11.3 TOWARD AN INTEGRATED SYSTEM FOR THE CALIBRATION/VALIDATION OF MULTISENSOR RADIANCES FROM OPERATIONAL SATELLITES

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1. INTRODUCTION

The quality of satellite radiances is essential for direct radiance assimilation in numerical weather prediction, for retrievals of various geophysical parameters, and for climate monitoring and reanalysis. It is also a measure of the success of the engineering and science efforts of our operational satellite program. However, past effort in postlaunch calibration/validation was a piecemeal approach, focusing on onboard calibration of individual instruments, with much less attention paid to the quality of radiance data of earth observations. Many instrument artifacts could remain undiscovered in the earth observation data until major impacts are found by users. The lack of on-orbit calibration standard and methodology for radiance verification also aggravated the problem. We believe that in order to meet the challenge of the increasing demand for better satellite data quality, an integrated approach for calibration/validation should be used, which includes several core components. This integrated system will bring together all operational satellite radiometers and make the radiances highly traceable among a constellation of global satellites in both polar and geostationary orbits. In this paper we introduce our efforts and progress in developing this integrated system and plans for supporting the calibration/validation and long-term monitoring of POES, MetOP, and NPOESS radiometers.

2. CURRENT STATUS OF CAL/VAL AND THE NEED FOR AN INTEGRATED SYSTEM

NOAA/NESDIS Office of Research and Applications has a long track-record of supporting the operational calibration of radiometers on polar-orbiting environmental satellites, transferring research results to operations, and performing advanced research in satellite instrument calibration. We also play an important role in re-calibrating historical data to support climate studies, through the scientific data stewardship program. We have accumulated valuable experience in support of the operational pre- and postlaunch of NOAA instruments, including those on NOAA-18, -17, and -16. We will continue our support to the POES program and are currently preparing to support MetOP and future NPP/NPOESS instruments. We have contributed greatly to the investigation of on-orbit instrument anomalies, provided improved calibration algorithms to operations, and resolved many calibration issues in algorithms, instrument noise and biases. We have extensive experience in evaluating the instrument performance in its life cycle, and broad experience working with the instrument manufacturers, NIST (National Institute of Standards and Technology), as well as the user community. Being part of the future NOAA Central for the NPOESS program, we are also uniquely positioned to provide significant technical contribution to NPP/NPOESS calibration/validation. The following work exemplifies our cal/val capabilities and the need for an integrated system.

2.1 ON-ORBIT VERIFICATION (OV) OF RADIOMETERS ON NOAA-18

Our expertise, experience, and capabilities in the postlaunch and prelaunch calibration/validation are exemplified in the recent NOAA-18 OV of the operational infrared sounder and imager. Before launch, we independently analyzed the thermal vacuum data, verified the nonlinearity characterization, generated the spectral response functions (SRF), and characterized the effects of SRF on observation biases through rigorous radiative transfer calculations. In the postlaunch OV, we made significant contributions to the investigation of the infrared sounder HIRS noise anomaly. As a member of the investigation team, we provided critical analysis, data, and information, including noise characterization in the radiometric, spectral, and spatial domains, and impact assessment of the noise on radiance assimilation and physical retrievals. We developed an online instrument performance monitoring system, which has been widely used by both the investigation team and the data users to closely monitor the instrument status. We worked closely with the instrument manufacturer and other members of the investigation team to find the root cause of the instrument noise in such areas as optical, electronic, external and internal interferences, and instrument design issues. Investigation results are presented at the NOAA-18 on-orbit verification meeting (Cao, 2005). The NOAA-18/HIRS is extremely sensitive to both external and internal vibrations, and the noise is a very challenging problem because of uncertainties in the new 10km design, complications related to the rotating filter wheel, lack of on-orbit diagnostic switches, and issues related to dynamic interactions with other instruments and the spacecraft. Some of these issues will likely have significant impacts on future launches.

Another important issue with NOAA-18/HIRS is the large biases relative to HIRS on previous satellites for several sounding channels. Understanding the biases has significant impacts on data assimilation, physical retrievals, and climate studies. We have studied the biases extensively using a number of methods, including forward calculations with line-by-line models, inter-satellite calibration at simultaneous nadir overpasses (SNO) with NOAA-17 in the polar regions, inter-comparison with hyperspectral sounder AIRS in the tropics with the “A-train” configuration, and intra-satellite calibration with other instruments. All results suggest that the biases relative to HIRS on previous satellites are due to differences in the spectral response functions instead of instrument calibration problems. These studies become excellent examples for diagnosing complex biases with the integrated cal/val system, and the findings are very helpful for establishing the confidence in the accuracy of the satellite data.

There are many lessons learned from the NOAA18/HIRS noise investigation. First, instrument diagnosis should include a comprehensive analysis of the status of the spacecraft and other instruments because of possible dynamic interaction among them. This requires an integrated approach in calibration/validation. Second, complex diagnosis requires participation of many different instrument specialists, such as optical, thermal, mechanical, and electronic. Without an integrated approach, the diagnosis can be very ineffective, time consuming and difficult. Third, in assessing the effect of noise and bias on products, it requires a close collaboration between the investigation team and the data users, which again requires an integrated approach.

2.2 Inter-Satellite Calibration of POES and NPOESS Instruments Using the SNO/SCO Method

Inter-satellite bias is one of the most important issues in assessing calibration accuracy. Unfortunately, unlike noise which can be characterized with calibration targets, bias characterization can be very difficult. This is because currently there is no on-orbit standard that the calibration can be traced to after launch. NIST traceability is very useful for prelaunch testing in thermal vacuum under thermal equilibrium conditions, but in-orbit thermal equilibrium is rarely reached for most instruments. Experience tells us that the calibration accuracy will likely vary depending on what orbit the satellite is in, in addition to orbital and seasonal variations in the accuracy. Over a long period of time, the calibration accuracy may change in response to a number of factors such as degradation and orbital drift. Based on our experience, this problem can become especially frustrating for the data providers because users may believe that their evidences of biases are compelling, and yet the causes for biases cannot be easily found in the instrument. Because of the complexity of this problem, in-depth knowledge of biases is essential in providing solid support to an operational program such as POES and NPOESS with the integrated approach.

It is essential to reduce the number of factors in inter-satellite calibration in order to analyze instrument calibration and identify the root cause of the biases, because without knowing the root cause, bias correction will not work correctly. By using the simultaneous nadir overpass (SNO)/simultaneous conical overpass (SCO) method for inter-satellite calibration (Cao and Heidinger, 2002. Cao, et al., 2004b), we effectively eliminate the time difference and off-nadir factors in the bias assessment, which greatly reduces the uncertainties for comparing radiances measured by similar instrument on different satellites, thus facilitates the identification of the root causes for the biases.

We have used the SNO method in a number of applications for all primary instruments on NOAA operational satellites, including long-term monitoring of operational instrument performance, and establishing the calibration link from POES to EOS, and NPOESS. Figure 1 shows the operational monitoring of the HIRS on NOAA-16 and -17 using the SNO method. The noise increase in NOAA-16/HIRS is clearly seen in this figure, however, the inter-satellite bias did not change significantly and thus did not cause major concerns for many users.

Inflight spectral calibration is very challenging for most radiometers because typically there is no onboard spectral calibration device. However, inflight spectral calibration using hyperspectral data can be performed at the SNOs. For example, we have experimented with the spectral calibration of HIRS using AIRS data at the SNOs (Cao and Ciren, 2004). As more and more hyperspectral sounders such as IASI on MetOP and CrIS on NPOESS become available in the future, this type of study will become very important. We also found that inter-satellite calibration at the SNOs are very useful for solar reflective bands, because of the low uncertainties due to the very small orbital variation in the calibration coefficients, the dry atmosphere, and a relatively large range of reflectance in the polar regions. Figure 2 shows that the agreement in the calibration between NOAA-16 and -17 AVHRR channel 2 at 0.86 um became much better after the calibration coefficients for NOAA-17 were updated, although the SNO time series also shows that a small difference still exists after the update.

Clearly an integrated calibration/validation approach is essential for inter-satellite calibration of radiometers. Onboard calibration of individual instruments alone can not insure the calibration consistency across satellites. The integrated approach will allow us to establish on-orbit traceability and consistency to meet the user demand for more accurate satellite radiance data.

2.3 Improving the calibration accuracy of operational instruments for climate studies.

We have extensive experience in evaluating the long-term calibration performance of radiometers. NOAA’s operational instruments have a typical life span of more than 5 years. The degradation of on-orbit calibration, along with the effect of orbital drift has been studied extensively at ORA. For example, in one study, we found that the cold bias of NOAA-14/AVHRR relative to ocean buoys is caused by the instrument degradation and orbital drift, instead of the hypothetical volcanic activities as some have suggested (Cao, et al., 2004a).

Climate studies require very high calibration accuracy. For example, to detect a global average temperature increase on the order of 0.5 C per century, it is necessary that the instrument calibration accuracy be several times better. Unfortunately, in the on-orbit verification and subsequent long-term monitoring, there is no objective method in judging the measurement accuracy to the desired level. To meet such challenges, we have further refined the inter-satellite calibration using the simultaneous nadir overpass (SNO) method and used it to quantify the inter-satellite biases for historical satellite data.

As an extension of the SNO method, the SCO (simultaneous conical overpass) method has also been developed for conical scanners such as SSMI and SSMIS on DMSP satellites. Inter-satellite calibration for all historical SSMI instruments is in progress. Figure 3 shows an example of the inter-satellite calibration of the 85v SSMI channel on F10 and F13, where a consistent bias on the order of 1 K is apparent, despite the variation in the biases over time. We have found that the SNO/SCO method works extremely well for microwave instruments sensing the mid-troposphere to upper stratosphere channels, where the uncertainty in the bias is far below the instrument noise. Part of the reason is that microwave instruments have identical and stable center frequency between instruments, in contrast to infrared instruments where biases can be caused by spectral response difference and the lapse rate. Figure 4 demonstrates the excellent agreement on the order of 0.1 K for the 53.6GHz channel of AMSU on NOAA-16 and -17.

Climate monitoring and reanalysis will benefit from the integrated calibiration/validation approach because the climate trend detected can be validated across instruments, and common issues across instruments can be better resolved to reduce the calibration uncertainties as well as their impact on climate trending analysis.

3 DEVELOPING AN INTEGRATED INSTRUMENT CALIBRATION/VALIDATION SYSTEM

The examples above demonstrates that there is a great need for an integrated system for calibration/validation of satellite radiometers, and we have developed many important components for the integrated system. We believe that the next natural step is to integrate all the components to build the integrated instrument calibration/validation system. This integrated system will be used to independently verify the radiances produced by the instruments in order to have a better understanding of the radiance data quality, so that we can better serve the user community. The core components of the system include the following: (1) on-orbit and prelaunch instrument characterization and long-term monitoring of instrument performance; (2) Inter-satellite calibration of radiances using the simultaneous nadir overpass (SNO) and simultaneous conical overpass (SCO) methods; (3) Forward calculation of radiances using state-of-the-science radiative transfer models and in situ atmospheric profiles for validation and resolving spectral response related biases; (4) On-orbit spectral calibration using hyperspectral data and atmospheric absorption features; (5) Intra-satellite calibration, or calibration between instruments on the same satellite, and inter-channel calibration; (6) Vicarious calibration at selected sites and atmosphere for instrument scan asymmetry characterization; (7) Spatial calibration, involving geolocation, alignment, and channel coregistration using geographic information systems and vector maps, as well as landmarks; (8) Cross platform calibration from POES to MetOP, NPOESS, and GOES. This integrated system will bring together all operational satellite radiometers and make the radiances highly traceable among a constellation of global satellites in both polar and geostationary orbits, and will become an essential tool for the implementation of GEOSS. The following provides a brief description of the selected components.

3.1 Prelaunch/postlaunch calibration support

We have been providing significant technical support to the prelaunch calibration of all POES in the past and will continue to do. For prelaunch calibration, we will emphasize prelaunch test issues that will likely affect the postlaunch performance. In the postlaunch calibration, we will focus on the characterization of instrument noise and biases using the integrated cal/val system, and complete the development of an on-line instrument performance trending system that monitors a selected number of key instrument parameters.

3.2 Inter-satellite calibration between POES, MetOP, DMSP, and NPOESS

We believe that the SNO/SCO method will be extremely useful for the calibration/validation of all instruments. For example, using this method, SNO observations for AVHRR vs. MODIS and VIIRS; HIRS vs. AIRS, IASI and CrIS; and AMSU vs. ATMS, and SSMI/SSMIS vs. CMIS can be directly compared and biases quantified routinely. Since the observations are precisely collocated and coincidental, it greatly reduces uncertainties, thus allows us to evaluate the relative performance of the radiometers and to establish the onboard calibration traceability between satellites with little ambiguity. We will continue the development of the SNO time series to establish the calibration links for all the operational radiometers. The web site development for the SNO/SCO system is in progress and the results are updated regularly on the web site.

3.3 Cross instrument calibration on same satellite (Intra-satellite calibration)

We will expand our intra-satellite calibration capabilities (currently limited to between AVHRR and HIRS) to include spectral calibration using hyperspectral sounders such as using IASI to calibrate other instruments. The intra-satellite calibration will also be used for geo-location, co-registration, and alignment checks between instruments, as well as evaluating on-orbit blackbody performance by analyzing the bias variation between instruments.

3.4 Integrate forward calculations with radiative transfer models

Forward calculations are extremely useful for resolving spectral response related biases. We will enhance our capability in this area by including more radiative transfer models. In addition to the current models such as LBLRTM and Modtran, we will add the community radiative transfer model, which has been developed and used by the Joint Center for Satellite Data assimilation. This will allow us to better communicate with the data users on calibration related issues such as biases. In addition, we will regularly compare forward calculations at selected sites, such as the ARM sites, with satellite observations. The results will be updated regularly on the web site.

3.5 Vicarious calibration, geo-location, alignment, and co-registration

Several vicarious calibration areas will be useful for the calibration/validation with the integrated approach. First, for atmospheric sounders, vicarious calibration using the mid to upper atmospheric channels will be useful for evaluating scan asymmetry. Second, traditionally, the solar reflective channels on AVHRR have been vicariously calibrated because there is no onboard calibration device for these channels. Also, to establish calibration consistency among POES, MetOP, NPOESS, and GOES, calibration links between them have to be developed through vicarious calibration. Currently we have found differences between MODIS and AVHRR calibrations due to traceability issues. These issues will be further studied and the differences resolved. Finally, vicarious calibration is very useful for geolocation, instrument alignment, and channel coregistration studies, in which high-resolution data sets, geographic information systems and vector maps, and cross calibration between instruments will be used.

3.6 Collaboration with product validation groups

Although our work focuses on instrument calibration and validation, we recognize the importance of product validation for cross checking calibration biases and data quality. Therefore, we will work closely with various product validation groups to address instrument calibration/validation issues. We plan to include selected algorithms to be implemented in the long-term monitoring of instrument performance. For example, aerosol, NDVI, OLR, and SST algorithms will be useful for validating the calibration if long-term time series are used, which will allow us to analyze small trends in calibration biases.

3. SUMMARY

An integrated calibration/validation system is needed to better serve the user community, and to facilitate the diagnosis of instrument problems. The integrated system includes independent verification of radiances through inter-satellite calibration using the SNO/SCO method, on-orbit and prelaunch instrument characterization, intra-satellite calibration between instruments on the same satellite, radiative transfer calculations to isolate calibration biases, on-orbit spatial and spectral calibration, cross comparison with vicarious calibration, and cross platform calibration with POES, MetOP, DMSP, NPOESS, and GOES. The integrated system will allow us to quantify the on-orbit calibration biases with little ambiguity, and in turn will significantly reduce the uncertainties for the data users in direct radiance assimilation in numerical weather prediction, physical retrievals, and climate monitoring and reanalysis.

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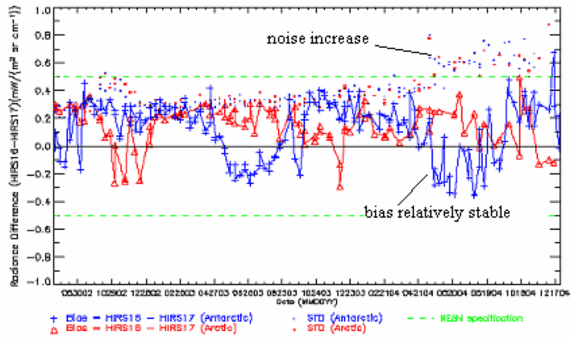

Figure 1. Operational monitoring of the HIRS instrument performance using the SNO method. Inter-satellite bias may not be affected by the noise increase. The seasonal change in the bias is due to differences in the spectral response functions.

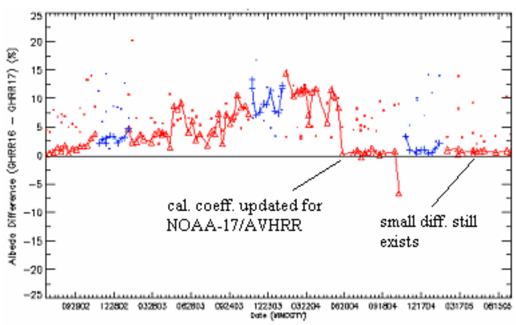

Figure 2. Example SNO applications for monitoring calibration coefficient updates for solar reflective bands

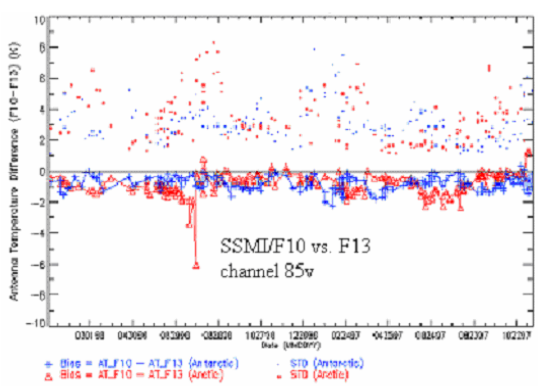

Figure 3. The SNO/SCO method has been used to inter-calibrate SSMI on DMSP satellites. A consistent bias is found between SSMI on F10 and F13.

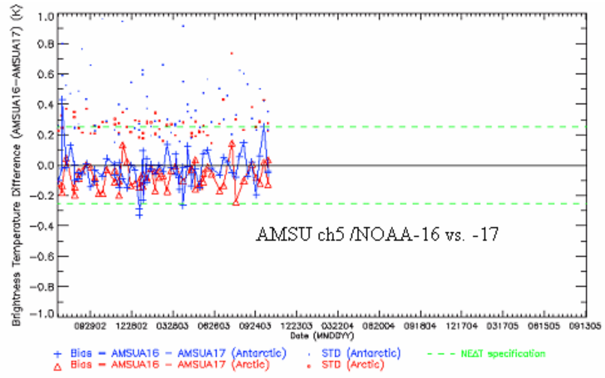

Figure 4. In the operational monitoring of AMSU, it is found that the 53.6 GHz channel of AMSU between NOAA16 and -17 agree extremely well at the SNOs.