Technique for monitoring performance of VIIRS reflective solar bands for ocean color data processing

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Abstract: A technique for monitoring and evaluating the performance of on-orbit calibration for satellite ocean color sensors has been developed. The method is based on the sensor on-orbit vicarious calibration approach using in situ ocean optics measurements and radiative transfer simulations to predict (calculate) sensor-measured top-of-atmosphere spectral radiances. Using this monitoring method with in situ normalized water-leaving radiance \( nL_w(\lambda) \) data from the Marine Optical Buoy (MOBY) in waters off Hawaii, we show that the root-cause for an abnormal inter-annual difference of chlorophyll-a data over global oligotrophic waters between 2012 and 2013 from the Visible Infrared Imaging Radiometer Suite (VIIRS) is primarily due to the VIIRS on-orbit calibration performance. In particular, VIIRS-produced Sensor Data Records (SDR) (or Level-1B data) are biased low by \(-1\%\) at the wavelength of \(551\) nm in 2013 compared with those in 2012. The VIIRS calibration uncertainty led to biased low chlorophyll-a data in 2013 by \(-30–40\%\) over global oligotrophic waters. The methodology developed in this study can be implemented for the routine monitoring of on-orbit satellite sensor performance (such as VIIRS). Particularly, long-term Chl-a data over open oceans can also be used as an additional source to evaluate ocean color satellite sensor performance. We show that accurate long-term and consistent MOBY in situ measurements can be used not only for the required system vicarious calibration for satellite ocean color data processing, but also can be used to characterize and monitor both the short-term and long-term sensor on-orbit performances.

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References and links


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(Chl-a) concentration [12], water diffuse attenuation coefficient at the wavelength of 490 nm (SWIR). In the visible wavelengths, the atmosphere and ocean surface radiance contributions at multiple wavelengths from the visible to the near-infrared (NIR) and shortwave infrared [74].

Z. Ahmad, B. A. Franz, C. R. McClain, E. J. Kwiatkowski, J. Werdell, E. P. Shettle, and B. N. Holben, “New Satellite ocean color sensors, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) [1], the Moderate Resolution Imaging Spectroradiometer (MODIS) [2], the Medium-Resolution Imaging Spectrometer (MERIS) [3], and the Visible Infrared Imaging Radiometer Suite (VIIRS) [4], measure the top-of-atmosphere (TOA) reflectance $\rho(\lambda)$ (or radiance $L(\lambda)$) at multiple wavelengths from the visible to the near-infrared (NIR) and shortwave infrared (SWIR). In the visible wavelengths, the atmosphere and ocean surface radiance contributions can account for more than ~90% of the TOA reflectance [5–7], and thus satellite ocean color products such as normalized water-leaving radiance spectra $nL_w(\lambda)$ [8–11], chlorophyll-a (Chl-a) concentration [12], water diffuse attenuation coefficient at the wavelength of 490 nm $K_d(490)$ (or at the domain associated with photosynthetically available radiation (PAR) $K_d(PAR)$ [13–16], etc., are highly sensitive to the performance of the satellite sensors, i.e., on-orbit sensor calibration [17–21]. In a recent study, Wang et al. (2013) [22] show that performance of VIIRS Sensor Data Records (SDR) (or Level-1B data) has significant impact on the VIIRS ocean color Environment Data Records (EDR) (or Level-2 data). In fact, it was found that the data quality of VIIRS operational ocean color products before February 6, 2012 was poor (and unusable) due to the use of the incorrect VIIRS SDR calibration lookup tables (LUTs) [22]. VIIRS ocean color EDR products were significantly improved with better sensor on-orbit calibration and became consistent with those from MODIS-Aqua in 2012. This demonstrates that it is critical to accurately characterize the sensor instrument performance and carry out on-orbit radiometric calibration correctly in order to achieve high data quality in the SDR and EDR.

VIIRS on the Suomi National Polar-orbiting Partnership (SNPP) was successfully launched on October 28, 2011. VIIRS has 22-spectral bands covering wavelengths from 410 nm to 11.8 µm that combine most features of the NASA satellite ocean color sensors SeaWiFS and MODIS, the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), and the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS). Of the VIIRS 22 spectral bands, there are 11 moderate-resolution (M) reflective solar bands (RSB) with a resolution of 750 m at nadir and 3 imaging-resolution (I) RSB with nadir resolution of 375 m. Preliminary

1. Introduction

Satellite ocean color sensors, such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) [1], the Moderate Resolution Imaging Spectroradiometer (MODIS) [2], the Medium-Resolution Imaging Spectrometer (MERIS) [3], and the Visible Infrared Imaging Radiometer Suite (VIIRS) [4], measure the top-of-atmosphere (TOA) reflectance $\rho(\lambda)$ (or radiance $L(\lambda)$) at multiple wavelengths from the visible to the near-infrared (NIR) and shortwave infrared (SWIR). In the visible wavelengths, the atmosphere and ocean surface radiance contributions can account for more than ~90% of the TOA reflectance [5–7], and thus satellite ocean color products such as normalized water-leaving radiance spectra $nL_w(\lambda)$ [8–11], chlorophyll-a (Chl-a) concentration [12], water diffuse attenuation coefficient at the wavelength of 490 nm $K_d(490)$ (or at the domain associated with photosynthetically available radiation (PAR) $K_d(PAR)$ [13–16], etc., are highly sensitive to the performance of the satellite sensors, i.e., on-orbit sensor calibration [17–21]. In a recent study, Wang et al. (2013) [22] show that performance of VIIRS Sensor Data Records (SDR) (or Level-1B data) has significant impact on the VIIRS ocean color Environment Data Records (EDR) (or Level-2 data). In fact, it was found that the data quality of VIIRS operational ocean color products before February 6, 2012 was poor (and unusable) due to the use of the incorrect VIIRS SDR calibration lookup tables (LUTs) [22]. VIIRS ocean color EDR products were significantly improved with better sensor on-orbit calibration and became consistent with those from MODIS-Aqua in 2012. This demonstrates that it is critical to accurately characterize the sensor instrument performance and carry out on-orbit radiometric calibration correctly in order to achieve high data quality in the SDR and EDR.

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assessment of the VIIRS onboard instruments indicates that VIIRS performed well in terms of the radiometric, spectral, and spatial quality [17]. The degradation in the VIIRS rotating telescope assembly (RTA) mirrors gradually levels off after reaching ~30% degradation. In fact, VIIRS RSB radiometric uncertainty is comparable to that of MODIS-Aqua Level-1B data Collection 6 [23] equivalent bands within ~2% [17].

Calibration experience with satellite sensors such as AVHRR, MODIS, and VIIRS shows that significant degradations can occur with satellite sensors for the visible, NIR, and SWIR bands [17, 24, 25]. The onboard calibrator can also degrade over time [25, 26]. Thus, it is necessary to characterize and vicariously calibrate satellite sensors, as well as to monitor the instrument’s short-term and long-term performance with Earth observations over some specific sites from both in situ and other satellite data. Several approaches have been developed to assess the radiometric stability and carry out the inter-comparison between different satellite sensors. A radiative transfer modeling approach, with inputs from ground-based aerosol information and in situ $nL_w(\lambda)$ measurements, has been developed and used to evaluate satellite sensor calibration performance [27, 28]. A vicarious intercalibration approach between two sensors has also been used to calibrate a satellite ocean color sensor to produce improved ocean color products [29]. In addition, stable terrestrial sites such as the Saharan and Arabian Deserts are used to monitor the onboard sensor calibration and radiometric stability [30–32]. Antarctic Dome C is also used as a reference standard towards consistent measurements from satellite observations [33, 34]. Studies have demonstrated that the approach of simultaneous nadir overpass (SNO) from different satellites can be used to conduct an inter-satellite comparison for calibration and validation of satellite sensors [35–37]. Upptey et al. (2013) [38] utilized extended SNO over ocean and North Africa Desert for inter-comparison between VIIRS and MODIS-Aqua and assessment of VIIRS SDR long-term performance. In addition to invariant terrestrial targets, deep convective clouds (DCC) located in the tropical tropopause layer (TTL) also have relatively flat visible reflectance, and thus are used as another invariant calibration target to calibrate and characterize satellite sensors such as AVHRR and MODIS [39–41].

In this paper, we develop a technique to monitor and evaluate the performance of VIIRS RSB for ocean color data processing. In situ $nL_w(\lambda)$ data from the Marine Optical Buoy (MOBY) in the water off Hawaii [42] are used to assess and evaluate VIIRS RSB SDR calibration and radiometric performance. MOBY has been continuously collecting high quality hyperspectral in-water radiance and irradiance data in oligotrophic water in Hawaii, coincident with the time of the VIIRS overpass, for the support of the VIIRS ocean color calibration and validation activities [22, 42]. Using the MOBY in situ $nL_w(\lambda)$ measurements, we developed a scheme to identify the root-cause for an abnormal inter-annual difference of VIIRS-derived global Chl-a data between 2012 and 2013, compared with those from MODIS-Aqua. The NOAA Multi-Sensor Level-1 to Level-2 (NOAA-MSL12) ocean color data processing system has been used to process satellite data [22]. MSL12 is an official NOAA VIIRS ocean color data processing system. Through a careful data analysis, the Chl-a error in 2013 is linked to the performance of the VIIRS SDR data (i.e., SDR calibration issue). We show that MOBY measurements can be used not only to vicariously calibrate the satellite ocean color sensors [43–47], such as SeaWiFS, MODIS, MERIS, and VIIRS, in order to derive accurate satellite ocean color products, but also can be used to characterize and monitor the miniscule changes (in relative short-term) of satellite sensors in order to produce long-term high quality satellite ocean color products.

2. Methodology and data

2.1. The ocean color data processing system

The NOAA-MSL12 ocean color data processing system has been used for processing satellite data from Level-1B (or SDR) to Level-2 (or EDR) products for both VIIRS and MODIS-
Aqua, as well as other sensors, e.g., the Korean Geostationary Ocean Color Imager (GOCI) [48]. MSL12 was developed for the purpose of using a consistent and common data processing system to produce ocean color data from multiple satellite ocean color sensors, i.e., it is measurement-based data processing system (common algorithms for all sensors) [22, 29, 48–50]. Specifically, NOAA-MSL12 is based on the SeaWiFS Data Analysis System (SeaDAS) version 4.6 with some important modifications and improvements. In particular, these improvements and updates include the SWIR-based and NIR-SWIR combined atmospheric correction algorithms for improved ocean color data products in coastal and inland waters [6, 7, 51–54], as well as some SWIR-related applications for ocean color data processing [55–57]. In addition, as the official VIIRS ocean color data processing system, MSL12 has been used for routinely producing VIIRS global ocean color products (including global daily, 8-day, monthly, and climatology images) since VIIRS was launched on October 28, 2011 [22] (http://www.star.nesdis.noaa.gov/sod/mecb/color/).

2.2. MOBY in situ measurements

In situ hyperspectral radiometric data were measured at the MOBY site [42] moored off the island of Lanai in Hawaii (http://moby.mlml.calstate.edu). The location of the MOBY site (20°49.0′N, 157°11.5′W) is usually in stable and clear-ocean (oligotrophic) waters (the main reason for choosing this location). The water mass at the MOBY site is generally horizontally homogeneous, clear, and deep, while the atmosphere over the MOBY site is predominantly marine aerosols with generally low aerosol reflectance contributions (i.e., low aerosol optical thickness) and free of terrestrial influence. The MOBY program has been providing consistently high-quality clear-ocean optics data since 1997, supporting various satellite ocean color missions, e.g., SeaWiFS, MODIS, MERIS, VIIRS, etc. To evaluate and assess VIIRS SDR (or Level-1B data) and ocean color EDR (or Level-2 data) products, the in situ $nL_w(\lambda)$ measurements at the VIIRS-spectrally-weighted wavelengths beginning in November 2011 to present were obtained from the NOAA CoastWatch website (http://coastwatch.noaa.gov/moby/). Although selected MOBY data have been used for the purpose of the on-orbit system vicarious calibration [43–47] for MSL12 ocean color data processing, high quality MOBY time series data have also been used for VIIRS SDR and EDR data quality monitoring [22]. It is particularly useful to evaluate the performance of the VIIRS on-orbit calibration performance and the stability of SDR by comparing VIIRS-derived $nL_w(\lambda)$ with those from MOBY in situ measurements. With this purpose, MOBY in situ optics data are useful and critical in evaluating VIIRS SDR performance as well as its data stability and quality for ocean color data processing [22].

2.3. Sensor on-orbit vicarious calibration for ocean color data processing

For satellite ocean color remote sensing, the key calibration procedure is the on-orbit system vicarious calibration [43–47, 58]. The basic strategy is to account for all of the components of the TOA radiances reflected from the ocean-atmosphere system from direct measurements or from predictions (calculations) based on in situ measurements and radiative transfer simulations (i.e., radiative transfer scattering theory) [43]. The computed TOA radiances are then compared with the results from sensor-measured radiances. Any difference between the sensor-measured and computed TOA radiance is attributed to error in the calibration of the sensor, and calibration gain coefficients can then be derived to force the measurements and computations into confluence, i.e., the computed/predicted TOA radiances are considered the correct values. Gordon (1998) [43] provided a strategy for the on-orbit vicarious calibration for satellite ocean color sensors. Basically, it assumes that the longest wavelength band (e.g., the NIR 865 nm) is perfectly calibrated (or calibrated with other methods), and then all other bands (shorter than the longest NIR band) are effectively calibrated with respect to this band (i.e., relative spectral calibration). Wang and Gordon (2002) [45] further show that as long as the calibration error at the longest NIR band is within ~5% in magnitude, the on-orbit system...
vicarious calibration can produce the TOA radiances that are sufficiently accurate to derive \( nL_w(\lambda) \) spectra with good accuracy. This is completely independent of the initial pre-launch calibration uncertainty for all the shorter wavelengths (e.g., shorter than the longest NIR band). This vicarious calibration methodology has been successfully applied to SeaWiFS, MODIS, VIIRS, etc., for producing accurate global ocean color products [22, 44, 46]. It is noted that the gain for the VIIRS NIR 745 nm band (or MODIS 748 nm band) is derived in the same way for all visible bands assuming that the gain for the VIIRS NIR 745 nm band (or MODIS 748 nm band) is derived in MODIS, VIIRS, etc., for producing accurate global ocean color products [22, 44, 46]. It is noted that the gain for the VIIRS NIR 745 nm band (or MODIS 748 nm band) is derived in MODIS, VIIRS, etc., for producing accurate global ocean color products [22, 44, 46]. It is noted that the gain for the VIIRS NIR 745 nm band (or MODIS 748 nm band) is derived in MODIS, VIIRS, etc., for producing accurate global ocean color products [22, 44, 46]. It is noted that the gain for the VIIRS NIR 745 nm band (or MODIS 748 nm band) is derived in MODIS, VIIRS, etc., for producing accurate global ocean color products [22, 44, 46].

Specifically, the TOA radiance for the ocean-atmosphere system \( L(\lambda) \) that satellite sensor measures is composed of radiance contributions from molecules (Rayleigh scattering) \( L(\lambda) \) [59], aerosols \( L(\lambda) \) (including Rayleigh-aerosol interactions) [5, 6, 60], sea surface whitecaps \( L_{w}(\lambda) \) [61–63], sun glint \( L_{g}(\lambda) \) [64, 65], and water-leaving radiance \( L_{w}(\lambda) \) [5, 6], i.e.,

\[
L(\lambda) = L_{g}(\lambda) + L_{s}(\lambda) + t(\lambda)L_{w}(\lambda) + T(\lambda)L_{t}(\lambda) + t(\lambda)L_{w}(\lambda),
\]

where \( t(\lambda) \) and \( T(\lambda) \) are the atmospheric diffuse and direct transmittance of the ocean-atmosphere system for the corresponding sensor viewing angle [64, 66]. In particular, \( t(\lambda) \) is the term that accounts for the effects of propagating \( L_{w}(\lambda) \) and \( L_{s}(\lambda) \) from just above the sea surface to the TOA [66]. It should be noted that the gas absorption effects in Eq. (1) have been accounted for. By avoiding (or masking) the sun glint region (necessary for on-orbit vicarious calibration), Eq. (1) is now:

\[
L(\lambda) = L_{s}(\lambda) + t(\lambda)L_{w}(\lambda) + T(\lambda)L_{t}(\lambda) + t(\lambda)L_{w}(\lambda).
\]

For the right-hand-side of Eq. (2), \( L_{s}(\lambda) \) can be accurately calculated (including polarization effects) with inputs of solar-sensor geometry and ancillary data on wind speed and atmospheric pressure [67–69]. \( L_{s}(\lambda) \) can be computed using the derived aerosol models (including polarization effects [70]) in the atmospheric correction procedure [5–7]. \( L_{w}(\lambda) \) is calculated using a model based on wind speed [61], and \( L_{s}(\lambda) \) data are computed with information of in situ optical measurements (e.g., from MOBY in situ-measured data noted as \( nL_{u}(\lambda) \) [42]). Atmospheric diffuse transmittance \( t(\lambda) \) can be derived using the derived aerosol information for each spectral band [66].\( nL_{u}(\lambda) \) data are computed with information of in situ optical measurements (e.g., from MOBY in situ-measured data noted as \( nL_{u}(\lambda) \) [42]). Atmospheric diffuse transmittance \( t(\lambda) \) can be derived using the derived aerosol information for each spectral band [66].\( nL_{u}(\lambda) \) data are computed with information of in situ optical measurements (e.g., from MOBY in situ-measured data noted as \( nL_{u}(\lambda) \) [42]). Atmospheric diffuse transmittance \( t(\lambda) \) can be derived using the derived aerosol information for each spectral band [66].\( nL_{u}(\lambda) \) data are computed with information of in situ optical measurements (e.g., from MOBY in situ-measured data noted as \( nL_{u}(\lambda) \) [42]). Atmospheric diffuse transmittance \( t(\lambda) \) can be derived using the derived aerosol information for each spectral band [66].\( nL_{u}(\lambda) \) data are computed with information of in situ optical measurements (e.g., from MOBY in situ-measured data noted as \( nL_{u}(\lambda) \) [42]). Atmospheric diffuse transmittance \( t(\lambda) \) can be derived using the derived aerosol information for each spectral band [66].\( nL_{u}(\lambda) \) data are computed with information of in situ optical measurements (e.g., from MOBY in situ-measured data noted as \( nL_{u}(\lambda) \) [42]). Atmospheric diffuse transmittance \( t(\lambda) \) can be derived using the derived aerosol information for each spectral band [66]. Thus, computed TOA radiance \( L_{t}(\lambda) \) in Eq. (2) (from model simulations and in situ \( nL_{u}(\lambda) \) data) can be compared with the sensor-measured TOA radiance \( L_{t}(\lambda) \), and vicarious gain coefficients \( g(\lambda) \) can be derived, i.e.,

\[
g(\lambda) = L_{t}(\lambda)/L_{t}(\lambda),
\]

with \( g(\lambda) < 1 \) (or \( g(\lambda) > 1 \)) indicating \( L_{t}(\lambda) < L_{t}(\lambda) \) (or \( L_{t}(\lambda) > L_{t}(\lambda) \)). It is noted that \( L_{t}(\lambda) \) is derived using radiative transfer simulations (the forward calculations in the same MSL12 data processing system) and in situ MOBY \( nL_{u}(\lambda) \) data.

2.4. Monitoring sensor on-orbit performance

In an ideal case, i.e., a case with flawless sensor on-orbit calibrations and perfect satellite algorithm performance, the derived vicarious gain \( g(\lambda) \) should be constant through the entire mission (independent of the time). However, due to on-orbit instrument calibration errors and uncertainties from satellite algorithms (e.g., atmospheric correction, radiative transfer simulations, etc.), there are variations in the derived \( g(\lambda) \) coefficients. We can re-write Eq. (3) with specific time \( t \) dependence, i.e.,

\[
L_{t}(\lambda,t) = g(\lambda,t) L_{t}(\lambda,t) = g^{(t)}(\lambda)[1 + \Delta(\lambda,t)] L_{t}(\lambda,t)
\]

with
where \( g^{(\lambda)}(\lambda) \) is the “True” gain factor that is the derived reference (or correct) gain independent of time, and \( \Delta(\lambda, t) \) is the variation (or error) in the derived vicarious gains due to on-orbit calibration errors and algorithm uncertainties (including uncertainties from all input data). In fact, Eq. (4) can be further written as:

\[
\Delta(\lambda, t) = \left[ g(\lambda, t) - g^{(\lambda)}(\lambda) \right] / g^{(\lambda)}(\lambda) = \Delta g(\lambda, t) / g^{(\lambda)}(\lambda),
\]

(5)

where \( L^{(C)}(\lambda, t) \) is the “True” TOA radiance that can be used to produce accurate satellite-derived \( nL_w(\lambda) \) spectra in ocean color data processing. Therefore, we can compute \( \Delta(\lambda, t) \) (or \( \Delta g(\lambda, t) \)) values to understand and monitor sensor on-orbit performance. Furthermore, sensor on-orbit performance can be monitored through evaluation of ocean color products. In fact, satellite-derived \( nL_w(\lambda) \) spectra from \( L^{(C)}(\lambda, t) \) in Eq. (6) are qualitatively \( \propto L^{(C)}(\lambda, t) \) \( \propto [1 + \Delta(\lambda, t)] L^{(C)}(\lambda, t) \) (see Eq. (2)), and changes in \( \Delta(\lambda, t) \) (or \( \Delta g(\lambda, t) \)) are directly reflected in changes of satellite-derived \( nL_w(\lambda) \) values (compared with in situ \( nL_w^{(M)}(\lambda) \) data). It is noted that satellite-derived \( nL_w(\lambda) \) data are different from in situ measured \( nL_w^{(M)}(\lambda) \) spectra, which are used for deriving \( g(\lambda, t) \) values. In the system vicarious calibration procedure, biased low (or high) satellite-derived \( nL_w(\lambda) \) values compared with in situ \( nL_w^{(M)}(\lambda) \) spectra (i.e., from atmospheric correction) lead to \( \Delta g(\lambda, t) > 0 \) (or \(< 0\)), i.e., \( g(\lambda, t) \) has to be increased (or decreased) to compensate for biased low (or high) satellite-derived \( nL_w(\lambda) \) values (compared with in situ \( nL_w^{(M)}(\lambda) \) data). Thus, in effect, it forces satellite-derived \( nL_w(\lambda) \) spectra to be the same as those from in situ-measured \( nL_w^{(M)}(\lambda) \) through the change in \( g(\lambda, t) \) (i.e., the calibration process).

In addition, because Chl-a values are a function of the \( nL_w(\lambda) \) ratio in the green and blue bands (e.g., \( \lambda_i = 443 \) or 486 nm and \( \lambda_j = 551 \) nm in VIIRS) \[12\], and assuming uncertainty is only from on-orbit calibration, for oligotrophic waters we can write:

\[
\text{Chl-a} \approx \left[ 1 - \Delta(\lambda_i, t) \right] L_i^{(T)}(\lambda_i, t) \left[ 1 - \Delta(\lambda_j, t) \right] L_j^{(T)}(\lambda_j, t).
\]

(7)

Assuming perfect satellite algorithm performance, i.e., accurate TOA radiance ratio (the last radiance ratio term in Eq. (7)) produces accurate Chl-a data, using Eqs. (5) and (7) with the understanding that \( g^{(\lambda)}(\lambda) \) is constant and close to 1, the Chl-a variation (or error) is then given by

\[
\Delta \text{Chl-a} \approx \left[ \Delta g(\lambda_i, t) - \Delta g(\lambda_j, t) \right].
\]

(8)

It is noted that there are “−” signs in \( \Delta(\lambda_i, t) \) and \( \Delta(\lambda_j, t) \) in Eq. (7) as high \( g(\lambda_i, t) \) and \( g(\lambda_j, t) \) values reflect biased low TOA radiances (i.e., biased low satellite-derived \( nL_w(\lambda) \) data compared with in situ-measured \( nL_w^{(M)}(\lambda) \) spectra). Equation (8) shows that the uncertainty (or variation) of satellite-derived Chl-a in oligotrophic waters is related to sensor on-orbit calibration errors in the form of \( [\Delta g(\lambda_i, t) - \Delta g(\lambda_j, t)] \) or \( [g(443, t) - g(551, t)] \) for VIIRS and MODIS, which can be derived from changes of vicarious calibration gain factors. Indeed, we can further write Eq. (8) as:

\[
\Delta g(\lambda_i, \lambda_j, t) = \Delta g(\lambda_i, t) - \Delta g(\lambda_j, t) = g(\lambda_i, t) - g(\lambda_j, t) - \left[ g^{(\lambda)}(\lambda_i) - g^{(\lambda)}(\lambda_j) \right]
\]

(9)

where \( [g^{(\lambda)}(\lambda_i) - g^{(\lambda)}(\lambda_j)] \) is a mean value (constant, independent of time) in a study period. In other words, \( [g(\lambda_i, t) - g(\lambda_j, t)] \) values are adjusted to a reference value of \( [g^{(\lambda)}(\lambda_i) - g^{(\lambda)}(\lambda_j)] \) in Eq. (9). Thus, long-term accurate (and consistent) Chl-a measurements over open oceans...
(from in situ or other satellite data, or probably from model data [71]) can be used as an additional source to monitor sensor on-orbit performance. This technique is quite useful because compared with high quality in situ optics measurements, there are many more in situ Chl-a data.

3. Results

3.1. VIIRS- and MODIS-derived global Chl-a comparisons in 2012 and 2013

Since the SNPP launch on October 28, 2011, VIIRS ocean color products such as $nL_w(\lambda)$ spectra, Chl-a, and the water diffuse attenuation coefficient at 490 nm $K_d(490)$ [15], have been routinely produced using MSL12. VIIRS-measured global Level-3 ocean color product images (daily, 8-day, monthly, and climatology) and some validation results can be found at the website (http://www.star.nesdis.noaa.gov/sod/mecb/color/). Some evaluation results show that the global spatial and temporal distributions of VIIRS-measured ocean color products are quite similar to those from MODIS-Aqua [22]. However, a quantitative comparison of VIIRS- and MODIS-Aqua-derived Chl-a data over global oligotrophic waters shows that, while VIIRS and MODIS-Aqua produced consistent Chl-a data in 2012, there are some significant Chl-a differences between these two satellite sensors in 2013.

Fig. 1. Comparison of MODIS-Aqua and VIIRS-derived mean Chl-a data over global oligotrophic waters (with depth > 1 km) for (a) time series of mean Chl-a of MODIS-Aqua (2002–2013) compared with VIIRS (2012–2013) (8-day mean) and (b) Chl-a comparisons only for years of 2012 and 2013 (daily mean), showing significant differences in 2013 between VIIRS-derived Chl-a and those from MODIS-Aqua. Note that the anomalous high VIIRS Chl-a values in early 2012 were caused by the initial VIIRS calibration errors, and were excluded in the gain analysis.

Figure 1 provides the Chl-a comparison results from VIIRS and MODIS-Aqua. Chl-a data were obtained from VIIRS and MODIS-Aqua over global oligotrophic waters with water depth > 1 km. Figure 1(a) shows Chl-a comparisons from 2002 to 2013, while Fig. 1(b) shows results only for 2012 and 2013 when both sensors produced Chl-a data. It is noted that MODIS-Aqua Chl-a data were directly obtained from NASA Ocean Biology Processing Group (OBPG) website (http://oceancolor.gsfc.nasa.gov). Since its launch in 2002, MODIS-Aqua-measured mean Chl-a data over global oligotrophic waters have shown repeatable seasonal variability from 2002 to 2013 (~12 years) (Fig. 1(a)). It reaches lows in March-April and October-November with Chl-a of ~0.05 mg m$^{-3}$ and highs in July-August of ~0.07 mg m$^{-3}$ (Fig. 1(a)). In comparison to the seasonal variability, the interannual variability is less significant and MODIS-Aqua-derived Chl-a has a reasonable annual repeatability. This suggests that MODIS-Aqua instrument has been reasonably well calibrated and characterized for the last 12 years, and it can be used to produce ocean color products such as Chl-a for long-term climate research and various applications in open oceans.
During 2012 and 2013, mean Chl-a of global oligotrophic waters from MODIS-Aqua shows similar seasonal patterns to all other years with highs of ~0.075 mg m\(^{-3}\) in August and lows of ~0.05 mg m\(^{-3}\) in April and November (Fig. 1(b)). In particular, seasonal and interannual variations in MODIS-Aqua-derived Chl-a data for 2012 and 2013 are quite similar to all other years (with good repeatability). In comparison, mean Chl-a of global oligotrophic waters from VIIRS shows similar seasonal patterns during 2012 as to MODIS-Aqua and Chl-a data from both sensors are quite consistent and match each other reasonably well (Fig. 1). However, beginning in January 2013, VIIRS-derived mean Chl-a values started to show some significant differences compared to those from MODIS-Aqua. In fact, global mean Chl-a values derived from VIIRS show significant interannual variability between 2012 and 2013. Specifically, in July-August of 2013, mean Chl-a derived from VIIRS was only ~0.05–0.06 mg m\(^{-3}\). This value is significantly lower than mean Chl-a of ~0.075 mg m\(^{-3}\) from MODIS-Aqua in the same period (~30%). Unless there were significant natural changes over global open oceans in 2013, VIIRS-derived global mean Chl-a data in 2013 are apparently not reasonable. Thus, we need to identify and understand the causes for the VIIRS abnormal Chl-a changes in 2013.

3.2. On-orbit characterization of VIIRS performance

Since ocean color remote sensing requires the high stability of sensor on-orbit calibration [72], we have to check VIIRS on-orbit calibration performance. As discussed previously, vicarious gain factors \(g(\lambda, t)\) and the corresponding \(\Delta g(\lambda, t)\) values can be used as an effective tool for monitoring and evaluating sensor performance. We provide our approach and evaluation results in this section.

To track and characterize the trends of \(g(\lambda, t)\) for VIIRS and MODIS-Aqua, 6-month medians of \(g(\lambda, t)\) values derived using Eqs. (1)-(3) (from NOAA-MSL12) with simultaneous MOBY in situ \(nL_w(\lambda)\) data are calculated between 2012 and 2013 for the RSB of VIIRS and MODIS-Aqua, respectively. We need 6-month (i.e., the time period \(t\) is 6-month) MOBY and satellite matchup data to have reliable and reasonable \(g(\lambda, t)\) values [46]. Figure 2 shows the derived \(g(\lambda, t)\) values as a function of time for different spectral bands of MODIS-Aqua (412, 443, 488, and 551 nm) and VIIRS (410, 443, 486, and 551 nm). It is noted that an \(11 \times 11\) box centered at the MOBY site was chosen to find matchup pixels between the satellite and in situ data. All matchup pixels in a half-year period were grouped to compute gain factor \(g(\lambda, t)\). For each of four half-year groups, the total number of pixels is all over 2000 (up to about 5000). Thus, with these data numbers for each group in computing \(g(\lambda, t)\) in Fig. 2, the results are statistically significant. In addition, we computed the standard deviation (STD) values of \(g(\lambda, t)\) in both the half-year period (Fig. 2) and the two-year period for both MODIS and VIIRS. The STD values from these two periods (half-year and two-year) are similar for both sensors, and range from about 0.005 (red band) to 0.015 (blue bands). These STD values are also consistent with those from a much longer period [46]. Thus, \(g(\lambda, t)\) results in Fig. 2 and particularly the variations in \(g(\lambda, t)\) should be reliable. Figure 2 shows that, in comparison to MODIS-Aqua, VIIRS \(g(\lambda, t)\) values have more variations between 2012 and 2013. In particular, Fig. 2(d) shows that \(g(551, t)\) for MODIS-Aqua ranges between 0.9796 in 2012 and 0.9834 in 2013 (changing ~0.4%), while \(g(551, t)\) for VIIRS changes from 0.9675 in 2012 to 0.9775 in 2013 (changing ~1%). It is noted again that high \(g(\lambda, t)\) values indicate low satellite TOA radiances, i.e., VIIRS-measured TOA \(L_w(551)\) values are generally biased low in 2013 compared with those in 2012. For satellite Chl-a retrievals, biased low \(nL_w(\lambda)\) at the green band 551 nm leads to biased low Chl-a data [12].
Fig. 2. The derived gain factor $g(\lambda, t)$ as a function of time (6-month median) from 2012 to 2013 for different spectral bands (a) MODIS 412 nm and VIIRS 410 nm, (b) MODIS and VIIRS 443 nm, (c) MODIS 488 nm and VIIRS 486 nm, and (d) MODIS and VIIRS 551 nm.

Results show that $g(\lambda, t)$ values for VIIRS are relatively stable for the band M1 410 nm (Fig. 2(a)), but have steady increase for the bands M2 443 nm (Fig. 2(b)) and M3 486 nm (Fig. 2(c)). In comparison, $g(\lambda, t)$ values are relatively stable for the corresponding MODIS-Aqua bands in the same period (Fig. 2), although there are obvious drops of $g(\lambda, t)$ in the period of July–December of 2012. The different trends of $g(\lambda, t)$ suggest that the sensor performance for MODIS-Aqua and VIIRS are different. It provides further evidence that high quality in situ $nL_w^{(M)}(\lambda)$ spectra measurements and the corresponding simulations of the TOA radiances can indeed act as an independent source to assess the performance of the characterization and calibration of the satellite sensors such as MODIS-Aqua and VIIRS.

To understand the significant discrepancy of Chl-a in 2012 and 2013 over global oligotrophic waters derived from MODIS-Aqua and VIIRS as shown in Fig. 1, $\Delta g(\lambda_o, \lambda_p, t)$ values as defined in Eq. (9) are calculated for both MODIS-Aqua and VIIRS for the same time periods of 2012 and 2013. Figure 3 provides results (in percent) of $\Delta g(443, 551, t)$ (Fig. 3(a)) and $\Delta g(486, 551, t)$ (Fig. 3(b)) derived from 6-month $g(\lambda, t)$ values from Fig. 2 for both MODIS-Aqua and VIIRS for the two-year period of 2012 and 2013. It is noted that in computing $\Delta g(\lambda_o, \lambda_p, t)$ values with Eq. (9) $[g(\lambda)(443) - g(\lambda)(551)]$ values (i.e., $[g(\lambda)(443) - g(\lambda)(551)]$) were derived using the two-year mean values of $\Delta g(\lambda_o, \lambda_p, t)$, i.e., $\Delta g(\lambda_o, \lambda_p, t)$ values were adjusted to reference (mean) values.
Figure 3(a) shows that MODIS-Aqua $\Delta g(443, 551, t)$ values are quite stable, while VIIRS $\Delta g(443, 551, t)$ values have some significant variations. In fact, for four periods in Fig. 3, MODIS-Aqua $\Delta g(443, 551, t)$ values are 0.24%, –0.15%, –0.05%, and –0.04% with the corresponding VIIRS values of 0.08%, 0.2%, –0.47%, and 0.18%, respectively. Figure 3(b) shows results of $\Delta g(488, 551, t)$ for MODIS-Aqua and $\Delta g(486, 551, t)$ for VIIRS, with MODIS-Aqua $\Delta g(488, 551, t)$ values of 0.10%, –0.32%, 0.12%, and 0.10% and the corresponding VIIRS $\Delta g(486, 551, t)$ values of –0.052%, 0.14%, –0.34%, and 0.25%, respectively. However, it is noted that for oligotrophic waters satellite Chl-a data are generally derived with the normalized water-leaving reflectance $\rho_w(\lambda)$ ratio at 443 and 551 nm. Thus, the calibration gain parameter $\Delta g(443, 551, t)$ is more important for Chl-a accuracy for global oligotrophic waters. Specifically, the VIIRS $\Delta g(443, 551, t)$ of –0.47% derived from the first half of 2013 (Fig. 3(a)) reflects the biased low Chl-a values in 2013 compared with those from MODIS-Aqua (Fig. 1). The $\Delta g(443, 551, t)$ variation in 2013 is mainly due to variations in the VIIRS M4 band (551 nm) on-orbit calibration in that year (i.e., biased low) as shown in Fig. 2(d).

The biased low $\Delta g(443, 551, t)$ of ~0.5% (corresponding to the TOA radiance changes of ~0.5% at 443 nm and ~1% at 551 nm in Fig. 2) is translated to ~10–20% biased high in the normalized water-leaving reflectance $\rho_w(\lambda)$ ratio (blue to green) that is the input to Chl-a algorithm. Figure 4 shows effects of errors in the ratio of normalized water-leaving reflectance $\rho_w(\lambda)$ (from ~–20% to +20%) on the satellite-derived Chl-a data using the VIIRS Chl-a algorithm. Results show that for reflectance ratio errors of ~10–20%, VIIRS-derived Chl-a data are biased low by ~30–40% for Chl-a values ~0.1 mg m$^{-3}$, which is consistent with VIIRS Chl-a results in 2013 compared with those from MODIS-Aqua (Fig. 1). Therefore, through this analysis, we identified the root-cause for the VIIRS biased low Chl-a data in 2013, which is mainly due to VIIRS M4 band (551 nm) calibration in 2013 compared with 2012 (biased low ~1%).

4. Discussions and summary

Over several years, several approaches have been developed to monitor and evaluate the on-orbit performance of satellite sensors and carry out satellite sensor inter-comparison to validate sensor calibration performance. Although these approaches such as the DCC [39–41] and SNO [35, 37, 38] can reasonably monitor and characterize the sensor on-orbit performance for high radiances, a lack of accurate ground-truth measurements as well as a relatively large uncertainty in the reference targets (e.g., the DCC and Antarctic DOME C) imply that these approaches may only be used to monitor the long-term trend of the sensor calibration and particularly for the targets with high TOA radiances. These approaches may not be able to accurately check sensor on-orbit performance over ocean waters (low TOA radiance).
radiances) for remote sensing of ocean optical, biological, and biogeochemical properties (e.g., in the order of ~0.1%).

Fig. 4. Effects of errors (from ~20% to +20%) in the two-band normalized water-leaving reflectance ratio (input to the Chl-a algorithm) on the satellite-derived Chl-a data using the VIIRS Chl-a algorithm.

To produce high-quality ocean color products to address the interannual and decadal ocean optical, biological, and biogeochemical changes, it is a prerequisite to derive accurate nLw(λ) spectra from satellite measurements. Unlike other Earth targets such as cloud, land, or ice, the TOA nLw(λ) spectra can only account for a small portion (generally < ~10%) of the TOA radiances that satellites measure on-orbit. This means that the nLw(λ) spectra are very sensitive to the sensor on-orbit performance (calibration and characterization) with required calibration accuracy in the order of ~0.1% [5, 72]. However, the specified requirement for the uncertainty of VIIRS TOA radiance is 2% [17]. Although this requirement (2% calibration accuracy) may satisfy the needs for land and atmospheric applications, it can lead to significant errors in VIIRS-derived nLw(λ) spectra and consequently all other nLw(λ)-derived ocean color products (e.g., Chl-a). This suggests that some current approaches, such as DCC and SNO, to monitor the performance of VIIRS may not be accurate enough for quantitatively evaluating VIIRS on-orbit performance for ocean color data processing.

In this study, we show that the VIIRS on-orbit calibration uncertainty can lead to significant errors in the global deep water Chl-a data even though the error in the VIIRS calibration (~1%) is below the VIIRS SDR calibration requirement. A method has been developed to use the MOBY optics measurements as the surface in situ target in order to characterize VIIRS on-orbit performance. We demonstrated that in situ nLw(M)(λ) measurements at the MOBY site can be used as an important data source to monitor instrument performance, especially for the subtle changes of the sensor instrument for ocean color applications, in addition to the fact that MOBY data provide the required sensor on-orbit system vicarious calibration [47].

The technique proposed in this paper is really for monitoring sensor on-orbit performance for the visible bands, and assumes that the on-orbit performance change in the longest NIR band (862 nm for VIIRS) has been well characterized and calibrated. The gain for the NIR 745 nm band has been derived for the study period (i.e., in two-year with a constant value). The SWIR data processing approach [7] has been used to derive the NIR gains. The change of the performance in the longest NIR band may have some effects on the derived vicarious gain factors, e.g., aerosol model selection in atmospheric correction [73]. However, as the vicarious calibration is essentially a relative spectral calibration approach [43], it is shown by Wang and Gordon (2002) [45] that satellite-derived nLw(λ) spectra are insensitive to the calibration for the longest NIR band (to within ~5%). In fact, different aerosol models have
been used for satellite ocean color data processing (e.g., for MODIS and VIIRS) [6, 7, 74], and they have produced consistent ocean color products [21, 22]. In addition, significant changes in the longest NIR band make more or less spectrally correlated changes in the derived gain factors (from atmospheric correction) and much reduced impact on Chl-a data [5]. Thus, as long as the longest NIR band performance is reasonably characterized (i.e., within ~5%), the proposed sensor performance monitoring technique should work well. It is noted that the accurate characterization and calibration of the longest NIR band is also important.

It should be noted that the vicarious calibration for ocean color data processing is the calibration for the entire system, i.e., including both instrument and algorithms [43, 47]. In this study, consistent algorithms and lookup tables (i.e., same data processing system) have been used to compute the TOA reflectance (or radiance) contributions in Eqs. (1) and (2) and to derive gain factors for both MODIS-Aqua and VIIRS. Thus, variations in the temporal gain factor shown in Figs. 2 and 3 are mostly driven by the sensor instrument performance instead of the algorithms (e.g., atmospheric correction), although the derived vicarious gain factors include both instrument on-orbit calibration errors and algorithms uncertainties.

In comparison with the DCC and SNO approaches, this method can have accurately characterized ground target measurements and thus can be used to quantitatively characterize the performance of the sensor instruments. Furthermore, effects of sensor on-orbit performance on the downstream ocean color products can also be evaluated and assessed. The technique for sensor on-orbit performance monitoring can be implemented to routinely assess and evaluate the sensor on-orbit calibration performance.

We used MOBY in situ optics (nLw(λ) spectra) measurements to address the notable discrepancy in Chl-a over global oligotrophic waters derived from MODIS-Aqua and VIIRS between 2012 and 2013. It is concluded that the instrument performance of MODIS-Aqua in 2012 and 2013 is reasonable to derive good quality nLw(λ) spectra and then to generate consistent biological and biogeochemical ocean property products such as Chl-a. This is further confirmed with the seasonal and interannual repeatability of the global open ocean Chl-a product derived from MODIS-Aqua measurements since 2002. On the other hand, results from this study show that in 2013 VIIRS-measured TOA radiances in visible wavelengths are overall biased low compared with those in 2012, in particular, for the VIIRS M4 band (551 nm). Specifically, compared with VIIRS-measured M4 band (551 nm) TOA radiances in 2012, VIIRS TOA radiance L(λ) at 551 nm in 2013 is generally biased low by ~1%. Furthermore, as performance of Chl-a in oligotrophic waters is related to the calibration parameter Δg(443, 551, t) values, it has been shown that Δg(443, 551, t) is about ~0.5% in 2013 compared with that in 2012 for VIIRS, leading to biased low Chl-a values of ~30–40% over oligotrophic waters. This is consistent with VIIRS Chl-a observations compared with those from MODIS-Aqua (Fig. 1). Thus, the biased low VIIRS-derived Chl-a in 2013 over global oligotrophic waters is primarily due to the VIIRS calibration issue in 2013. Indeed, if the corrected gains for VIIRS blue and green bands were used in the first half of 2013, we found that the global mean VIIRS Chl-a in April 2013 would be increased from the current 0.050 mg m⁻³ (Fig. 1(b)) to 0.057 mg m⁻³, and the VIIRS Chl-a would be increased from ~0.06 mg m⁻³ in August 2013 (Fig. 1(b)) to 0.068 mg m⁻³. These values would make VIIRS Chl-a in that period generally match those from MODIS-Aqua.

It should be emphasized that, for ocean color remote sensing, the performance of stability for the sensor on-orbit calibration is the most important, i.e., we must accurately characterize sensor on-orbit degradation trends over time. In fact, comparison of results in 2012 and 2013 for VIIRS are really in relative sense between these two years, i.e., with the vicarious calibration one could adjust VIIRS Chl-a result matchups with MODIS-Aqua in 2013, but Chl-a from VIIRS in 2012 would be biased high due to calibration differences for the VIIRS 551 nm band between 2012 and 2013.
As discussed in this paper, the proposed method is to monitor and verify the sensor on-orbit performance and to identify any sensor calibration issue, e.g., calibration problem with specific bands. Therefore, various sensor on-orbit calibration methodologies [17–21] can be improved. Methodologies using the onboard solar diffuser (SD) and solar diffuser stability monitor (SDSM) have been used to characterize and calibrate VIIRS [20]. However, there are still some issues as shown and discussed in this study. A recent study shows that when using both solar and lunar calibration approaches, VIIRS ocean color data can be improved (with improved VIIRS calibration), in particular, with improved VIIRS Chl-a data [21]. We also obtained similar results using both solar and lunar calibrations. This suggests that enhanced instrument calibration using both solar and lunar approaches is required for current and future ocean color satellite remote sensing in order to produce long-term high quality ocean color products.

Furthermore, results from this study show that consistent and accurate on-orbit instrument calibrations for producing accurate SDR (or Level-1B data) (e.g., calibration lookup tables, onboard sensor calibration strategy and methodology, etc.) for the entire VIIRS mission, as well as mission-long data reprocessing for both SDR and EDR ocean color products are necessary in order to produce consistent mission-long and high-quality VIIRS ocean color products.

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