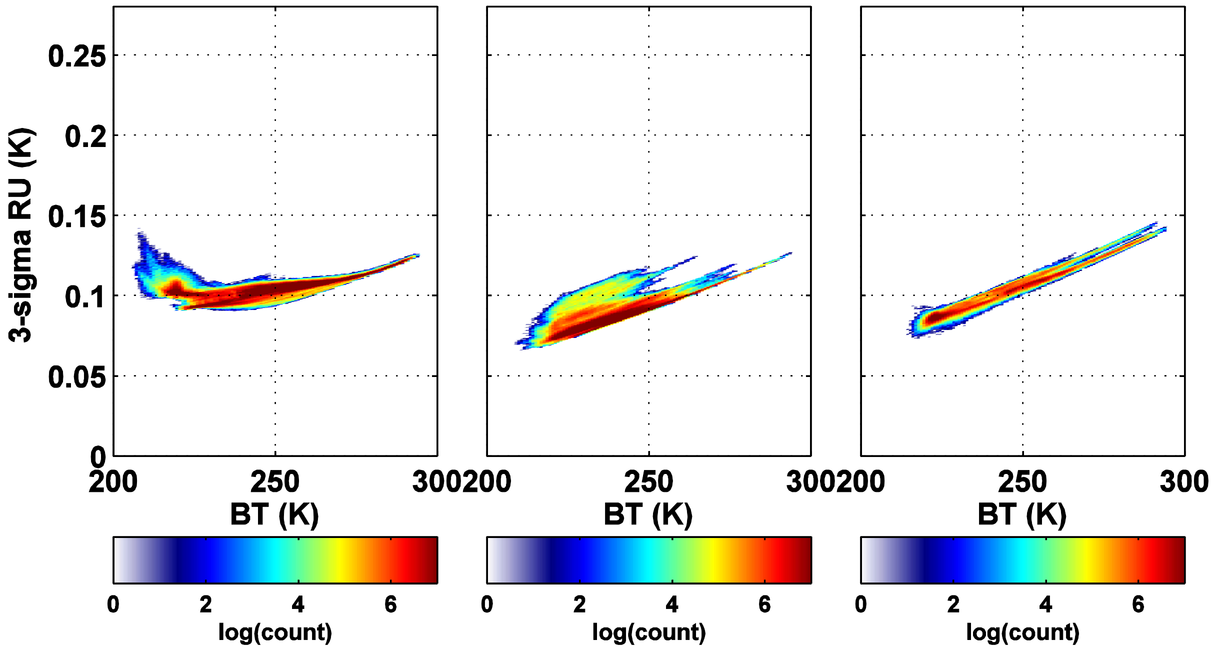


Figure 7. Sample of on-orbit 3-sigma Brightness Temperature uncertainty for 24 February 2012.

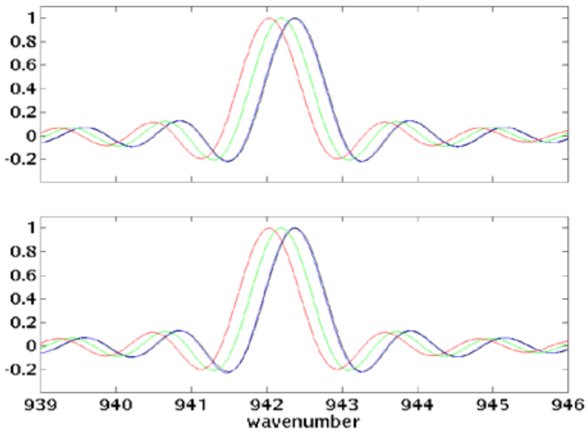
There are a couple of relatively small liens on CrIS radiometric performance that are currently under investigation, namely (1) larger than expected Gibbs ringing that effects some wavelengths, and (2) an unexplained difference with both AIRS and IASI for regions of very low radiance in the shortwave band. These issues are being studied as part of both our NASA and NOAA activities.

In Summary, the sample comparisons with AIRS and IASI shown in this section make it clear that the basic CrIS spectral radiances, which have the same spatial sampling properties as AIRS, are capable of continuing the EOS data record.

2. CrIS Spectral Calibration Accuracy and Stability

The CrIS spectral calibration accuracy and stability are also excellent and generally better than 1 ppm. As such, it is an improvement over the EOS AIR sensor which displays substantially larger changes during every orbit and from year to year.

Again for easy reference, we show the pre-flight spectral response measurements (or Instrument Line Shapes, ILS) compared to those expected from the way the CrIS sensor was built in Figure 8. SDR techniques for normalizing the ILS to a sinc function for all FOVs were proven before launch.



		Center FOV	Side FOV	Corner FOV
centroid (cm^{-1})	Obs	942.367	942.195	942.034
	Calc	942.366	942.195	942.034
FWHM (cm^{-1})	Obs	0.747	0.757	0.767
	Calc	0.751	0.759	0.767
Lfoot	Obs	0.358	0.329	0.313
	Calc	0.347	0.328	0.313
Rfoot	Obs	0.347	0.326	0.311
	Calc	0.345	0.329	0.313

Figure 8. CrIS Instrument Line Shapes measured with a CO_2 laser compared to calculations.

The results of relative FOV-to-FOV comparisons achieved for provisional SDR status are shown in Figure 9. These results also demonstrate a high degree of relative stability.

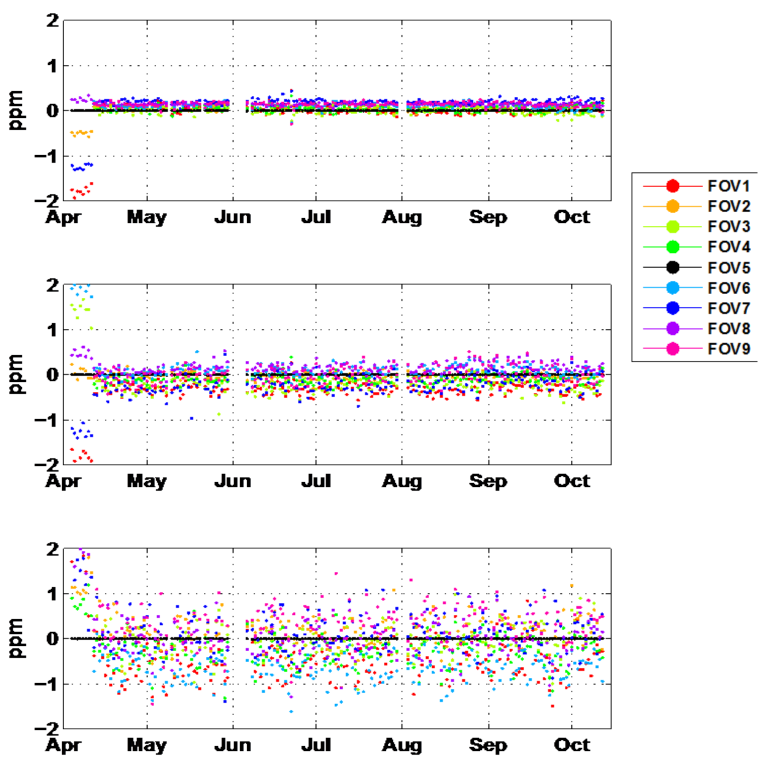


Figure 9. On-orbit comparison of agreement among nine FOV spectral calibration.

Finally, the absolute spectral calibration for CrIS is based on its own Neon lamp wavelength reference measurements, which can be verified using spectral calibration from lines in the atmospheric spectrum. There is also a highly stable diode laser used to trigger sampling of the interferogram signal. The stability of diode laser relative to the Neon calibration lamp is illustrated in Figure 10.

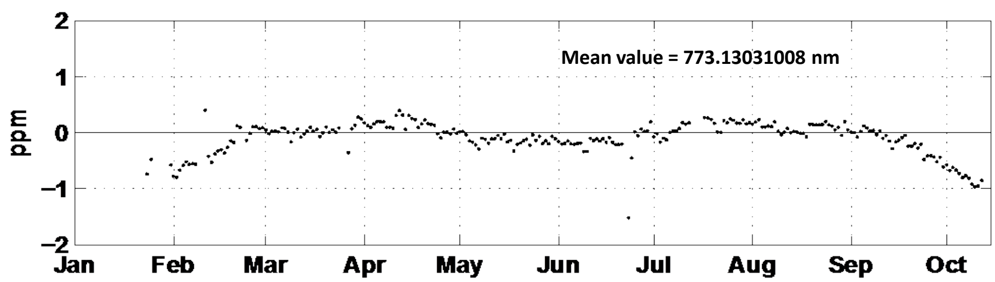


Figure 10. Stability of the FTS sampling laser relative to the on-board Neon calibration source is on the order of 1 ppm.

Verification of the CrIS spectral calibration has been performed using line-by-line calculations based on laboratory (HITRAN) measurements of gaseous absorption lines in the infrared. The assessment of the accuracy of the atmospheric verification is in progress, but preliminary results by UMBC are consistent with the neon calibration.

3. Brief Summary of Comparison to EOS AIRS for Climate Applications

The overall performance of the CrIS advanced sounder is excellent, assuring that it is fully capable of continuing where AIRS leaves off. More specifically,

a. Detailed assessments of radiometric uncertainty suggest that is it at least as accurate as AIRS. Relative comparisons with IASI and AIRS actually suggest that it may turn out to be notably better than AIRS.
b. While the spectral knowledge of CrIS and AIRS are both excellent, the spectral properties of CrIS are even better known and more stable than those of AIRS.
c. The spectral resolution of the full resolution CrIS (routine downlink expected mid-2013) is higher than AIRS.
d. The noise performance of CrIS is superior,
e. Spatial sampling properties and spectral coverage are very nearly the same.

Therefore, the overall information content for climate process studies, for creating long-term climate products, and for assessing long-term trends is certainly at least equal to that of the legacy EOS sensor.

IV. ALGORITHMS

This section includes an assessment of the current IDPS algorithm status, quality, and maturity for use in generating climate products and provides recommendations for alternative approaches. For this discussion, we define the term "algorithms" to include both the literal algorithms as defined by Algorithm Theoretical Basis Documents (ATBDs) and the software implementation for IDPS calibration to geo-located radiances (SDRs) and retrieval products (EDRs). Subsequent sections discuss the resulting sensor and environmental data records.

1. IDPS SDR Algorithms

The CrIS SDR algorithm currently running in IDPS is adequate to meet NWP needs. This is the result of on-going efforts by the Cal/Val team to identify and fix issues with the operational code. Initially, the IDPS software had several major issues, and it took several months after CrIS was powered on for IDPS to produce reasonable spectra, despite off-line codes such as CCAST and ADL/CSPP producing accurate spectra much earlier. The issues with the IDPS code and implementation ultimately trace back to the overall NPOESS structure, where the calibration algorithm experts were not included in the SDR algorithm development until only recently. The Cal/Val team continues to identify and attempt to fix issues with the IDPS processing.

Despite this success, the IDPS SDR code and processing and resulting SDR record is not adequate for climate needs. Several concrete examples of this include: 1) the inability of IDPS to properly handle and include "repair granules", resulting in invalid and/or missing spectra, 2) the lack of a re-processing capability in IDPS; like other climate sensors, for many reasons the CrIS SDRs will need to be re-processed in order to produce climate data records, 3) the IDPS software has been re-written by contractors during several stages of the program such that it is not absolutely clear what the algorithm is doing (examples include fringe count detecton/correction, and spectral calibration updates), 4) the IDPS software is not capable of processing the full spectral resolution data expected in June 2013, and 5) there is no clear path to provide needed upgrades to the IDPS software as changes to the algorithm are required.

2. IDPS EDR Algorithms

This section comments on the EDR algorithm status, quality, and maturity as described in the CrIMSS ATBD and the software code implementation on IDPS, the actual EDR product assessment (to date) is provided in a subsequent section. The original IPO EDR requirement inherited by the JPSS program was for only three products; atmospheric vertical pressure profiles (PP), atmospheric vertical temperature profiles (AVTP), and atmospheric vertical moisture profiles (AVMP). In response to these requirements, the IPO vendor proposed a Cross-track Infrared Microwave Sounder Sensors (CrIMSS) EDR product, and several intermediate products (IPs), using an algorithm developed under contract to NGST by AER, Inc. The CrIMSS ATBD describes the detailed algorithm approach to retrieve the pressure, temperature, and water vapor vertical profiles from collocated ATMS microwave and CrIS infrared measurements (see http://npp.gsfc.nasa.gov/science/sciencedocuments/2013-01/474-00056_RevABaseline.pdf).

This algorithm builds upon the heritage algorithms of the ATOVS sensors (AMSU-A, AMSU-B, and the HIRS/3) on the NOAA series of polar satellites and AIRS/AMSU-A/HSB on the EOS Aqua platforms while implementing a unique retrieval methodology. A similar complement of sensors (IASI/AMSU-A) flies on the METOP series of polar orbiters as part of the joint EUMETSAT EPS polar program and are also valuable for Suomi NPP science team studies. The following italicized paragraphs are extracted from the CrIMSS ATBD as a description of the unique aspects of the CrIMSS EDR algorithm.

The inversion methodology adopted for both microwave and infrared is based on a constrained non-linear least squares approach (e.g., Rogers 1976). The methodology of the vendor supplied algorithm is summarized briefly below (see ATBD link for details):

1. Initialization
2. Input and pre-processing
3. Microwave-only retrieval
4. Scene classification
5. Joint microwave and infrared retrieval
6. Quality control
7. Output and post-processing

The flowchart for the joint microwave and infrared retrieval is shown in Figure 11. The output products of the CrIMSS algorithm are given in Table 1. For each FOR, the retrieval consists of the following steps;

> *1. Microwave-only retrieval provides first guess estimates of temperature and moisture profiles, skin temperature, surface emissivity, and cloud parameters.*
> *2. The scene classification module uses microwave results to identify clear FOVs.*
> *3. The scene classification module groups FOVs into clusters and sets retrieval flags for each cluster. These flags determine the appropriate retrieval strategy.*
> *4. If the cluster has no thermal contrast between CrIS FOVs, radiances within that cluster are averaged.*
> *5. If the scene is partly cloudy, an estimate of clear infrared radiances Rclr is obtained by applying the forward model to the current estimate of the state vector. Cloud-clearing is performed using Rclr and radiances from pre-selected FOVs .*

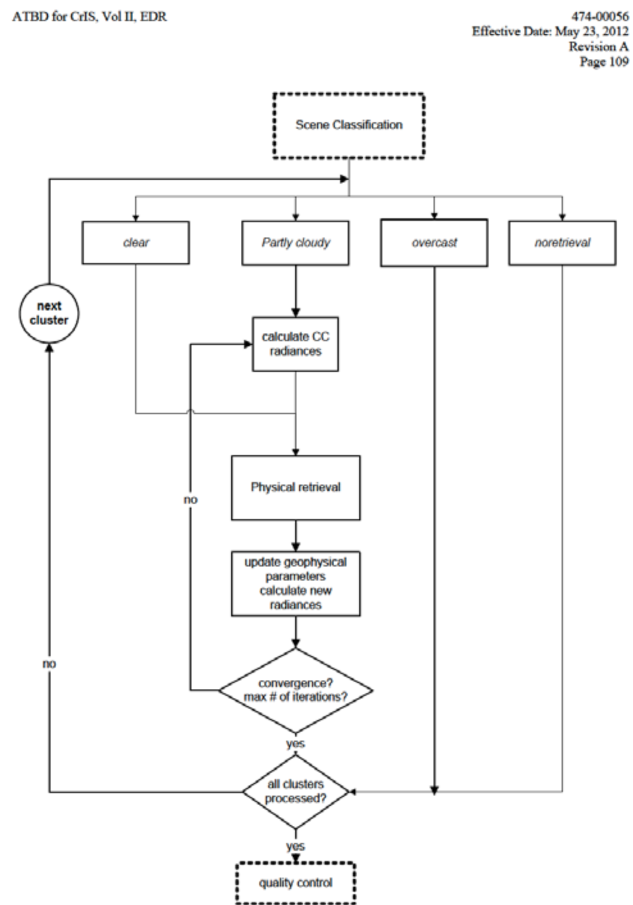


Figure 11. Joint microwave and infrared retrieval flow chart.

6. If the cluster is overcast, IR retrieval is skipped and the MW only retrieval results from step 1 are reported.
7. If the cluster is inhomogeneous (i.e., the number of FOVs with predominant surface type is less than the number of cloud formations), the scheme will skip this cluster and provide no EDRs.
8. A physical retrieval is performed using the radiances obtained from step 4 or 5 and the MW radiances. Temperature and moisture profiles, MW and IR emissivities, IR solar reflectivities, MW cloud parameters, and skin temperature are retrieved simultaneously.
9. If the solution has converged (see below) or the maximum number of iterations is reached, the process stops (the maximum number of iterations is currently set to 4). Otherwise, steps 8-9 are repeated.
10. Quality control is performed and EDRs are reported with appropriate quality flags.

Aspects of each stage of the methodology described above have been vetted in the literature and particularly at the AIRS science team meetings over the past decade, with various studies on the pros and cons of different retrieval methodologies. **However, for climate trending, special care is necessary to avoid false trends (e.g. guarding against having incomplete separation of the effects of temperature and CO_2 changes). Further, for trending, there is a need to have the**

algorithm work equally well on AIRS and IASI, as well as CrIS data. These issues have not been addressed for the IDPS algorithm, and at this point, we feel that there are potentially better ways to address them than the CrIMSS algorithm approach. Rather than provide a piecemeal critique of the CrIMSS methodology, the Suomi NPP atmospheric sounding science team believes there is great utility in the comparison of separate complete algorithm methodologies applied to the same ATMS/CrIS data for the evaluation of retrieval systematic bias, RMS single profile error, and overall yield. For this reason, we recommend that the Suomi NPP science team evaluate the JPSS EDR algorithm through comparison with the following alternative algorithm implementations that are already set up to operate on both CrIS and AIRS data:

1) An off-line version of the CrIMSS algorithm implemented by NASA LaRC at NOAA and compatible with the Raytheon JPSS software development framework. The refinement of the CrIMSS algorithm is led by Dr. Xiu Lu (LaRC). A key unique aspect of this activity is the simultaneous retrieval of microwave and infrared channels to retrieve a "best fit" atmospheric state. This requires careful attention to both sensor calibration (esp. microwave) and radiative transfer systematic bias across the microwave and mid-IR bands. To date this off-line algorithm has been applied to Golden Days to evaluate coding changes and algorithm improvements.

2) The AIRS v5.x code as implemented at NOAA for off-line processing of ATMS/CrIS sensor data. This code was originally developed under the leadership of Dr. Joel Susskind and has extensive heritage through a decade long support of NASA, NOAA, and University investigators in software that represents the current "collection 5" in the GESDIS AIRS products. Dr. Chris Barnet (NOAA/NESDIS) is currently the lead investigator who is responsible for the maintenance of this algorithm. This algorithm uses sequential retrieval (rather than simultaneous) to obtain profile retrieval solution that fits the measured radiances. A primary NESDIS requirement applied to this algorithm is to routinely generate products from both the METOP series (AMSU/IASI) and the JPSS series (NPP, J1, etc.) and archive those products in the NOAA CLASS archive.

3) The University of Wisconsin Dual Regression retrieval algorithm as implemented in the Community Satellite Processing Package (CSPP) for processing Suomi NPP data obtained from direct broadcast or from archived radiance files. Dr. Bill Smith (UWisc/HamptonU) and Dr. Elisabeth Weisz (UWisc) jointly developed this algorithm for application to AIRS and IASI data and have extended it to CrIS data for Suomi NPP/JPSS. The algorithm is based upon statistical regression with cloud classification and applies to individual fields of view (14 km) rather than fields of regard (50 km). One advantage of the methodology is that the same regression training set is used for all sensors (AIRS, IASI, CrIS), which provides algorithm consistency across multiple sensors on multiple platforms and makes it a candidate algorithm for climate trending where traceability to the radiances is an important objective.

We also recommend that comparisons be made for AIRS data using the above and the version 6 AIRS algorithm described below:

The AIRS v6.x as developed at MIT LL, NASA GSFC, and NASA JPL. The lead algorithm support for this latest version of the AIRS retrieval algorithm is jointly held between Dr. Bill Blackwell (MIT/LL) and Dr. Joel Susskind (NASA GSFC). This algorithm follows the outlines of previous AIRS science team algorithms but adopts a neural network training based on training data. The implementation of this methodology in version 6 has led to a much closer connection to the training dataset, in this case the ECMWF analysis fields, than any previous retrieval methodology applied to AIRS data. Evaluation of this methodology for long-term trending is an important consideration for the Suomi NPP science team, with possible arguments made for and against this approach for climate studies. AIRS v6.x is will be used in the reprocessing of all AIRS data and will replace v5.x in the GESDIS archive.

For EDRs, the ATBD is incomplete when dealing with the full range of climate products that could be derived from the infrared and microwave Suomi NPP data, including carbon monoxide, carbon dioxide, methane, and other minor gases, as well as surface properties. Table 1 lists ozone, surface temperature, and surface emissivity as intermediate products (IPs) of the current CrIMSS product suite. These IPs must be included in the assessment of the overall climate quality of the CrIMSS products and as long as the IPs are archived at NOAA CLASS these could in principle form the basis for a climate record. However there are other products that exist only as unfunded P3I product concepts under JPSS but which have been developed with NASA funding previously. The potential climate products not currently being produced by JPSS from the ATMS and CrIS data but that have been routinely produced with Aqua AIRS data include;

1) Carbon Dioxide. This would continue the important record of mid-tropospheric CO_2 from AIRS begun through the efforts of Drs. M. Chahine, Chris Barnet, and Larrabee Strow. This work should be extended to include IASI and CrIS with additional characterization of the vertical sensitivity of the measurements. Multiple algorithms exist for potential implementation.

2) Carbon Monoxide. This will continue the important record from the AIRS and IASI sensors in afternoon and morning orbits respectively. While EUMETSAT supports the retrieval of CO from the IASI sensor through it's SAF program, there is no corresponding support for CO products from the CrIS sensor in the afternoon orbit. This should be a high priority for NASA.

3) Methane. This will continue the important record of CH4 from the EOS AIRS data. These data are being used to investigate the tropospheric methane content in polar regions where climate change is postulated to lead to a positive feedback. Continuation of this record is in jeopardy with eventual de-orbiting of the Aqua and Aura spacecraft.

4) Cloud Properties. The vertical resolving power of the CrIS advanced sounder substantially augments the information about cloud altitude offered by IR imaging sensors. This is an area where cooperation with the VIIRS team and the Atmosphere PEATE is very important.

Output	Description
AVTP EDR	Atmospheric vertical temperature profile EDR which consists of vertically averaged atmospheric temperature (K) for 42 layers
AVMP EDR	Atmospheric vertical moisture profile EDR which consists of vertically averaged atmospheric water mass mixing ratios (g/kg) for 22 layers.
PP EDR	Atmospheric vertical pressure profile EDR which consists of atmospheric pressure at 31 altitudes. (hPa)
AVTP Level IP	Second stage (MW + IR) temperature retrieval data at the OSS levels. (K)
AVMP Level IP	Second stage (MW + IR) moisture retrieval data at the OSS levels. (g/kg)
AVTP MW Level IP	First stage temperature retrieval data at the OSS levels. (K)
AVMP MW Level IP	First stage moisture retrieval data at the OSS levels. (g/kg)
IR Surface Emissivity IP	IR surface emissivity at the surface emissivity hinge points.
Ozone IP	Retrieved ozone profile at the OSS levels. (ppmv)
CrIS Cloud Cleared Radiance IP	Cloud cleared CrIS radiances. (mw/m2/str/cm-1)
MW Surface Emissivity IP	MW surface emissivity for each of the ATMS channels.
Skin Temperature IP	Skin temperature retrieval data (K)

Table 1. Output products of the CrIMSS algorithm (474-00065_OAD-CrIMSS-EDR_B).

V. CrIS SENSOR DATA RECORDS (SDRs)

This section discusses the status of the actual CrIS radiance data record from IDPS. The completeness and maturity of IDPS geo-located radiances are not adequate for the generation of optimum climate records. The SDRs that are produced are generally quite accurate for creating traditional EDRs to initiate climate process studies but are considered inadequate for climate studies due to deficiencies in the data processing perform at the IDPS. These issues include;

- Incomplete data record due to missing or corrupted RDRs
- Current inability to process full spectral resolution CrIS data
- Difficulty/inefficiency of making even minor software version updates
- Discontinuities in radiometric calibration due to software version changes, and due to calibration coefficient changes
- Discontinuities in spectral calibration, due to the way IDPS triggers updates in the spectral corrections at irregular intervals.

The UW and UMBC have developed a set of “science code”, named CCAST, which is highly assessable, flexible, and faster than the vendor supplied IDPS code. A CCAST-based approach for generating reprocessed radiances is recommended for the development of reprocessed climate data records in order to preserve a direct traceability of the radiance record to SI standards (on orbit calibration and corresponding error budget). This reprocessed SDR radiance record should be performed by NASA to facilitate the close interaction of scientific experts with the climate products while avoiding the introduction of programming errors introduced by third party software vendors. We suggest that NASA adopt science code for the production of climate records and reject the vendor supplied IDPS code for this important purpose.

VI. CrIS IDPS ENVIROMENTAL DATA RECORDS (EDRs)

At the time of this report (January 2013), the CrIMSS EDR products are in transition from "beta" to "provisional" status. The results presented below are a high level summary of results by the NPP science team members, some of whom are also JPSS Cal/Val team members. The top level conclusion is that the CrIMSS product has seen rapid improvements since launch in the very capable hands of the JPSS EDR Cal/Val team lead (Chris Barnet) at NOAA NESDIS working closely with the original CrIMSS algorithm innovator (Xiu Lu) at NASA LaRC. The result is that Mx 6.4 (Oct. 15, 2012 to current) is much improved in both bias, RMS, and yield (1% to 25% in MW+IR) over the previous version Mx6.3 and off-line evaluations of Mx7 suggest further improvements in yield (about 50% in MW+IR) will be obtained in the next IDPS version update (approx. Feb. 2013). Performance results are summarized in Figure 12.

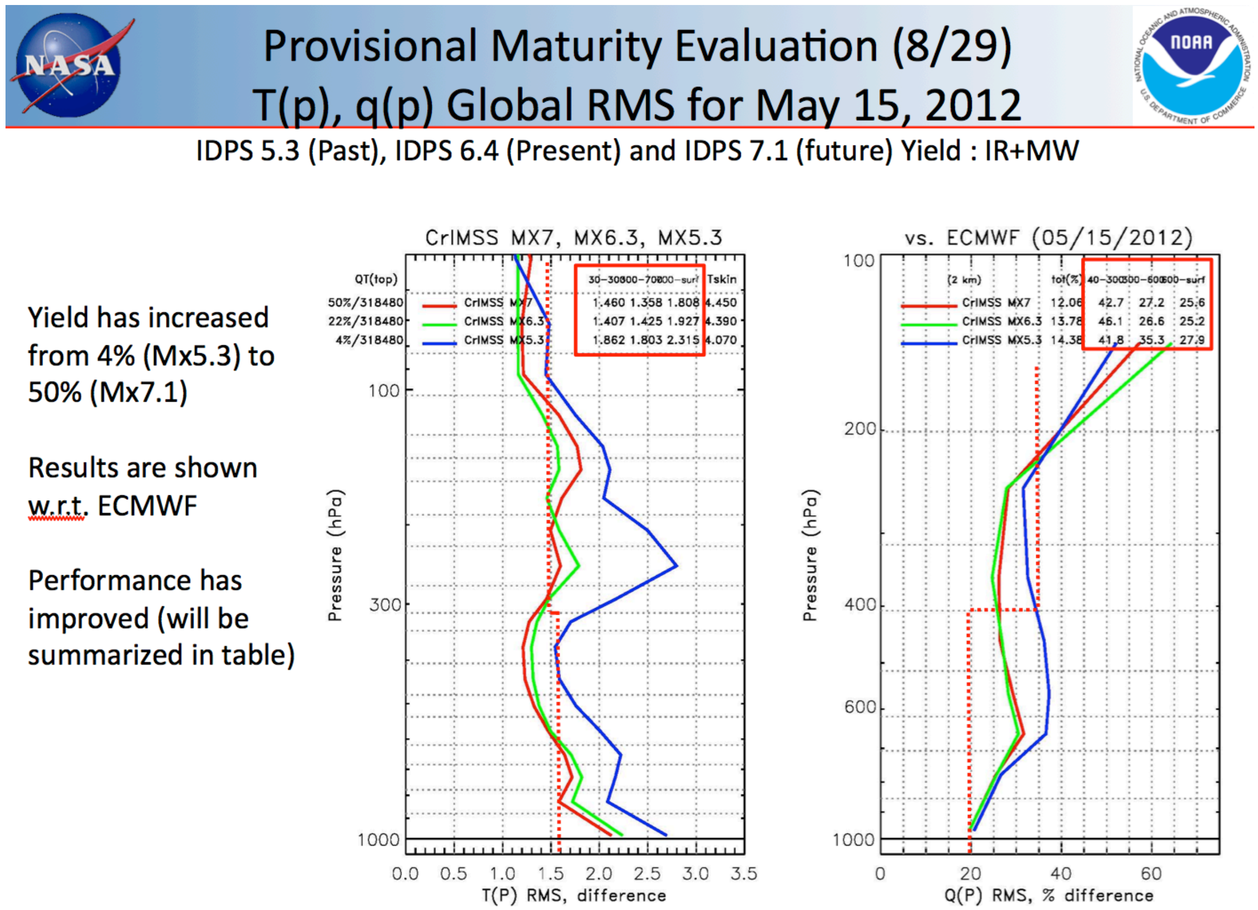


Figure 12. Provisional maturity evaluation of Mx5.3 (past), Mx6.4 (current), and Mx7.1 (future) performance of CrIMSS algorithm versions implemented for IDPS compared to JPSS requirements (*from Chris Barnet, NOAA*).

One possible criticism of the NOAA validation approach is over reliance on an NWP analysis field (in this case ECMWF) for the “truth” field. Too mitigate this concern; the team members are making assessments of the CrIMSS product against “independent” measurements. (Note, since many data types, including satellite data, are assimilated into NWP models and because NWP model fields are used in retrieval regression training, the term “independent” is used here in a qualitative sense only.) The independent measurements being used to assess the CrIMSS product for climate quality include 1) Vaisala RS92 radiosondes launched co-incidentally with NPP overpasses (supported by JPSS Cal/Val), 2) the global radiosonde upper air network (supported by JPSS Cal/Val), 3) the COSMIC GPS RO network (analysis supported in part by JPSS Cal/Val), 4) Water vapor Raman Lidar (upper troposphere humidity) and total column water vapor (SUOMINET) (analysis supported by JPSS Cal/Val), 5) sea surface temperature using the Reynolds dataset, 6) cloud top temperature of convective clouds, and 7) aircraft validation campaigns using the NASA ER-2 and Global Hawk (supported by NOAA JPSS). None of these validation data are directly supported by the NPP science team project but all of these data are invaluable for the assessment of the climate quality of the NPP products. The detailed assessment following from these validation activities is just beginning, but is expected to be available for the next NPP assessment report in early 2014.

The basic measures of performance of the AVTP and AVWP EDR products are bias and RMS statistics against ECMWF analysis fields augmented in the Cal/Val process with independent measurements using radiosondes and other remote sensed products such as from the COSMIC RO and SUOMINET GPS networks. This assessment is based upon the experience of the NPP science team in the evaluation of heritage sensors (e.g. AIRS/AMSU). The following figures illustrate the heritage type of assessments against independent measurements that are being applied to CrIMSS data currently.

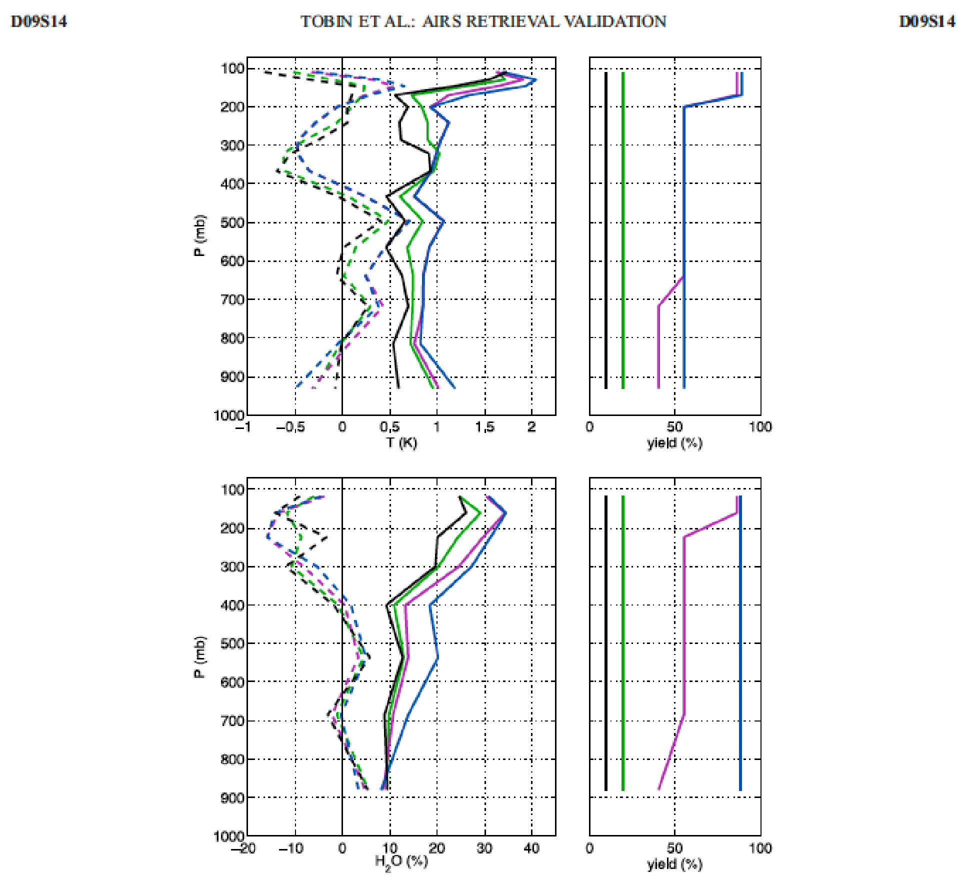


Figure 13. Validation of AIRS version 4 atmospheric profile retrievals using ARM TWP site profiles. (top left) The 1 km layer temperature differences (AIRS-ARM), (top right) temperature retrieval yield, (bottom left) percent difference in 2 km layer water vapor amounts (100(AIRS-ARM)/ARM), and (bottom right) water vapor retrieval yield. Each panel includes the bias (dashed curves) and RMSE (solid curves) for four selections of quality control flags (QC1, black; QC2, green; QC3, purple; QC4, blue) as discussed in the text. Note that when computing the mean and RMS water vapor profiles, the percent differences are weighted by the ARM water vapor amounts.

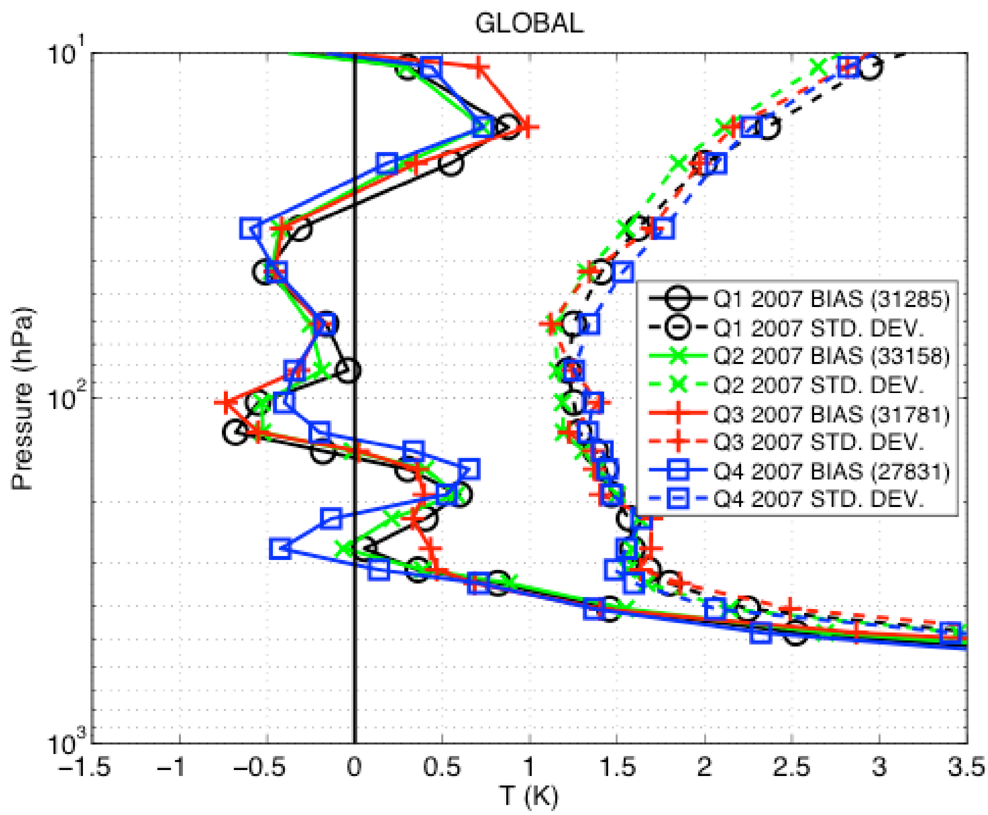


Figure 14. AIRS validation against COSMIC GPS RO dry temperature. Global bias and standard deviation for each quarter of the year 2007.

As stressed in Section IV, similar types of analyses of the adequacy for climate applications needs to be performed for several alternative retrieval algorithms.

VII. RECOMMENDATIONS FOR IMPROVEMENTS AND NEW PRODUCTS

This section begins with a summary of the improvements to IDPS SDR and EDR algorithms, and products discussed in previous sections; and finishes with a discussion of key climate products that go well beyond those provided by IDPS SDRs and EDRs.

1. Summary of Improvements to Existing IDPS CrIS Data Processing

Our recommendations for improvements are listed below by topic.

a. **The Sensor Characterization** process has demonstrated accuracy well suited to creating important climate products, so no improvement to the current process is needed at this time.
b. **The Algorithm for IDPS SDR radiance generation** provides data with reasonable accuracy, but is cumbersome to change. Therefore, to facilitate effective reprocessing

for climate data record generation, the IDPS SDR algorithm should be replaced. We recommend basing climate SDR code for generating refined, reprocessed radiances on the CrIS Calibration Algorithm and Sensor Testbed (CCAST) developed jointly by UW-Madison and UMBC.

c. **The Algorithm for IDPS SDR radiance generation** does not generate direct climate products from radiances or brightness temperatures. We recommend science team support for development of algorithms to generate appropriate Level 3 products, including means, higher moments, and probability distribution functions, along with uncertainty estimates.
d. **The Algorithm for IDPS EDR generation** is adequate for climate process studies from CrIS, but is not sufficiently versatile to be used to create a continuous climate record that includes AIRS and IASI data sets and has not yet been evaluated for assessing potential biases for long-term trending. It is premature to recommend detailed algorithm changes, but we do recommend making use of several other retrieval algorithms for helping to evaluate the climate quality of retrievals (see Sect IV). Also, we may ultimately recommend using one of the alternative algorithms to create long-term climate records.
e. **The IDPS SDR data** have been carefully evaluated and have demonstrated high accuracy, although refinements are expected to be valuable for climate applications for several years. A high percentage of data passes all current QC tests, and SDRs are expected to achieve NOAA "Validated" status by mid-2013.
f. **The CrIS IDPS SDR data** have missing data (due to the way "Repair Granules" are handled) that will pose problems for climate applications that depend on unbiased sampling. Current alternatives include using SDRs generated with ADL-based software that makes use of all Repair Granules to create a complete record. Ultimately, our recommendation is to use NOAA supported SDRs generated at UW using the UW/UMBC CCAST code that will be reprocessed at regular intervals to reflect the best available refinements.
g. **The IDPS EDR data** have not yet been carefully evaluated for climate applications. The data is certainly useful for initial studies, and we expect that EDRs will achieve NOAA "Provisional" status by mid-2013.
h. **The IDPS EDR data** suffer from the same outages as the SDR data, and as previously mentioned, should not be expected to be fully compatible with AIRS EDRs for some climate applications. These data are certainly useful for processing studies, but more complete and consistent records are desirable for climate trending and long-term data records. Ultimately, we recommend that long-term climate data products be generated by the same basic type of algorithm applied to AIRS and IASI, as well as CrIS data. The common algorithm should be chosen to minimize biases over space and time; Several candidate algorithms are defined in Section IV.

2. New Products for Advancing Climate/Global Change Science

Because of the very limited scope of IDPS EDRs for CrIS, many new products are needed to take full advantage of the data for climate applications. As discussed in the preceding sections, these new products relate to both physical properties not derived by the IDPS EDR algorithm and to the form of level 3 products needed to effectively study the climate signatures from CrIS.

We believe that multiple analysis streams should be followed to more confidently conclude that any observed climate trends are real. These streams should involve the creation of (1) products from direct physical observables, (2) retrieved Earth system properties, and (3) assimilated Earth system properties. At least the first two types should be prepared under Suomi NPP for use in trend assessment and for comparison to the corresponding properties of climate models.

a. New Products from Radiances and Brightness Temperatures\

The advantages of pursuing climate trend information with directly measured radiances are (1) avoidance of biases related to the assumptions made in performing retrievals to Earth system properties, and (2) better traceability of uncertainties.

An example of a Level 3 gridded product strongly connected to UTLS water vapor is shown in Figure 15. Such products are useful for studying climate processes and testing model behavior.

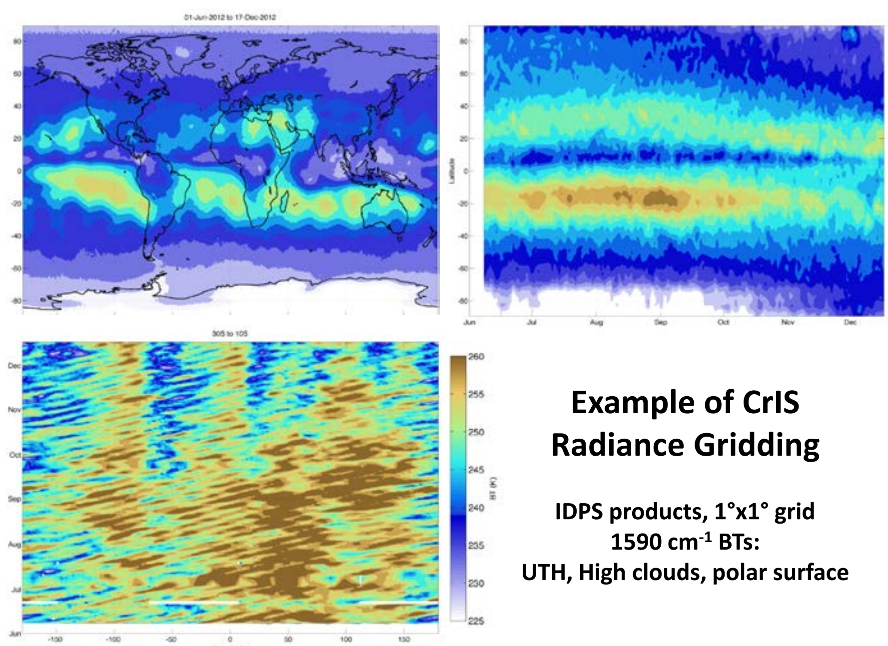


Figure 15. Examples of CrIS Brightness Temperature Gridding related to high level water vapor, high cloud and polar surface emission at 1590 cm^{-1}. Upper left is the mean global perspective for 1 June to 17 December 2012, upper right is the variation of zonal mean structure over the same time period, and lower left shows the correlation of longitudinal time variations (Hovmoller Plot).

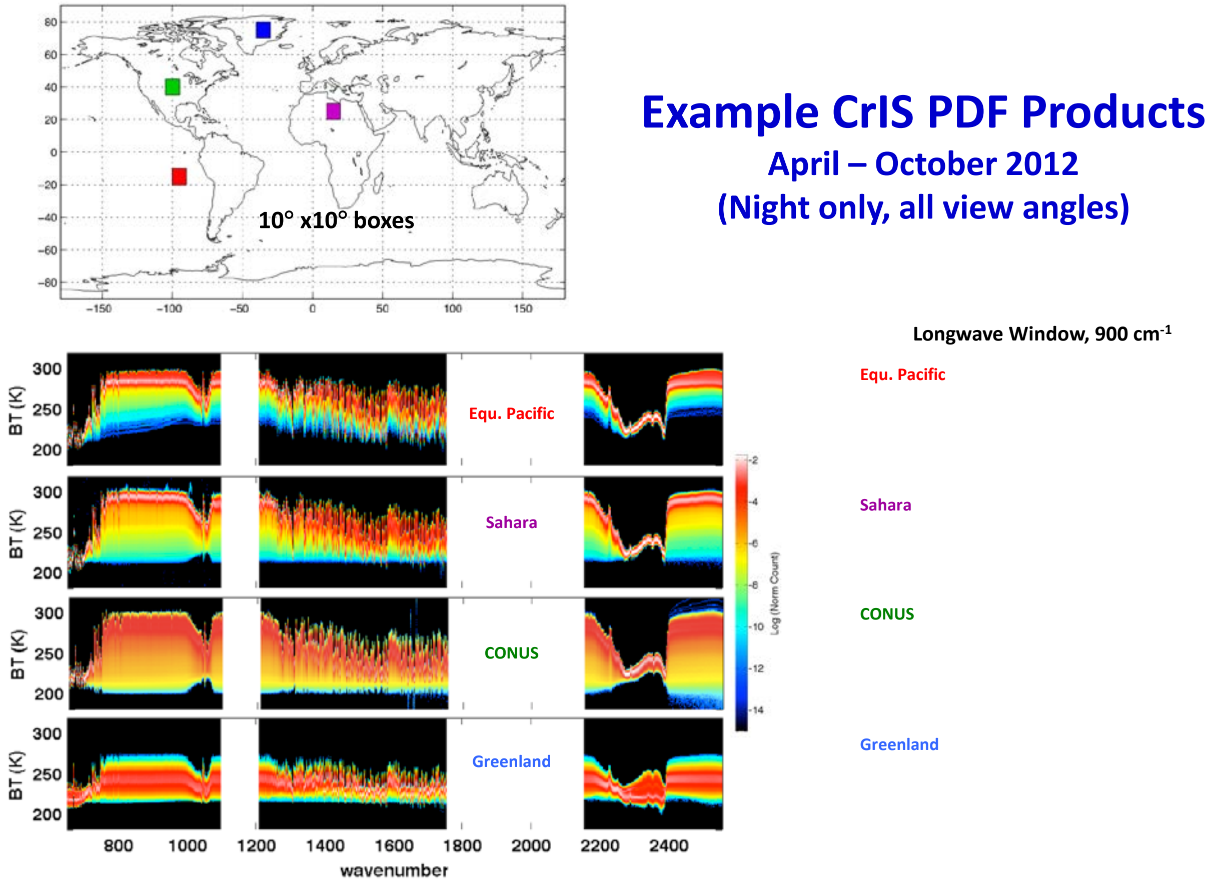


Figure 16. Example Probability Distribution Functions from CrIS for four 1x1 degree boxes located in (1) moist, tropical E Pacific ocean, (2) similar N latitudes in the Sahara, (3) continental US, and (4) polar land over Greenland. Both the range and density of brightness temperature spectra represent the nature of monthly variations for the different locations. The PDFs for a longwave window region channel (lower right) show long, low temperature tails that characterize the seasonal changes in cloud properties in each of these very different regions.

Part B. VIIRS Radiometric performance Studies

VIIRS On-orbit Spectral Performance

During the first year on-orbit, the SNPP VIIRS spectral characterization was updated (May 2012). Improvements in this update included adoption of the govt. team *final* spacecraft level RSR product for VisNIR bands (replacing a *preliminary* release), an update to the laboratory water vapor correction for band M9, and improved filtering of low quality response in the out-of-band region of each band.

A spectral darkening of the rotating telescope assembly (RTA) mirrors due to the presence of tungsten on the mirror surfaces has been influencing SNPP VIIRS VisNIR and SWIR band Relative Spectral Response (RSR) since exposure to sun light on-orbit. On-orbit F-factors (gain) have been used to track this influence and tune a NASA physical absorption model so that the spectral modulation of VIIRS RSR can be quantified and used to produce a so-called Modulated RSR. The Modulated RSR for a snapshot date of Feb 1, 2013 have been reviewed for impact on VIIRS SDR product and validation activities with an impact below 0.5%. The Modulated RSR are now considered the best characterization of VIIRS VisNIR and SWIR band on-orbit RSR and therefore will be used to update the baseline on-orbit RSR characterization. These Modulated RSR will be available to the VIIRS science community alongside previous VIIRS RSR releases.

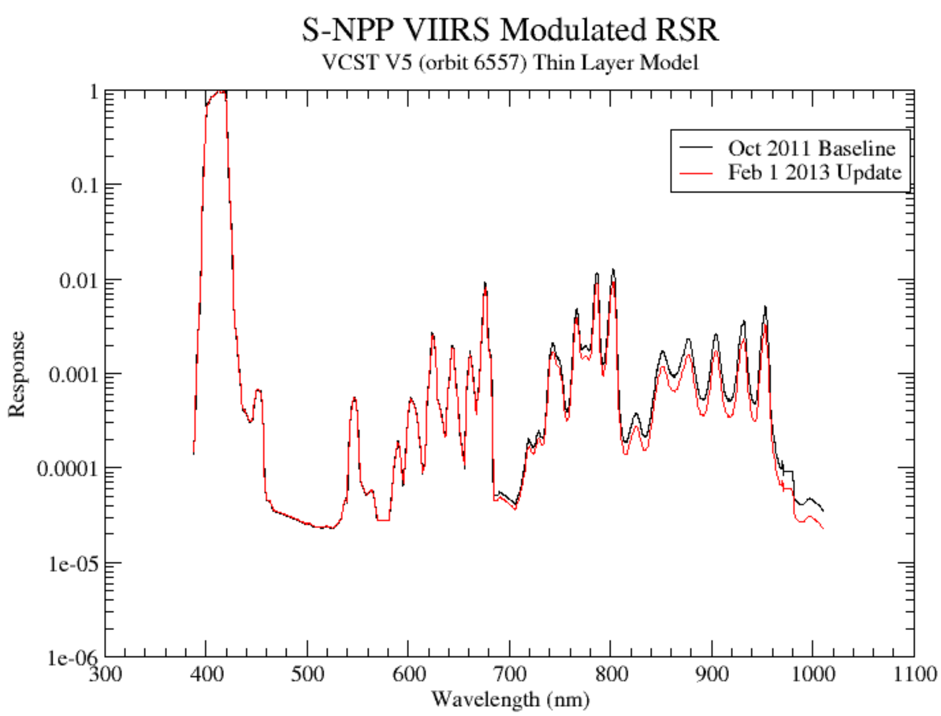


Figure CCM1. SNPP VIIRS band M1 showing baseline and modulated (Feb 1, 2013) Relative Spectral Response. VIIRS Reflected Solar Band RSR are modulated by darkening of the VIIRS RTA mirrors due to tungsten contamination. This causes a noticeable relative reduction in M1 response beyond 600nm.

VIIRS- CrIS On-orbit Comparisons

SNPP VIIRS reflected solar and thermal emissive bands have exceeded one year of nominal operation on-orbit. The VIIRS SDR product achieved a “Beta” designation in the 2nd quarter of 2012 and is currently under consideration for “Provisional” status. UW evaluations during the on-orbit Intensive Cal/Val (ICV) phase have contributed to the body of evidence supporting these designations.

Because they are deployed together as payload on the Suomi NPP spacecraft, the CrIS and VIIRS instruments present a daily opportunity for global comparison of their common spectral bands. In a given 24 hour period, over 2 million potential matchups between CrIS and VIIRS are obtained, providing a robust data set for understanding the relative performance of these instruments and their evolution on-orbit. A daily performance record that now exceeds one year has been built up, providing insight on performance over various timescales and events. These comparisons have shown:

1. Excellent calibration performance at typical scenes for bands M13, M15, and M16 with differences < 0.1 K for typical scenes (CrIS does not contain spectral coverage for M12 and M14). These comparisons however also reveal linear scene temperature dependence for bands M15 and M16. This dependence peaks for cold scene temperatures at about -0.4 K for M15 and about -0.15 K for M16. Band M13 shows a non-linear behavior at cold scenes that suggests that M13 may have a larger cold scene temperature bias than M15 or M16.
2. Excellent stability in M13, M15, and M16 with any longterm trends at or below 10mK/year (Figure B-2). This finding also portrays remarkable fidelity of the VIIRS (and CrIS) data sets.
3. VIIRS on-orbit warmup/cooldown events consistently reveal that VIIRS-CrIS comparisons for M13, M15, and M16 converge when the VIIRS OBC is operated at ambient temperature (Figure B-3). This unexpected finding suggests that some component(s) of VIIRS calibration is biased by operating the OBC at the nominal 292.5 K operational temperature. The calibration adjustment is small (~ 0.1 K) for these bands but nevertheless is highly systematic, suggesting that it may be corrected by a change to the SDR algorithm process and/or LUTs.
4. Angular dependence in the reflectance of the VIIRS HAM (RVS) for bands M13, M15, and M16 is well characterized. The comparisons show that scan angle dependence is below 0.1 K. This behavior is also stable over the on-orbit nominal data collection period.

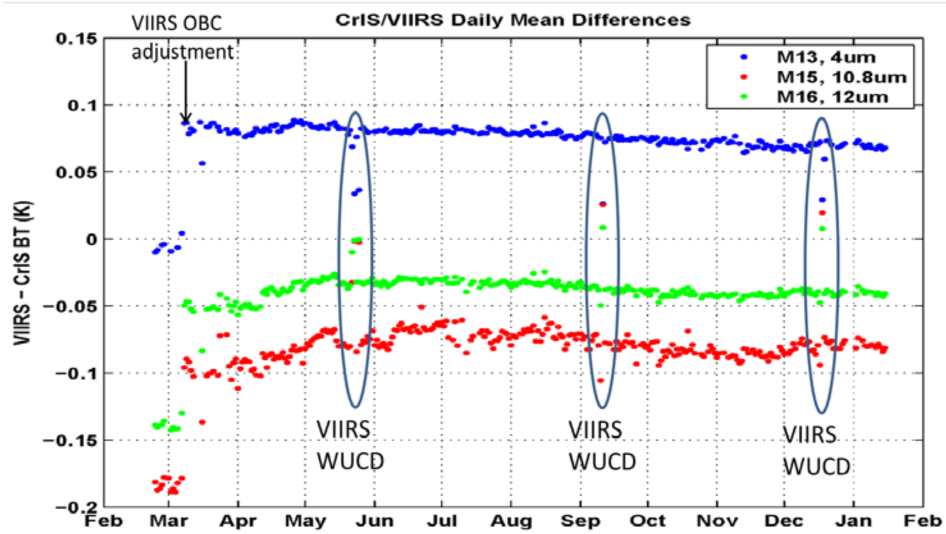


Figure B-2. VIIRS-CrIS spectral radiance differences from March 2012 – Jan 2013 demonstrating excellent stability in VIIRS (and CrIS) radiometric calibration. VIIRS calibration was adjusted in March 2012, improving the comparison to CrIS. VIIRS Warmup-Cooldown (WUCD) events are planned blackbody (OBC) exercises and do not represent an anomaly but do demonstrate a dependence of VIIRS calibration on the operating temperature of the OBC (see item 3 in text).

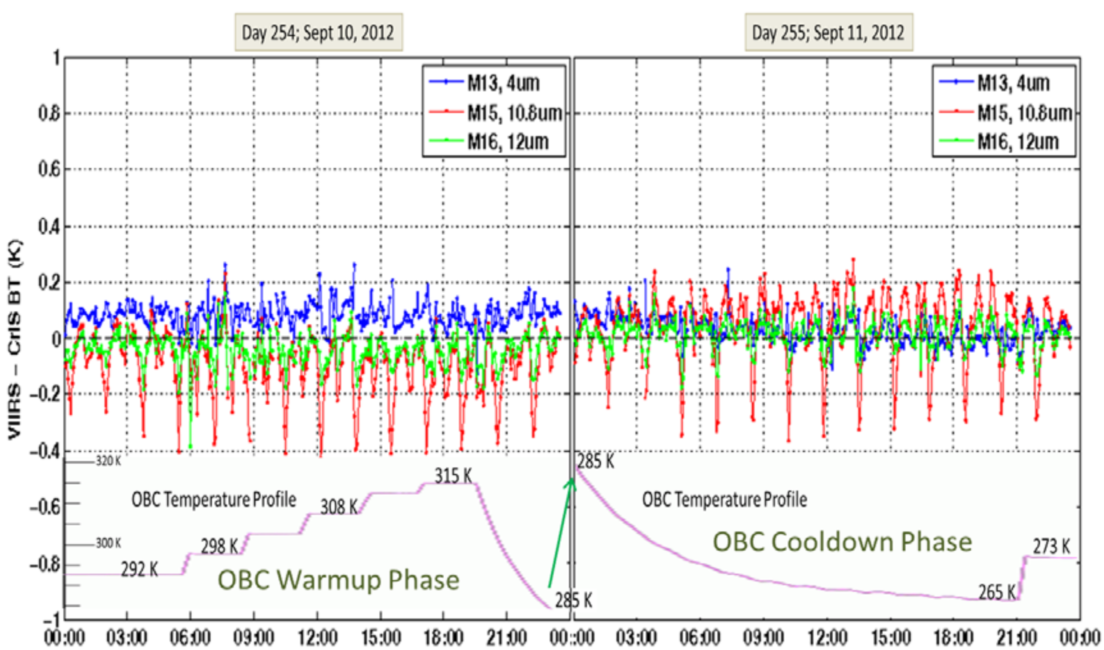


Figure B-3. VIIRS-CrIS spectral radiance differences of Sept 10-11, 2012 during a VIIRS OBC warmup/cooldown event. The temperature profile of the OBC is given in the lower portion of the figure. At nominal (292.5 K) OBC temperature and above, the VIIRS-CrIS differences remain separated by band (left), but as the VIIRS OBC is allowed to cool down to ambient (265 K), the VIIRS-CrIS differences of each band merge near 0 K difference (right). Note however that scene temperature dependent spikes in the VIIRS-CrIS differences are not mitigated by operating the OBC at ambient temperature.