CGMS-34, NOAA-WP-17
Prepared by M. Goldberg
Agenda Item: II/6
Discussed in xWG2

REPORT ON INTERSATELLITE CALIBRATION AT NOAA/NESDIS

In NOAA-WP-17, Working Group II was informed that the calibration accuracy of satellite radiances is critical for both numerical weather prediction and climate change detection. In the last few years, NOAA/NESDIS has developed a system for the intersatellite calibration of polar-orbiting satellites using the Simultaneous Nadir Overpass (SNO) / Simultaneous Conical Overpass (SCO) (for conical microwave scanners). Studies have shown that this system can be used for the intersatellite calibration of microwave, infrared, and visible/near-infrared radiometers with small uncertainties. Preliminary studies suggest that intersatellite calibration using the SNO/SCO method works best for the sounding channels of microwave radiometers, and it works well for the visible/near-infrared channels for instruments with identical or similar spectral response functions. For traditional infrared sounders, the small differences in spectral response functions tend to introduces seasonal biases between satellites, but this is likely resolved with the hyperspectral sounders. The applicability of this method to nearly all radiometers, its low uncertainty and cost effectiveness has stimulated a number of applications in recent years. Results of these studies have been published in peer reviewed journals and conference proceedings. Based on these studies, it is recommended that an on-orbit calibration reference network should be established using the SNO/SCO method. This will allow us to link the calibration of all operational radiometers to better serve the NWP and climate community.

REPORT ON INTERSATELLITE CALIBRATION AT NOAA/NESDIS

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EXECUTIVE SUMMARY

The calibration accuracy of satellite radiances is critical for both numerical weather prediction and climate change detection. In radiance data assimilation, biases have to be removed before the data can be assimilated. In climate change detection, a small calibration bias may lead to different conclusions about the climate trend. In addition, calibration links across international satellites need to be established to support the GEOSS (Global Earth Observation System of Systems) and GSICS (Global Satellite Inter-Calibration System). The demand for more accurate radiances presents a challenge to the calibration science and compels us to develop better methodologies to further improve the calibration accuracy. Intersatellite calibration is developed to address some of these issues by quantitatively evaluating whether any given two satellite radiometers produce consistent radiances with an acceptable uncertainty.

In the last few years, NOAA/NESDIS has developed a system for the intersatellite calibration of polar-orbiting satellites using the Simultaneous Nadir Overpass (SNO) / Simultaneous Conical Overpass (SCO) (for conical microwave scanners). Studies have shown that this system can be used for the intersatellite calibration of microwave, infrared, and visible/near-infrared radiometers with small uncertainties. The system has been used for operational instrument performance monitoring and diagnosis, risk reduction of future instruments, and recalibration of historical satellite data for climate studies. It has become an important tool supporting both current and future operational satellite programs, as well as new initiatives such as GSICS.

Preliminary studies suggest that intersatellite calibration using the SNO/SCO method works best for the sounding channels of microwave radiometers, and it works well for the visible/near-infrared channels for instruments with identical or similar spectral response functions. For traditional infrared sounders, the small differences in spectral response functions tend to introduces seasonal biases between satellites, but this is likely resolved with the hyperspectral sounders. The applicability of this method to nearly all radiometers, its low uncertainty and cost effectiveness has stimulated a number of applications in recent years. Results of these studies have been published in peer reviewed journals and conference proceedings. Based on these studies, it is recommended that an on-orbit calibration reference network should be established using the SNO/SCO method. This will allow us to link the calibration of all operational radiometers to better serve the NWP and climate community.

I. INTRODUCTION

As more and more meteorological satellites become operational, the increasing amount of satellite data provides more options for both numerical weather prediction and climate change detection. At the same time, user requirements and expectations for radiance accuracy have also changed. For example, the NOAA satellite radiometers were initially designed for traditional weather applications with no stringent requirement for calibration accuracy, while numerical weather prediction does not tolerate biases between observations and forward calculations in data assimilations because bias directly affects the cost function (Weng and Liu, 2003). These biases are constantly monitored at the NWP centers, and in most cases bias adjustments have to be applied before the radiances can be assimilated in the NWP models. For climate change detection, a much higher calibration accuracy is desirable since the signal of climate change can be as small as 0.1 K per decade. Given a satellite radiometer's typical design life of about five years, the detection of decadal climate trend relies on observations from a series of satellites. It is well known that despite the best effort in prelaunch and postlaunch calibration, the same series of radiometers on different satellites, such as the Microwave Sounding Units (MSU) on NOAA satellites, do not necessarily produce consistent measurements. This leads to intersatellite biases which have become major concerns in constructing time series for climate change detection. As has been demonstrated in the tropospheric temperature trend study using MSU channel 2 observations, the intersatellite biases can become so critical that depending on how the biases are handled, it may lead to different conclusions about the troposperic warming (Zou, et al, 2006; Vinnikov and Grody, 2003; Christy, et al., 1998). Unlike instrument noises that can be quantified precisely with on-orbit calibration targets, biases are very difficult to characterize due to the lack of commonly traceable on-orbit absolute calibration standard, and the variable nature of biases both short term and longterm in response to the operating environment. These are fundamental issues that cannot be resolved without accurate and robust intersatellite calibration methodologies. Although several methods have been used for intersatellite calibration in the past (Gunshor, et al., 2004; Christy, et al., 1998; Minnis, et al., 2002), one particular area that has witnessed significant progress in recent years is the application of the Simultaneous Nadir Overpass/Simultaneous Conical Overpass (SNO/SCO) method.

2. THE SIMULTANEOUS NADIR OVERPASS (SNO) /SIMULTANEOUS CONICAL OVERPASS (SCO) METHOD AND ITS APPLICATIONS

The Simultaneous Nadir Overpass (SNO) method (Cao, et al, 2004, 2005a, 2005b) was developed in recent years for quantifying intersatellite biases initially for instrument performance monitoring and has now been extended to constructing time series for climate change detection studies (Zou, et al., 2006). This method is relatively simple and robust, and it is based on the fact that any pair of polar-orbiting satellites with different altitudes pass their orbital intersections regularly nearly simultaneously. The frequency of occurrences (typically once every 2-10 days) is a function of the altitude difference between the two satellites. Observations from the two satellites at the SNOs can then be collocated pixel-by-pixel and the biases between them quantified. The uncertainties in the SNO analysis are further reduced in a SNO time series where the intersatellite biases at the SNOs are shown as a function of time.

Applications of the SNO method for Microwave radiometers have shown very promising results for climate trending analysis (Zou, et al., 2006). Several factors contributed to this success: first, the microwave channel center frequencies between instruments are presumably made to match precisely, which significantly reduces or eliminates uncertainties related to spectral differences. Second, the intersatellite biases for Microwave instruments appear to be relatively constant short-term. Third, each microwave instrument has its own onboard blackbody calibration which keeps each instrument's calibration in-check independently. It is found that the SNO method works very well for microwave instruments sensing the mid-troposphere to upper stratosphere channels, where the uncertainty in the bias is much smaller than the instrument noise. Figure 1 shows the excellent agreement on the order of 0.1 K for the 53.6 GHz channel of AMSU on NOAA-16 and -17. Recent analysis on intersatellite biases for AMSU on NOAA and EOS/AQUA satellites also revealed small but unambiguous calibration biases on NOAA18/AMSU (Iacovazzi and Cao, 2006). In addition to the SNO, the Simultaneous Conical Overpass (SCO) method is also developed for conical scanners (imagers) such as SSMI on the DMSP satellites, although further improvements are needed to reduce the uncertainties due to surface non-uniformity and atmospheric path differences.

Applications of the SNO method to the visible/near-infrared have yet to reach their fullest potential. Studies have shown that the SNO method is very effective in quantifying the intersatellite biases for these channels. Since the biases are short-term invariant for the visible/near-infrared instruments, they can be used for inter-calibrating the satellites for global observations. The dry atmosphere and highly reflective surface with a range of solar zenith angles at the SNO sites in the polar regions are advantages for calibrating these channels (Jaross, et al, 1998; Masonis and Warren, 2001). Figure 2 shows that the calibration biases between NOAA-16 and -17 AVHRR channel 2 at 0.86 um are significantly reduced after the calibration coefficients for NOAA-17 were updated in June 2004, although a small difference still exists. However, since the SNO method only provides a relative calibration between two satellites and none of the NOAA-satellites has onboard calibration for the visible/near infrared channels, the SNO calibration alone is not sufficient for developing an improved long-term time series for these channels. This method is more useful if one satellite can be relied on as a stable standard, such as in the intercalibration of MODIS and NOAA radiometers (Heidinger, et al., 2002), but the difference in the spectral response functions between them introduces uncertainties and can make the inter-calibration difficult to analyze.

For infrared radiometers, studies have shown that the SNO method can quantify intersatellite biases with uncertainties smaller than the instrument noise (Cao and Heidinger, 2002). However, additional uncertainties exist when compared to that of the microwave and visible instruments. First, the calibration accuracy may vary over an orbit for some instruments, such as AVHRR in terminator orbits. As a result, biases found at the SNOs may not be the same as in other parts of the orbit, and the bias may be orbital and seasonal dependent. The calibration accuracy may also change longterm in response to a number of factors such as degradation and orbital drift. Second, for infrared sounders, a small difference in the spectral response functions may mean that a different layer of the atmosphere is observed, thus producing seasonal biases(Figure 3, Cao, et al., 2005b). It is expected that this effect will be significantly reduced with hyperspectral sounders such as AIRS and IASI (Wang, et al., 2006).

Studies have shown that the SNO method is able to resolve intersatellite biases on the order of <0.1 K in the sounding channels of the microwave and infrared instruments, and 1% in the visible/near-infrared imagers with a 1 km spatial resolution. Larger uncertainties are found for low resolution surface channels of sounders where surface inhomogeneity and pointing accuracy become issues.

It should be noted that the SNO/SCO method is a complement to the other methods for intersatellite calibration. Prelaunch and onboard calibration remains to be the key to accurate radiometer calibration. Aircraft based intercalibration have also been shown as extremely valuable (Tobin, et al., 2006, Revercomb, et al., 2003, Green and Pavri, 2002). Significant progress has been made in the intersatellite calibration using the moon, which is reported elsewhere (Barnes, et al., 2006; Xiong, et al., 2005; Barnes, et al., 2004).

3. IMPEDIMENTS TO PROGRESS

A major impediment to further progress in inter-calibration is the lack of common and stable on-orbit calibration targets of climate quality. The moon can probably be used as a target for the visible/near-infrared calibration but is currently limited to stability monitoring instead of absolute calibration, and its use for calibrating infrared and microwave instruments requires further studies. Another major impediment is the lack of tools for analyzing intersatellite biases with the desired accuracy, which limits our understanding of the biases. The SNO/SCO method represents a major progress in this area. However, the method has its limitations. First, we found that differences in the spectral response functions (SRF) between instruments can introduce uncertainties. Although these uncertainties can be reduced given the surface spectral features, the SNOs occur at many different locations in the polar regions where the spectral characteristics are currently not well quantified. Second, while the SNO method works well for the sounding channels in the microwave and infrared, it does not work as well for the surface channels where inhomogeneity becomes a major factor for these instruments. Finally, the SNO method is very sensitive to geolocation and sampling errors, for example, the AVHRR 5KM GAC data do not match perfectly with the MODIS 1 KM data due to the sampling scheme used in AVHRR, which introduces uncertainties in intercalibrating AVHRR and MODIS. Some of these issues can be resolved in the near future, once the SNO sites are fully characterized. The availability of the global 1 KM AVHRR data from MetOP-A will also lead to a major reduction in uncertainties.

Due to these issues discussed above, the current knowledge of intersatellite biases is still limited in the context of climate change detection. Study of intersatellite biases is typically conducted in short term projects, and the findings may contain large uncertainties. The short term duration of these projects makes it difficult to understand the nature and the root cause of the intersatellite biases, and the findings are usually not well documented. Data users may be insensitive to small biases which can persist for many years. A case in point is the bias on the order of 10% between AVHRR and MODIS for channel 1 at 0.63 um, which existed since the MODIS launch but was not recognized until recently in SNO studies (Cao, 2006a). The uncertainty in the intercalibration methods directly affect the ability to intercalibrate satellites. Understanding the root cause of the biases requires close collaboration between scientists and instrument engineers but in many cases such collaboration is lacking.

4. RECOMMENDATIONS

Recommendation 1: Establish an on-orbit calibration reference network using the SNO method: Aside from the proposed dedicated climate quality satellite (or benchmark) missions which may not be available for another decade, a practical and cost effective initiative is to develop and maintain an on-orbit calibration reference network (Cao, 2006b), which monitors the long-term time series of intersatellite biases at the SNOs, GEO/LEO satellites, and selected vicarious sites for all operational satellites. Even without an absolute scale, this will tie the calibration of all the satellites together to provide traceability of individual satellites to the calibration reference network. It is difficult to know which radiometer produces the absolutely correct radiance, but truth is likely to emerge from the measurements of a group of satellites. International collaboration under the GEOSS should facilitate data sharing and allow us to intercalibrate radiometers globally to establish a calibration reference network and a quasi on-orbit standard.

In addition, airborne radiometers can be used as checking points for the longterm time series to provide calibration links to the absolute standard. Further research in moon calibration may also allow us to use the moon as absolute calibration check in the visible/near-infrared for the longterm time series. The moon as an on-orbit absolute calibration standard for the visible/near infrared channels should be further explored.

Recommendation 2: Refine the SNO method to further reduce uncertainties for the window channels: Uncertainties in the SNO method can be further reduced with SNO site characterization with highly accurate spectral, spatial, BRDF, and elevation models. This will be especially helpful for the window or surface channels. The reduced uncertainty will allow us to better quantify the intersatellite biases and small trends in the satellite measurements. Longterm observation of vicarious sites such as the Dome Concordia, Greenland, Libyan Desert, Rairoad Valley, and other sites with stable instruments will also provide independent site stability and calibration accuracy assessments.

Recommendation 3: Ensure satellite mission overlap and channel consistency in mission planning: Satellite mission overlap is essential to most intercalibration techniques, which requires not only time overlap, consistency in local observation time, but also assurance of spectral continuity in channel selection between satellites. For example, the small frequency change from MSU channel 2 to AMSU channel 5 created problems in climate trending. Channel discontinuities were also created when some HIRS channel center wavenumbers were changed in the history of the NOAA satellite series. Such changes should be strictly avoided if possible in mission requirements. Also, in cases where hyperspectral instrument is not an option, technologies for producing identical instrument spectral response functions become highly desirable and should be promoted.

Recommendation 4: Advance the science and technology in onboard calibration: Further improvements in onboard calibrators, i.e., blackbody in the infrared and microwave, and solar diffusers in the visible/near-infrared will reduce calibration uncertainties and facilitate the establishment of on-orbit calibration standard. For instruments with onboard calibration, not only the biases between satellites, but also the root cause of the biases, should be investigated. This is because bias correction without knowing the root cause could be unreliable. Once the root cause is identified, this information can be used as feedback to the instrument development process to improve the calibration devices for future instruments.

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