Preliminary Study of the On-orbit Radiometric Traceability and Artifacts for the VIIRS Longwave Infrared Channels during Blackbody Temperature Changes

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ABSTRACT

The Visible Infrared Imaging Radiometer Suite (VIIRS) has been continuously observing the Earth with global coverage twice daily in the longwave infrared channels since January 20, 2012. These channels are primarily used for cloud detection, and for retrieving sea surface temperatures globally, as well as a number of other applications. The VIIRS sensor data records (SDR), aka level 1b data, have been shown to be accurate and stable at 0.1K level since the data reached validated maturity on March 18, 2014. However, during the scheduled quarterly warm-up/cool-down of the onboard blackbody calibration source, a calibration bias on the order of 0.1 K is introduced. The bias is further amplified by the sea surface temperature (SST) retrieval algorithm up to 0.3 K which causes an apparent spike in the SST product time series. Our previous study [1] reveals that this bias is likely caused by a fundamental assumption on the radiometric traceability of the VIIRS calibration equation, pertaining to the shape of the calibration curve. In this study, we further analyzed the equation and presented an improved correction algorithm known as Ltrace 2. This algorithm attempts to fundamentally reconcile the calibration curve shape assumption such that the calibration bias can be removed during the WUCD with better performance for all bands. Sample test results are presented to show the improvements using this algorithm.

Keywords: S-NPP, VIIRS, warmup/cooldown, thermal emissivity bands; longwave infrared; sea surface temperature; calibration anomaly; correction algorithm.

INTRODUCTION

The Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Partnership (Suomi NPP) Satellite plays two important roles in the global satellite observations of the earth. First, it serves as a replacement and follow-on to NASA's Moderate-resolution Imaging Spectroradiometer (MODIS) in this important joint mission. Second, it has become the operational imager for the NOAA operational afternoon satellite, as a follow-on to the NOAA-19 in the afternoon orbit, which is the final satellite for the heritage NOAA satellite series since NOAA-6 launched in 1979. The Suomi NPP satellite will be followed by the NOAA JPSS-1 satellite, which is to be launched in fall 2017 with the latest VIIRS onboard. Additional VIIRS instruments (from JPSS2 to JPSS4) are also in the works, which will make VIIRS one of the longest imagers observing the earth, following the tradition of the AVHRR. Therefore, the performance of the VIIRS instrument will have profound impacts on the observations of the earth for decades to come.

The Suomi NPP longwave channels (aka Thermal Emissive Bands or TEB) have been continuously observing the Earth with global coverage twice daily since January 20, 2012. These channels are primarily used for cloud detection, and for retrieving sea surface temperatures globally. The VIIRS sensor data records (SDR), aka level 1b data, have been shown to be accurate and stable at 0.1K level since the data reached validated maturity on March 18, 2014. However, during the scheduled quarterly warm-up/cool-down of the onboard blackbody calibration source, a calibration bias on the order of 0.1 K is observed in M15. The bias is further amplified by the sea surface temperature (SST) retrieval algorithm up to 0.3 K which causes an apparent spike in the SST product time series. Our recent study [1] reveals that this bias is likely caused by a fundamental assumption on the radiometric traceability of the VIIRS calibration equation, pertaining to the shape of the calibration curve. In the current study, we further analyzed the equation and presented an improved correction algorithm known as Ltrace 2. This algorithm attempts to fundamentally reconcile the calibration curve shape assumption so that the calibration bias can be removed during the WUCD with better performance for all bands. Sample

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test results are presented to show the improvements using this algorithm. In the following sections, we summarized previous studies, analyzed the calibration equations, presented the new algorithm, as well as test results.

BACKGROUND AND PREVIOUS STUDIES

Previous studies using VIIRS SDR data have shown that the calibration accuracy is overall excellent with an estimated uncertainty about 0.1K, based on comparisons with other satellite radiometers such as MODIS, CrIS, as well as aircraft campaigns [2,3]. The instrument noise in the longwave TEB is on the order of 0.05K at 292.5K, and there is no appreciable degradation in the instrument responsivity for these long-wave bands. The anomalous calibration bias found in SST retrievals during the quarterly blackbody temperature warmup/cooldown (WUCD) is found to be up to 0.3K although the bias for single M bands such as M15 is smaller, on the order of 0.1K (https://www.star.nesdis.noaa.gov/sod/sst/micros/#, under "timeseries").

Previous study has shown that during such events, one of the calibration coefficients (known as the F factor) has an anomalous behavior that is closely related to the blackbody temperature [1]. During the blackbody warmup, the F-factor for M15 decreases, and vice versa during the blackbody cooldown. The F-factor act as a multiplier to the calibrated radiances, any erroneous fluctuations in the F-factor will directly introduce bias in the earth observed radiances. Other longwave infrared channels have similar behavior during the WUCD, although the magnitude of the anomaly becomes smaller towards the shorter wavelength channels.

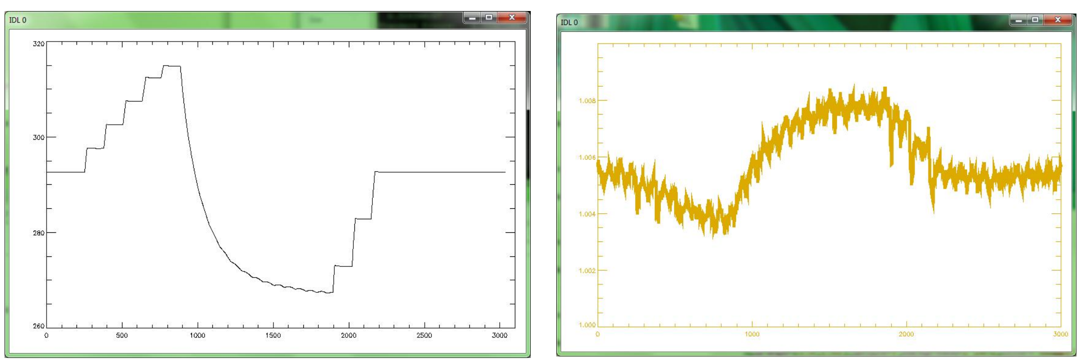

Figure 1. VIIRS onboard blackbody temperature (Tbb) change during WUCD (left) and correlation with F-factor for M15 (right)

After analyzing the VIIRS calibration equation, we recognize that the VIIRS calibration algorithm takes a very different approach compared to the heritage algorithm (MODIS or AVHRR), by carrying all three calibration coefficients in a nonlinear calibration from prelaunch to on-orbit. This approach is based on the assumption that the prelaunch laboratory test using NIST traceable large area blackbody calibration source (BCS) provides the best characterization of the instrument and the derived coefficients from prelaunch are the most reliable. All post-launch calibration could be made traceable to prelaunch measurements by using this approach. Therefore the prelaunch BCS test provides the radiometric reference standard, from which the following calibration equation can be established with the following equation:

$$L_{model} = c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^{\ 2} \qquad (1)$$

Where: c_0, c_1, and c_2 are coefficients derived from prelaunch test data. L_{model} is the modeled blackbody radiance based on blackbody temperature measured by the 6 embedded thermistors, and radiative interaction including blackbody emitted, reflected, and mirror emitted radiances, as well as response versus scan angle (RVS) effects:

$$L_{model} = RVS_{bb}\left(\varepsilon_{bb} L_{bb} + (1-\varepsilon_{bb}) \cdot L_{env}\right) + (RVS_{bb} - RVS_{sv}) \cdot L_{mirror} \qquad (2)$$

Where RVS_{bb} is the response versus scan angle factor when viewing the blackbody (relative to the RVS_{sv} of space view which is set to 1); L_{bb} is the computed band averaged blackbody radiance based on blackbody thermistor measurements; L_{env} is the environmental radiance incident on the blackbody; and L_{mirror} is the mirror emission due to differences in the response versus scan angle, dominated by the half angle mirror (HAM), and the rotating telescope assembly (RTA). Equation (2) is a simplified version of the equation 37 in [6], in which the terms are ordered in significance of contribution following the traditional infrared calibration equation. The full equation with all detailed terms can be found in the JPSS VIIRS SDR ATBD document [4].

According to the VIIRS radiometric calibration algorithm theoretical basis document [4], it was decided that an assumption had to be made to make this calibration transfer from prelaunch to on-orbit possible. It was assumed that the degradation can simply be represented by a single F-factor.

$$F = \frac{L_{\mathrm{model}}}{c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^2} \quad (3)$$

Apparently, for prelaunch test data, F-factor is unity based on equation (1). With the F-factor, the degradation of the instrument can be accounted for using the following equation with prelaunch coefficients (c_0,c_1,c_2) for calculating earth view radiances (L_{ev}):

$$L_{ev} = \frac{F\left(c_0 + c_1 \cdot dn + c_2 \cdot dn^2\right) - (RVS_{ev} - RVS_{sv}) \cdot L_{mirror}}{RVS_{ev}} \quad (4)$$

The key assumption made here is stated in the JPSS VIIRS SDR Algorithm Theoretical Basis [4] document (page 84).

> *"Equation 3 is used on-orbit to update the coefficients. However, since there are three unknowns in one equation, some assumptions or constraints need to be made in order to solve for the coefficients. Making the assumption that the* ***shape of the response curve is preserved*** *allows the application of same scale factor F to all three coefficients. The updated coefficients, designated as C_0 to C_2, are scaled equally by the change in scale (or gain) of the response".*

However, the described assumption above doesn't give us much confidence because it appears that this is an irresolvable issue so an unproven assumption like this has to be made to make the algorithm work. Further analysis reveals that this calibration curve shape issue can be divided into two separate issues: one is whether the calibration curve shape changes from prelaunch to postlaunch under identical operating condition or configurations; the other is whether the operating conditions or configurations are really the same between prelaunch and postlaunch. The former is far more difficult to prove than the later, because identical operating conditions do not exist on-orbit matching the prelaunch test [1].

As a result, a remedy was provided in the previous study to mitigate this issue. Given the fact that both the SST and the OBCBB are normally stable short-term based on global daily average values, the VIIRS calibration anomaly can be diagnosed and reconciled by introducing a compensatory term called L_{trace}, such that the calibration curve during WUCD matches the shape of the prelaunch calibration curve. This makes the WUCD calibration curve proportional to the prelaunch curve, which satisfies the curve shape assumption. Mathematically, based on equation (3), this means [1]:

$$F = \frac{RVS_{bb}[\varepsilon_{bb} L_{bb} + (1-\varepsilon_{bb}) \cdot L_{env}] + (RVS_{bb} - RVS_{sv}) \cdot L_{mirror} + L_{trace}}{c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^2} = f\,\frac{c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^2 + L_{trace}}{c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^2} = \frac{L_{WUCD}}{L_{prelaunch}} \quad (5)$$

L_{trace} can be solved numerically,

$$L_{trace} = F_{norm} \cdot \left(c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^2\right) - RVS_{bb}\left(\varepsilon_{bb} \cdot L_{bb} + \left(1 - \varepsilon_{bb}\right) \cdot L_{env}\right) - \left(RVS_{bb} - RVS_{sv}\right) \cdot L_{mirror} \quad (6)$$

L_{trace} is a diagnostic term and it represents the radiance difference between prelaunch and post-launch curves and can be derived using WUCD data by applying the ideal short term nominal constant *f* ratio (or F_{norm}) which is the nominal F value at the typical blackbody temperature of 292.5K at the time before and after the WUCD event. It has been shown in the previous study that L_{trace} can be applied to the calibration as a function of blackbody temperature. After the L_{trace} is applied to the calibration, the F-factor during the WUCD becomes flat. The remaining oscillations (0.05% or ~30mK) are dominated by orbital variations that existed previously during normal operations.

In recent studies, the L_{trace} method has been successfully tested in the sample reprocessing of VIIRS SDR data[5]. It has been shown that it effectively removed the M15 bias which is the dominant source for the SST biases during WUCD. After the correction, the observed brightness temperature was increased during the blackbody warmup period slightly, and decreased about 0.1K during the cooldown period.

AN IMPROVED CORRECTION ALGORITHM: LTRACE 2

The previous study by [1] presented an empirical correction to the WUCD bias problem. The correction is based on the correlation between the F-factor and the blackbody temperature during the WUCD period. While the algorithm works well for M15, it has a number of deficiencies. First, while the previous paper analyzed the fundamental issue with the calibration algorithm, it did not provide a physical solution to the problem. An empirical correction has limitations because it is not physics based. To resolve this problem, we further studied the calibration equation and present the following fundamental physics based correction in the following known as Ltrace2:

For prelaunch calibration, we derived the following equation to establish the relationship between instrument delta output digital number (dn), and radiance according to the nonlinear response:

$$L_{pre} = c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^2 \qquad (7)$$

Similarly, during WUCD postlaunch, we can also derive the equation based on the WUCD data:

$$L_{wucd} = c'_0 + c'_1 \cdot dn_{bb} + c'_2 \cdot dn_{bb}^2 \qquad (8)$$

As discussed earlier, there is difference between prelaunch and postlaunch calibration during the WUCD period. This difference can be expressed as the ratio between the two:

$$f = \frac{L_{wucd}}{L_{pre}} = \frac{c'_0 + c'_1 \cdot dn_{bb} + c'_2 \cdot dn_{bb}^2}{c_0 + c_1 \cdot dn_{bb} + c_2 \cdot dn_{bb}^2} \qquad (9)$$

Where c_0', c_1', and c_2' are the post-launch coefficients derived from WUCD; and c_0, c_1, c_2 values are derived from prelaunch delta C LUT during the WUCD event. Using this equation, we input the *dn* (blackbody view count minus space view count) values representing different blackbody temperatures (such as from 270 to 315K). If the two curves have the same shape, then the *f* ratio would be a constant with respect to different *dn* values. However, as discussed earlier, this is not the case. Instead, for M15 as an example, during cooldown, the *f* ratio increases, while it decreases during warmup. Since the *f* directly affects the earth view radiance calculations as shown in the calibration equation, this explains why there is positive bias during blackbody cooldown and a negative bias during blackbody warmup for M15.

We believe that this f effect (due to differences between prelaunch and postlaunch response) inherently exists in the computed F factor during the WUCD. To remove this effect, we divide the F factor during WUCD by f. Then, the nominal f during normal operations $\bar{f}$ can be multiplied for normalization to derive the corrected f-factor or F':

$$F' = \frac{F}{f} \bullet \bar{f} \qquad (10)$$

Where:

F=nominal operational F factor during WUCD;
F'=F factor after correction;
$\bar{f}$ =The constant f during normal operations, obtained from equation above when dn = nominal bb temperature.
f =Ltrace2 correction function

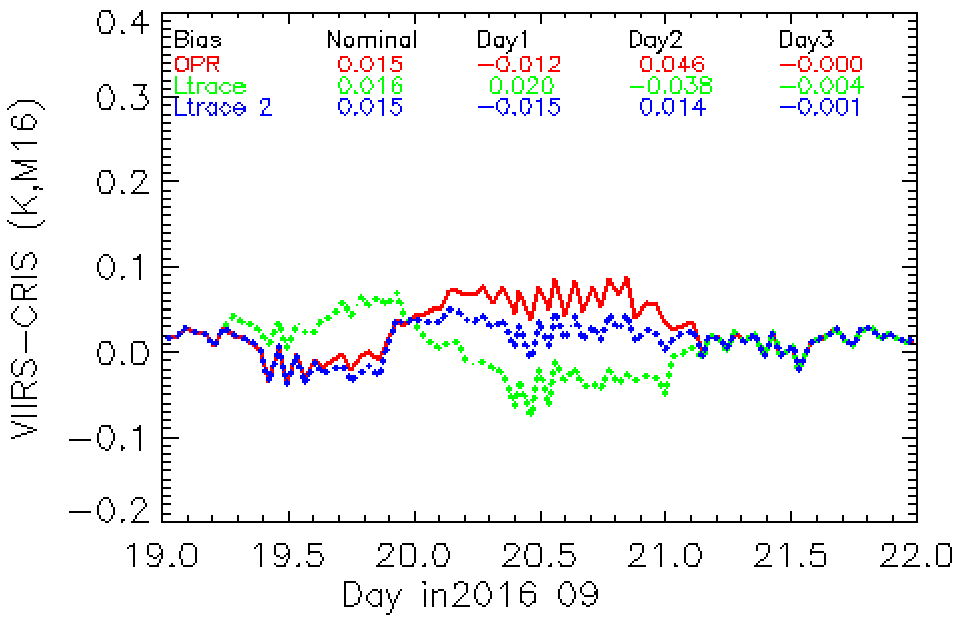

Figure 2. Comparison of correction results between Ltrace and Ltrace 2 (September 19-21, 2016 WUCD event)

To demonstrate that this new algorithm works better, we have reprocessed the same data set used for the previous algorithm. Figure 2 shows that when compared to CrIS data, the Ltrace 2 correction has less bias during the cooldown period on day 2 of the WUCD (middle section of the plot in blue), which is the dominant source for the SST bias, although the Ltrace 2 correction still has a slight bias during the Warmup period (left section of the plot). Apparently the previous algorithm had an overcorrection during the cooldown period (green curve). The result also shows that not only the algorithm works better for the M15 band which is the primary band required correction, the new algorithm also works well for several other bands including M16, M14, and M13. Detailed validation results will be presented in the future.

SUMMARY

The Suomi NPP VIIRS has been performing well since launch except an anomaly during quarterly warmup/cooldown which leads to a bias spike on the order of up to 0.3K in the SST time series. In a recent study, we have analyzed the root cause of the anomaly and provided an empirical correction in [1]. However, after a more thorough analysis of the calibration equation, we present in this paper an improved correction algorithm called Ltrace 2. This algorithm removes the calibration shape anomaly during warmup cooldown by dividing the derived shape function, which is based on the ratio between postlaunch and prelaunch calibration. This approach has been shown to improve the correction not only for the primary channel M15, but also for other longwave infrared channels. The validation results will be presented in the future.

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