remote sensing

Review

Comparison of the Calibration Algorithms and SI Traceability of MODIS, VIIRS, GOES, and GOES-R ABI Sensors

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Abstract: The radiometric calibration equations for the thermal emissive bands (TEB) and the reflective solar bands (RSB) measurements of the earth scenes by the polar satellite sensors, (Terra and Aqua) MODIS and Suomi NPP (VIIRS), and geostationary sensors, GOES Imager and the GOES-R Advanced Baseline Imager (ABI) are analyzed towards calibration algorithm harmonization on the basis of SI traceability which is one of the goals of the NOAA National Calibration Center (NCC). One of the overarching goals of NCC is to provide knowledge base on the NOAA operational satellite sensors and recommend best practices for achieving SI traceability for the radiance measurements on-orbit. As such, the calibration methodologies of these satellite optical sensors are reviewed in light of the recommended practice for radiometric calibration at the National Institute of Standards and Technology (NIST). The equivalence of some of the spectral bands in these sensors for their end products is presented. The operational and calibration features of the sensors for on-orbit observation of radiance are also compared in tabular form. This review is also to serve as a quick cross reference to researchers and analysts on how the observed signals from these sensors in space are converted to radiances.

Keywords: remote sensing; calibration algorithm; calibration equations; SI traceability; LEO and GEO optical sensors

1. Introduction

The current activity at National Oceanic and Atmospheric Administration (NOAA) National Calibration Center (NCC) for calibration algorithm harmonization and establishing SI traceability for satellite optical sensor measurements can be traced back to late 1980s. The American Institute of Aeronautics and Astronautics (AIAA) initiated a special task group to specifically address the concern of the radiometric measurement community for the widely diverse approaches being taken in definition, performance and evaluation of sensor systems in space. As a result of their effort, the NIST Handbook on "Recommended Practice; Symbols, Terms, Units and Uncertainty analysis for Radiometric Sensor Calibration" was published [1]. The recommended practice for enabling harmonization and establishing SI traceability gathered more impetus for meeting the need for high accuracy observations across the globe for monitoring climate change. A series of workshops sponsored by NOAA and supported by National Aeronautics and Space Administration (NASA) and National Institute of Standards and Technology (NIST) over the last decade culminated in the establishment of NOAA NCC in 2011 as a virtual center to provide a knowledge base for calibration algorithm harmonization following best practices for achieving SI traceability of operational sensors [2–7]. The center's knowledge base helps the Calibration Working Groups (CWG) and teams on each operational sensor at NOAA/NESDIS/STAR to work with NASA and the instrument vendors towards SI traceability from pre-launch testing to on-orbit operations.

Based on the International Vocabulary of Metrology (VIM) SI traceability can be defined as the result of a measurement that can be related to a reference standard through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [8]. The emphasis is to create a common basis so that the measurement result can be related to other measurements through their common SI reference and the uncertainty budget accounts all the known components of uncertainly, Type A and Type B, following the Guide to the expression of uncertainty in measurement (GUM) [9]. The best practice guideline for radiometric measurements from space is to compare results obtained through different measurement approaches such as simultaneous observations from different sensors in space through the Global Space-based Inter-calibration System (GSICS) [10] and to use standards such as the moon for RSB radiometric validation. The calibration algorithm and its implementation on orbit to deduce radiances should be flexible enough to study independently the anomalies observed compared to expectations. In all this the calibration equation plays an important role to take into account all possible effects contributing to measured radiance. Both Pre- and Post-launch calibration activity is critical for continuous maintenance of SI traceability of the sensor through its life time [11].

In this article the basic equations that describe radiance measurements by a multiband sensor are first introduced drawing from the recommended practice for radiometric sensor calibration [1]. These equations are recast to the commonly used forms in the Calibration Algorithm Theoretical Basis Documents (C-ATBD) for measuring radiance at the aperture stop of each sensor considered in this article. The optical sensors considered in this article are filter radiometers and the channels defined by the filters are divided as reflective solar bands (RSB) for wavelengths range between 400 nm and 2500 nm and as thermal emissive bands (TEB) for wavelengths in the range 2.5 μm and 100 μm. However the longest wavelength TEB among the sensors in this review is in MODIS at 14.4 μm.

Measurement Equation and Calibration Equations

The general form of the measurement equation illustrates that the response in digital counts of the detector in the sensor focal plane array for flux at the entrance aperture of a band pass filter radiometer is obtained by integration over the appropriate variables:

$$\mathrm{DN} = Gain \iiint \int L(\lambda)\ R_{\mathrm{I}}(\lambda) \cos\theta \, \mathrm{d}A_{\mathrm{s}} \, \mathrm{d}\omega_{\mathrm{s}} \, \mathrm{d}\lambda \, \mathrm{d}t \tag{1}$$

where DN is the digital output by a detector in the instrument assuming linear response for simplicity, *Gain* is gain of the instrument detector plus digitization electronics, $L(\lambda)$ is the source spectral radiance, $R_{\mathrm{I}}(\lambda)$ is the sensor absolute (bandpass) spectral responsivity, θ is the angle the sensor subtends at the source, A_{s} is the area of the source, ω_{s} is the solid angle subtended by the sensor entrance aperture at the source, $\mathrm{d}\lambda$ is the wavelength interval and $\mathrm{d}t$ is the time interval [1]. Instrument response non-linearity and background are not shown in Equation (1). As a first step, the spectral and spatial domains can be considered independent and also the radiance can be considered spatially uniform and stable in time so that the variables can be separated in Equation (1), and Δt is the integration time assuming stable response.

$$\mathrm{DN} = Gain\,\Delta t \int L(\lambda)\, R_{\mathrm{I}}(\lambda)\, \mathrm{d}\lambda \int \cos\theta \ \mathrm{d}\omega_{\mathrm{s}} \int \mathrm{d}A_{\mathrm{s}} \tag{2}$$

The spatial integral:

$$\int \cos\theta \ \mathrm{d}\omega_{\mathrm{s}} \int \mathrm{d}A_{\mathrm{s}} = A_{\mathrm{s}}\,\Omega_{\mathrm{s}} = A_{\mathrm{c}}\,\Omega_{\mathrm{c}} \tag{3}$$

is the source throughput and by the reciprocity theorem equal to the sensor throughput $A_c\,\Omega_c$ where A_c is the sensor aperture area Ω_c is the projected solid angle subtended by the source at the sensor aperture. It is the sensor field-of-view for a uniform extended area source. The sensor absolute responsivity $R_I\,(\lambda)$ is determined by the quantum efficiency (QE (λ)) of the detector for the incident photon energy and the transmittance (ρ) of the sensor optics. The optical transmittance ρ of the instrument optics (refractory and reflective) can be represented by:

$$\rho\,(\lambda) = \prod_{1}^{N_{opt}} \rho_i\,(\lambda) \tag{4}$$

where ρ_i is the transmittance of optical elements and N_{opt} is the number of optical elements. Therefore:

$$R_I\,(\lambda) = QE\,(\lambda)\,\frac{\lambda}{hc}\rho \tag{5}$$

In general the relative spectral responsivity (RSR) of the sensor is defined by using the pre-launch laboratory data of the sensor for each spectral band.

$$\mathrm{RSR}(\lambda) \;=\; \frac{\mathrm{QE}\,(\lambda)\lambda\;\rho(\lambda)}{\max\,\{\mathrm{QE}\,(\lambda)\lambda\;\rho(\lambda)\}} \tag{6}$$

Therefore Equation (2) becomes the following measurement equation

$$\mathrm{DN} = \frac{Gain\,\Delta t\,A_c\,\Omega_c\,\max\,\{\mathrm{QE}\,(\lambda)\lambda\;\rho(\lambda)\}}{hc}\int L(\lambda)\,\mathrm{RSR}(\lambda)\,\mathrm{d}\lambda \tag{7}$$

By rewriting Equation (7) as follows, the band averaged radiance, $\overline{L\;(\lambda)}$ can be obtained.

$$\overline{L\;(\lambda)} \;=\; \frac{\int L(\lambda)\,\mathrm{RSR}(\lambda)\,\mathrm{d}\lambda}{\int \mathrm{RSR}(\lambda)\,\mathrm{d}\lambda} \;=\; m\,\mathrm{DN}\;and\;m \;=\; \frac{hc}{Gain\,\Delta t\,A_c\,\Omega_c\max\,\{\mathrm{QE}\,(\lambda\,)\,\lambda\,\rho\;\;(\lambda\,)\}\int \mathrm{RSR}(\lambda)\,\mathrm{d}\lambda} \tag{8}$$

Equation (8) is called the Calibration Equation where the quantity m is the calibration coefficient. To simplify Equation (8), we can assume that the variables in the integral do not have strong wavelength dependence. This is valid for an instrument with narrow bandwidth channels. Equation (2) can be rewritten using Equations (3)–(5) as below [12].

$$\mathrm{DN} = Gain\;A_c\,\Omega_c\,L(\lambda)\,\Delta\lambda\,\mathrm{QE}\,\frac{\lambda}{hc}\,\rho\,\Delta t \tag{9}$$

Again instrument response non-linearity and background are not shown in Equations (7) and (9). These quantities are determined in pre-launch instrument characterization tests and are incorporated in instrument radiometric models and in the production of measured radiances.

Equation (9) can be re-written as the calibration equation equivalent to Equation (8) for obtaining radiance from the detector response in digital counts

$$L(\lambda) \;=\; m\;\mathrm{DN} \tag{10}$$

where

$$m = \frac{hc}{Gain\;A_c\,\Omega_c\,\Delta\lambda\,\mathrm{QE}\,\lambda\;\rho\,\Delta t} \tag{11}$$

The calibration coefficient m (in Equation (8) or (11)) is determined pre-launch by viewing uniform sources of known radiance, such as blackbodies for TEB, and well characterized integrating sphere sources for RSB. It is also determined from characterization of individual components such as mirror reflectance, polarization responsivity, spectral radiance responsivity based on the sensor specifications and operational requirements. The individual component level measurements are also used as input to sensor radiometric mathematical models to predict sensor performance and the calculation of band by band measurement uncertainty. Both sensor performance predictions and the system level measurements of m help to establish its pre-launch SI traceable calibration uncertainty. On-orbit the calibration coefficient m is monitored by viewing on-board sources of known radiance. For TEB the on-board blackbody maintained at constant known temperatures serves as a SI traceable standard. However, the background from the emission of the scanning optics in front of its aperture adds to the signal and is to be accounted and subtracted. In general, to accomplish this as a second point of calibration, the sensor on orbit is provided to have a space view of zero radiance.

For RSB, the radiance in Equation (1) can be written for observing the earth as solar reflected radiance,

$$\mathrm{DN} = Gain \iiint E_{sun}(\lambda)\, \mathrm{BRDF}\,(\phi_h, \phi_v)\; R_{\mathrm{I}}(\lambda) \cos\theta \, \mathrm{d}A_{\mathrm{s}}\, \mathrm{d}\omega_{\mathrm{s}}\, \mathrm{d}\lambda \, \mathrm{d}t \tag{12}$$

where E_{sun} *is* the solar spectral irradiance, BRDF is the bi-directional reflectance distribution function and φ_h, φ_v are the horizontal and the vertical incidence angles of solar illumination on the reflectance standard or the earth scene. The instrument calibration for RSB is performed on orbit using a reflectance standard such as Spectralon™ to observe reflected solar radiation in comparison to the reflected light from the earth scene. Again, space view helps to discriminate any background contribution.

In Sections 2 and 3 below the radiometric calibration methods of the sensors, the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Imaging Radiometer Suite (VIIRS) in polar orbit, *i.e.*, low earth orbit (LEO) and the Geostationary Operational Environmental (GOES) Imager and the GOES-R Advanced Baseline Imager (GOES-R ABI) in geostationary orbit (GEO) are analyzed. However, the symbols and terminology used in their Algorithm Theoretical Basis Documents (ATBD) are followed without changing for this article as there will be less confusion to refer back to the literature on these sensors. The calibration equations for TEB and RSB are separately discussed for these sensors in each section due to the difference in calibration instrumentation and methodology for these two spectral regions. Both equations and the SI traceability are analyzed for each sensor. In the discussion Section 4 the wavelength bands and the calibration features of MODIS and VIIRS, and GOES Imager and GOES-R ABI are compared. The conclusion is given in Section 5. The authors note given as Appendix shows Table A1 comparing the few terms and symbols used differently across the various sensor algorithms.

2. Methods of Radiometric Calibration—Polar Satellite Sensors

2.1. MODIS

2.1.1. MODIS TEB Radiometric Calibration

The MODIS Level 1B ATBD describes the sensor instrumentation and develops the calibration equation [13]. The MODIS scan cavity and on-board calibrators and the schematic of the optical system are shown in Figures 1 and 2 of Reference [13]. The double sided Primary mirror (scan mirror) scans the earth scene and the two calibrators, the on-board blackbody (BB) and the space view for zero radiance. It is set to scan the on board calibrators at different angles of incidence compared to the earth observations. As the mirror rotates the scan angles for earth observations on each side is accompanied by the calibrator observations on the same side. These observations alternate between sides. The scan angles are given in Figure 4a of Reference [13].

The TEB radiometric calibration for MODIS is performed by using the digital counts from the two point observations of the BB and Space.

In BB Look, the radiance observed by the sensor through the optics in the beam path is given by the following radiometric equation and it holds for each mirror side, spectral band and detector (Equation (3.1) in [13]),

$$L_{BB\_Path} = RVS_{BB}\ \varepsilon_{BB}\, L_{BB} + (1 - RVS_{BB})\ L_{SM} + RVS_{BB}\ (1 - \varepsilon_{BB})\, \varepsilon_{CAV}\, L_{CAV} + L_{BKG} \tag{13}$$

where L_{BB_Path} is the radiance of all elements in the beam path when the sensor views the blackbody (BB), RVS_{BB} is the normalized system response *versus* scan angle when the sensor views the BB. It is essentially the reflectance of the scan mirror for the appropriate angle. The important pre-launch characterization is the *RVS* measurement for each band and the mirror side. It is normalized for each viewing angle to its value at the BB viewing angle of -152.5°.

ε_{BB} is the emissivity of the BB (Pre-launch characterization).
L_{BB} is the radiance from the BB at its set temperature. It is the averaged over the *RSR*.
L_{SM} is the radiance of the scan mirror at its temperature.
ε_{CAV} is the emissivity of the cavity formed by the housing of all the optics (Pre-launch Characterization).
L_{CAV} is the radiance of the scan housing that acts as a cavity emitting radiation based on its temperature.
RVS_{BB} is the normalized system response *versus* scan angle when the sensor views the BB.
L_{BKG} is the radiance from the common path background.

Equation (13) essentially shows the total radiance observed by the sensor while viewing the BB as the sum of radiance from BB emission, the radiance due to the scan mirror emission, the radiance of the optics housing cavity reflected by the blackbody and the scan mirror, and any other unaccounted back ground.

In the Space Look, the sensor views deep space through the Space View (SV) port at the scan angle of -99° on each mirror side and the sensor response establishes the "zero radiance" for each band. The radiance at Space view (*SV*), $L_{SV\_\ Path}$ is given by

$$L_{SV\_Path} = (1 - RVS_{SV}) \times L_{SM} + L_{BKG} \tag{14}$$

where RVS_{SV} is the normalized sensor response *versus* scan angle when the sensor views deep-space. Space itself is considered providing zero radiance.

The difference in counts between the BB view and the space view, $\mathrm{DN}_{BB} - \mathrm{DN}_{SV}$ is measured as dn_{BB}. The calibration equation with instrument response in counts written as a quadratic function of dn_{BB} is as follows,

$$RVS_{BB}\, \varepsilon_{BB}\, L_{BB} + (RVS_{SV} - RVS_{BB})\ L_{SM} + RVS_{BB}\, (1 - \varepsilon_{BB})\, \varepsilon_{CAV}\, L_{CAV} = a_0 + b_1 dn_{BB} + a_2 dn_{BB}^2 \tag{15}$$

The calibration coefficients a_0, b_1 and a_2 are the quadratic polynomial coefficients. The linear coefficient b_1 is determined scan by scan using on–orbit data of the sensor response to the BB in its view. In fact Equation (15) allows determining the dominant Calibration Coefficient, b_1 whereas the offset, a_0 and the non-linearity term, a_2 available from pre-launch calibration are updated by the fitting process to reduce the size of the residuals.

In the Earth Scene Look, the sensor views the earth scene over the scan angles $\pm 55^{\circ}$ and corresponding Earth radiance, L_{EV} is determined by the following calibration equation similar to Equation (15) above accounting for the background for the earth view. The term $RVS_{BB}\ (1 - \varepsilon_{BB})\, \varepsilon_{CAV}\, L_{CAV}$ in Equation (15) drops out as there is no reflected IR radiance in the earth scene. Therefore the calibration equation for the earth scene radiance L_{EV} is:

$$RVS_{EV} \cdot L_{EV} + (RVS_{SV} - RVS_{EV}) \cdot L_{SM} = a_0 + b_1 \cdot dn_{EV} + a_2 \cdot dn_{EV}^2 \tag{16}$$

where dn_{EV} is the difference in counts between the earth view and the space view, $\mathrm{DN}_{EV} - \mathrm{DN}_{SV}$. The earth scene radiance L_{EV} is obtained from Equation (16) as all the other quantities are known from Equation (15) evaluated in the same scan.

2.1.2. MODIS RSB Radiometric Calibration

The calibration equation for the bands in the reflective solar wavelength region (RSB) is described in Section 4 of Reference [13]. For RSB, Equation (12) describes the measured digital counts in terms of the reflected radiance due to the solar irradiance of the earth scene. The On-board calibrator for RSB is the Solar Diffuser (SD) panel made from space-grade Spectralon™. Also MODIS is equipped with on-board Solar Diffuser Stability Monitor (SDSM) to monitor and correct for SD degradation. Extensive pre-launch calibration and characterization was performed for RSB on the Response *vs.* Scan Angle (RVS) of the rotating half angle mirror, the Focal Plane Array Detectors, the SD and the SDSM. The MODIS Radiometric Calibration Equation for the RSB Earth view radiance is given below based on earth view and space view digital counts.

The earth view reflectance factor is related to the digital counts by:

$$\rho_{EV}\cos\left(\theta_{EV}\right) = m_1 dn^*_{EV} d^2_{ES} \tag{17}$$

where ρ_{EV} earth view scene reflectance, θ_{EV} the the solar Zenith angle of the earth view pixel, m_1 the calibration coefficient is determined from the on orbit measurements of the solar diffuser (SD) and SD Stability Monitor (SDSM) and updated regularly, d_{ES} the earth-sun distance at the time of the earth view scene observation and dn^*_{EV} the background subtracted, earth view angle difference adjusted, and instrumental temperature effect corrected digital signal. It is evaluated by:

$$dn^*_{EV} = \left(\mathrm{DN}_{EV} - \langle \mathrm{DN}_{SV} \rangle\right)\left(1 + k_{inst}\Delta T\right)/RVS_{EV} \tag{18}$$

where DN_{EV} and $\langle \mathrm{DN}_{SV} \rangle$ are earth view and space view raw digital counts, respectively, k_{inst} represents the relative dependence of the digital count on the instrument temperature, ΔT is the difference of the instrument temperature from its reference value, and RVS is the response *versus* scan angle normalized at the angle of incidence of the SD. For each band and detector, k_{inst} was calculated from pre-launch measurements using the response of detector at different instrument temperatures. RVS was measured pre-launch and updated from on-orbit characterization and monitoring.

The linear calibration coefficient m_1 is determined from the measurements of the SD and SDSM through

$$m_1 = \frac{\rho_{SD}\cos\left(\theta_{SD}\right)}{dn^*_{SD} d^2_{ES\_SD}} \Gamma_{SDS} \Delta_{SD} \tag{19}$$

where ρ_{SD} is the SD reflectance measured pre launch and dn^*_{SD} is the corrected digital signal given by Equation (18) when measuring SD. The d_{ES_SD} is the Earth- sun distance in AU at the time of SD measurement. The Δ_{SD} is the SD degradation factor determined from the SDSM. For high gain bands, a solar diffuser screen (SDS) is closed to attenuate direct Sun light and Γ_{SDS} is the vignetting (transmission) function. It is unity when the SDS is open and not attenuating the sunlight.

The calibration equation for Earth view radiance can be written using Equation (16) for the reflectance factor.

$$L_{EV} = E_{Sun}\rho_{EV}\cos\left(\theta_{EV}\right)/\pi d^2_{ES} = m_1 dn^*_{EV} \frac{E_{Sun}}{\pi} \tag{20}$$

where E_{Sun} is the solar irradiance normalized with π at $d_{ES} =$ 1 AU and dn^*_{EV} and m_1 are obtained from Equations (18) and (19) respectively.

2.1.3. Analysis of the MODIS Calibration Algorithm and SI Traceability

The development of Equation (16) for TEB and Equation (20) for RSB for MODIS reflects the best practice as the radiometric calibration methodology accounts for various possible contributions to the radiance and is amenable to be modified to implement corrections or improvements based on observations on-orbit.

For example, the case of MODIS sensor in Terra satellite is discussed below [14]. Due to various limitations during pre-launch the scan angle dependence of the scan mirror contribution at large angles for the 2nd term in Equation (16) could not be characterized well and the task was left for post launch. A satellite maneuver was carried out to orient the earth view port to view cold space during the eclipse part of an orbit. Such a satellite maneuver is called the deep space maneuver (DSM). The measured radiances from the earth view and the normal space view in such a configuration are both due to the mirror radiance except its dependence on the mirror angle as shown below.

$$(RVS_{SV} - RVS_{EV})\ L_{SM} = a_0 + b_1 dn_{EV} + a_2 dn_{EV}^2 \tag{21}$$

The RVS_{EV} for the entire Earth view was determined using Equation (21), by knowing dn_{EV} from DSM. The scan mirror emitted radiance, L_{SM} is calculated from its on orbit measured temperature. The offset term a_0 and the nonlinear term a_2 are provided in the Look up Tables (LUT) from pre-launch calibration or updated from blackbody warm-up and cool-down cycles (WUCD) performed quarterly. The WUCD cycle allows the measurement of TEB detectors responses over a range of radiances corresponding to the blackbody temperature variation from 270 K to 315 K. The linear coefficient b_1 of each detector is determined every scan knowing the blackbody temperature and other variables in the Equation (15). This new *RVS* improved the Terra imagery and reduced the calibration errors [14]. Based on the lesson learned from Terra MODIS Aqua MODIS pre-launch *RVS* characterization was much more comprehensive and the performance of the sensor was much more stable with fewer corrections to be made [15]. The degradation of the Solar Diffuser tracking using Solar Diffuser stability Monitor (SDSM) and lunar observations is another example of on-orbit flexibility of the calibration algorithm to track and maintain calibration of RSB for both Terra and Aqua sensors. The spacecraft roll maneuver was performed 9 to 10 times per year for lunar observations through space view port and special SD/SDSM operations during spacecraft yaw maneuvers allowed to derive the SD screen vignetting function [16]. Similarly using on-orbit data sets and the calibration equations, the MODIS team was able to track potential changes to be made to the calibration algorithm to monitor and maintain the on-orbit calibration of TEB and RSB. The uncertainty evaluation of TEB and RSB radiances was done based on the analysis of respective calibration equations [17,18]. It stands as an exemplary effort for the uncertainty analysis for follow up sensors. The analysis followed the important feature of GUM identifying component uncertainties and combining them by square root of sum of squares to arrive at total uncertainty. However, the GUM terminology and procedure of identifying the component uncertainties with uncertainty budget distinguishing as Type A or Type B was not followed. The best practice guideline of using GUM will allow evaluation of the relative contributions from individual variables in the calibration equation. It enables optimization of the calibration equation in a transparent way by removing negligible effects from consideration in meeting the requirements.

2.2. VIIRS

The VIIRS optics has the Rotating Telescope Assembly (RTA), the Half Angle Mirror (HAM) and all of the optics past HAM called *aft.* Reflected and emitted radiation from the earth enters the sensor through the RTA and is reflected from HAM into the *aft* optics sub system. The HAM is a two sided mirror and derives its name as half angle mirror because it rotates at half the angular speed of RTA as both sides of the mirror become active one after another in its full revolution to reflect the radiation from the RTA via a fold mirror into the aft optics. The VIIRS ATBD Section 2.2.2 describes the Opto-Mechanical Module in full detail [19]. The on-board calibrators are the black body (OBCBB) for

TEB and the Solar Diffuser (SD) for RSB with a Solar Diffuser Stability Monitor (SDSM) to monitor SD degradation just as in MODIS. The radiometric equations are developed in Section 2.3 in Reference [19].

The transmittance through the RTA follows Equation (4) and an assumption is made that the scan angle dependence and the wavelength dependence of the transmittance (ρ) of the optics are separable as the spectral wavelength is narrow for each band. The scan angle dependence of the response is due to the rotation of HAM presenting different angles during its scan and is denoted as Response Versus Scan (RVS (θ,B)). It is measured in pre-launch testing and is an important parameter in the development of calibration equation. The term in the brackets in the equation below is the product of the reflectance of HAM wavelength dependence part and the angular dependence part of HAM reflectance.

$$\rho_{sys}(\lambda) = \prod_{1}^{N_{op}} \rho_j(\lambda) = \rho_{rta}(\lambda)\ \rho_{aft}(\lambda)\left[\rho_{ham}(\lambda)\ \mathrm{RVS}\ (\theta, B)\right] \tag{22}$$

The angle independent transmittance of the system is combined as $\rho_{fix}(\lambda)$ given by

$$\rho_{fix}(\lambda) = \rho_{rta}(\lambda)\ \rho_{ham}(\lambda)\ \rho_{aft}(\lambda) \tag{23}$$

where $\rho_{rta}(\lambda)$, $\rho_{ham}(\lambda)$, $\rho_{aft}(\lambda)$ denote the transmittance through rotating telescope assembly, the HAM and the aft assembly respectively.

The VIIRS (RTA) has three views, the space, the blackbody and the earth. They are abbreviated as sv, obc and ev.

The measurement equation is given by Equation (8) in Section 2.3 of Reference [18],

$$N_e = \frac{\Omega_{stop} \cdot \Delta t \cdot A}{hc} \int \mathrm{QE}(\lambda) \cdot \lambda \cdot \left[L_{ap}(\lambda, \theta) \cdot \rho_{fix}(\lambda) \cdot \mathrm{RVS}(\theta, B) + \frac{E_{bkg}(\lambda, \theta)}{\Omega_{stop}}\right] d\lambda \tag{24}$$

where N_e is the number of photo electrons per detection, Ω_{stop} is the solid angle of the aperture stop as seen from the field stop and A is the area of the field stop, $L_{ap}(\lambda, \theta)$ is the spectral radiance at the aperture at angle θ, and $E_{bkg}(\lambda, \theta)$ is the spectral irradiance at the field stop due to the self-emissive background detected at the scan angle θ.

Equation (24) is in integral form to account for wavelength dependence within the band. Also, in Reference [4] the relative spectral response, RSR is defined as in Equation (6) in Section 1.

$$\mathrm{RSR}(\lambda) = \frac{QE(\lambda) \cdot \lambda \cdot \rho_{fix}(\lambda)}{max\left(QE(\lambda) \cdot \lambda \cdot \rho_{fix}(\lambda)\right)} \tag{25}$$

The following notation was used in Reference [18] for any quantity to be band averaged. For example, the quantity $F(\lambda)$ is band averaged as follows

$$\overline{F(\lambda)} = \frac{\int \mathrm{RSR}(\lambda) \cdot F(\lambda)\, d\lambda}{\int \mathrm{RSR}(\lambda)\, d\lambda} \tag{26}$$

Using Equations (25) and (26), the quantities in the bracket of Equation (24) are band averaged and the resulting quantity is called the band-averaged detectable radiance, $\overline{L_{det}}(\theta, B)$.

$$\overline{L_{det}}(\theta, B) = \mathrm{RVS}(\theta, B) \cdot \overline{L_{ap}}(\lambda, \theta) + \overline{L_{\mathrm{det\_}bkg}}(\theta, B) \tag{27}$$

Equation (27) is transformed into the calibration equation as shown below

$$\overline{L_{det}}(\theta, B) = G\ N_e \tag{28}$$

where the quantity G relates N_e to the radiance at the detector.

Equation (27) relates the radiance at the detector as due to radiance entering the aperture modified by the response *vs.* scan angle of the HAM and the background radiance.

The space view (*sv*) provides zero radiance entering the aperture. It is a calibration of zero external radiance input for the sensor output, *i.e.*, $L_{ap}\,(\lambda, \theta_{SV}) = 0$ and in the notation B representing each band can be replaced with corresponding λ for that band; *i.e.*, $\overline{L_{ap}}\,(\theta, B) = \overline{L_{ap}}\,(\lambda, \theta)$.

By defining

$$\overline{\Delta L_{det}}\,(\theta, B) = \overline{L_{det}}\,(\theta, B) - \overline{L_{\mathrm{det}\_bkg}}\,(\theta_{SV}, B) \tag{29}$$

$$\overline{\Delta L_{det\_bkg}}\,(\theta, B) = \overline{L_{\mathrm{det}\_bkg}}\,(\theta, B) - \overline{L_{\mathrm{det}\_bkg}}\,(\theta_{SV}, B) \tag{30}$$

Substituting from Equations (27) and (30), the net radiance detected, in Equation (29) is given by

$$\overline{\Delta L_{det}}\,(\theta, B) = \mathrm{RVS}\,(\theta, B) \cdot \overline{L_{ap}\,(\lambda, \theta)} + \overline{\Delta L_{\mathrm{det}\_bkg}}\,(\theta, B) \tag{31}$$

Basically, we have the radiance causing the detector to respond $\overline{\Delta L_{det}}\,(\theta, B)$ given by Equation (31) that excludes the space view background. The non-linearity effects and the temperature effects of the detectors in the FPA and the electronics are parameterized by coefficients C_i and expresses $\overline{\Delta L_{det}}\,(\theta, B)$ as $\sum\limits_{i=0}^{2} C_i dn^i$ where dn is the detector output signal in digital counts after subtracting the space view counts accounting for the space view background. The detector output is expressed as a second order polynomial and coefficients C_i which are theoretically analyzed as combination of individual components a_i for the detector and b_i for the electronics and shown in Tables 11–13 in Section 2.3.1 in Reference [19] for various possible scenarios of VIIRS performance. The C_i determined pre-launch are changed to C_i' post launch and are being tracked and calibrated. A scale factor F is introduced to account for the change quantitatively and to be dynamically calibrated on orbit. It is assumed that all three coefficients change by the same factor F and $c_i' = F\,.\,c_i$.

Therefore,

$$\overline{\Delta L_{det}}\;\;(\theta, B) = \overline{\Delta L_{det}}\;\;(dn) = \sum_{i=0}^{2} C'_i dn^i = F\ldots\ldots \sum_{i=0}^{2} C_i dn^i \tag{32}$$

where $= DN - \overline{DN_{sv}}$, is the background subtracted counts.

2.2.1. VIIRS TEB Radiometric Calibration

The RTA views the emissive sources in all three of its views, the space, the earth and the on-board blackbody and always having the background contribution from the optics and any reflected radiation. In Reference [19] all background sources within the solid angle of the aperture stop are analyzed and it is assumed that all components of the RTA are at same temperature T_{rta} and the temperature of the HAM mirror T_{ham} will be different.

The band averaged residual background for any view subtracting the space view is given in Reference [19] Equation (44).

$$\overline{\Delta L_{\mathrm{det}\_bkg}}(\theta, B) = (RVS(\theta, B) - RVS(\theta_{SV}, B)) \cdot \left(\frac{\{(1 - \overline{\rho_{rta}(\lambda)}) \cdot \overline{L(T_{rta}, \lambda)} - \overline{L(T_{ham}, \lambda)}\}}{\overline{\rho_{rta}}(\lambda)} \right) \tag{33}$$

So Equation (31) transforms to the following equation which is essentially Equation (45) in Reference [18].

$$\begin{gathered} \mathrm{RVS}\,(\theta, B)\,\overline{L_{ap}}\,(\theta, B) = \overline{\Delta L_{det}}\,(\theta, B) - \overline{\Delta L_{\mathrm{det}\_bkg}}\,(\theta, B) = \overline{\Delta L_{det}}\,(dn) - \overline{\Delta L_{\mathrm{det}\_bkg}}\,(\theta, B) = \\ \sum_{j=0}^{2} C\prime_j dn^j - \overline{\Delta L_{\mathrm{det}\_bkg}}\,(\theta, B) \end{gathered} \tag{34}$$

The OBCBB look is used for calibration as the RTA views it in each scan. The contribution to the radiance from other possible sources that add to the OBC radiance is analyzed. Other sources are the reflections from the blackbody shield, the cavity and the telescope. The band averaged radiance at the aperture stop for OBC look is given by

$$\overline{L_{ap}}\ (\theta_{obc}\ ,\ B) = \overline{\left[\epsilon_{obc}\,(\lambda)\cdot L\ (T_{obc}\ ,\ \lambda) + L_{obc\_rfl}\ (T_{sh}\ ,\ T_{cav}\ ,T_{tele}\ ,\lambda)\right]} \tag{35}$$

So the measurement equation while viewing the OBC is given as essentially Equation (111) in Reference [18] and can be written with the Cal factor F in Equation (32) as below.

$$\begin{aligned} F\cdot\sum_{j=0}^{2} C_j dn^j = \mathrm{RVS}\ (\theta_{\text{o</mi>}},\ B)\cdot \overline{\left[\epsilon_{\text{o</mi>}}\,(\lambda)\cdot L\ (T_{\text{o</mi>}}\ ,\ \lambda) + L_{\text{o</mi>}c_{\text{r</mi>}}}\ (T_{\text{s</mi>}}\ ,\ T_{\text{c</mi>}}\ ,T_{\text{t</mi>}}\ ,\lambda)\right]} + \\ \left(\mathrm{RVS}\ (\theta_{\text{o</mi>}}, B) - \mathrm{RVS}\ (\theta_{\text{S</mi>}}, B)\right)\cdot\left(\frac{\left\{\left(1-\overline{\rho_{\text{r</mi>}}(\lambda)}\right)\cdot \overline{L\,(T_{\text{r</mi>}},\ \lambda)} - \overline{L\,(T_{\text{h</mi>}},\ \lambda)}\right\}}{\overline{\rho_{\text{r</mi>}}}\,(\lambda)}\right) \end{aligned} \tag{36}$$

F can be determined as part of On Board calibration. The RVS is arbitrarily normalized to one scan angle (Space view angle) RVS $(\theta_{SV}, B) = 1$. The calibration factor F is determined from Equation (36).

$$\begin{aligned} F = \frac{\mathrm{RVS}\ (\theta_{\text{o</mi>}},\ B)\cdot\left[\overline{\epsilon_{\text{o</mi>}}\,(\lambda)}\ \cdot\overline{L\ (T_{\text{o</mi>}}\ (t)\ ,\ \lambda)} + \overline{L_{\text{o</mi>}}\ (T_{\text{s</mi>}}\ (t)\ ,\ T_{\text{c</mi>}}\ (t)\ ,T_{\text{t</mi>}}\ (t)\ ,\lambda)}\right]}{\sum_{j=0}^{2} C_j dn_{\text{o</mi>}}{}^{j}} + \\ \frac{\left(\mathrm{RVS}\ (\theta_{\text{o</mi>}}, B) - 1\right)\cdot\left(\frac{\left\{\left(1-\overline{\rho_{\text{r</mi>}}(\lambda)}\right)\cdot\overline{L\,(T_{\text{r</mi>}}\ (t)\ ,\ \lambda)} - \overline{L\,(T_{\text{h</mi>}}\ (t)\ ,\ \lambda)}\right\}}{\overline{\rho_{\text{r</mi>}}}\,(\lambda)}\right)}{\sum_{j=0}^{2} C_j dn_{\text{o</mi>}}{}^{j}} \end{aligned} \tag{37}$$

The band averaged OBC blackbody reflected radiance is:

$$\overline{L_{obc\_rfl}\ (T_{sh}\ ,\ T_{cav}\ ,T_{tele}\ ,\lambda)} = \left(1 - \overline{\varepsilon_{obc}\ (\lambda)}\right)\cdot\ \left(F_{sh}\cdot\ \overline{L\ (T_{sh}, \lambda)} + F_{cav}\cdot\ \overline{L\ (T_{cav}, \lambda)} + F_{tele}\cdot\ \overline{L\ (T_{tele}, \lambda\ )}\right) \tag{38}$$

where the factors F_{sh}, F_{cav} , F_{tele} represent the fraction of the reflectance off the OBC blackbody originating from the blackbody shield, cavity and telescope. Assuming the emissivity of these three sources to be 1, it follows $F_{sh} + F_{cav} + F_{tele} = 1$. The OBC blackbody reflected radiance is routinely updated knowing the temperatures of all relevant components in Equation (38).

The scene radiance $\overline{L_{ap}}\,(\theta, B)$ is obtained for Earth view angle θ using the Equations (34)–(37) and is given by the following calibration equation

$$\overline{L_{ap}}\,(\theta_{ev}, B) = \frac{F\ \sum_{j=0}^{2} C_i\,(T_{det}, T_{ele})\ dn_{ev}{}^{j} + (1 - \mathrm{RVS}\ (\theta_{ev}, B))\left(\frac{\left\{\left(1-\overline{\rho_{rta}(\lambda)}\right)\ \overline{L\,(T_{rta},\ \lambda)} - \overline{L\,(T_{ham},\ \lambda)}\right\}}{\overline{\rho_{rta}}\,(\lambda)}\right)}{\mathrm{RVS}\ (\theta_{ev},\ B)} \tag{39}$$

The above equation essentially gives the radiance (Earth view) as the sum of Calibrated FPA signal converted to radiance accounting for HAM scan angle dependence and the residual background from the RTA and the HAM.

In summary, for evaluating Equation (39), the pre-launch data provide the HAM scan angle dependence of the RVS (response vs scan angle) as LUTs. The background is evaluated from the emitted radiance determined at the temperature of the optics dynamically measured on-orbit. The $\overline{\rho_{rta}}\,(\lambda)$ is determined pre-launch and stored in the LUTs. The gain Coefficient F is determined from the blackbody view and Equation (37).

2.2.2. VIIRS Radiometric RSB Calibration

The calibration equation shown below for the RSB is developed from the general calibration algorithm developed earlier *i.e.*, Equations (31) and (32).

$$\overline{L_{ap}}\,(\theta, B) = \overline{L_{ap}\,(\theta, \lambda)} = \frac{\overline{\Delta L_{det}}\,(\theta, B)}{RVS\,(\theta, B)} = \frac{F\ .\ \sum_{i=0}^{2} C_i\ .\ dn^i}{RVS\ \ (\theta, B)} \tag{40}$$

The calibration source for RSB is the solar diffuser (SD) for which the reflectance factor, ρ_{sd}, is determined as discussed for MODIS sensor, by the pre-launch measurements of the SD Bi-directional Reflectance Distribution Function (BRDF) and corrected to account for the SD degradation on-orbit based on the trending of the solar diffuser stability monitor (SDSM) output. There is also a SD screen (SDS) at the entrance to the instrument aperture to attenuate the solar irradiance when pointing to the SD. The radiance at the entrance aperture viewing the SD can be written as:

$$L_{ap}\ (\theta_{sd},\lambda) = \ \tau_{sds}\ (\phi_h,\phi_v,\ \lambda,d).E_{sun}(\ \lambda,d_{se}).\cos{(\theta_{inc})}\ .\mathrm{BRDF}\,(\phi_h,\phi_v,\ \lambda) \tag{41}$$

where ϕ_v and ϕ_h are the vertical and horizontal incidence angles of solar illumination upon the SD, θ_{inc} is the incidence angle onto the SD relative to normal, d_{se} is the distance from the sun to the earth, τ_{sds} (ϕ_h, ϕ_v, λ, d) is the transmittance of the SDS, d is detector index and $E_{sun}(\lambda,d_{se})$ is the irradiance from the sun upon a surface with its normal pointing toward the sun. Integrating Equation (41) over the spectral band "B" and substituting it into Equation (40), we obtain the measurement equation.

$$F = \frac{RVS\,(\theta_{sd},B)\,.\cos{(\theta_{inc})}\,.\left[\overline{\tau_{sds}\ \ (\phi_h,\phi_v,\ \lambda,\ d)\,.E_{sun}\,(\lambda,d_{se})\,\mathrm{BRDF}\,(\phi_h,\phi_v,\ \lambda)}\right]}{\sum_{i=0}^{2} c_i\ .\ dn_{sd}^{i}} \tag{42}$$

where the average denotes the averaging over the spectral band "B". It is further assumed that τ and BRDF are invariant with wavelength within the narrow band and are taken out of the integral. All the variables on the right of Equation (42) are based on preflight measurements and on angles that can be determined from the geometry. All values on the right are known. The three c coefficients are determined pre-launch and Equation (40) allows the scale factor F to be determined for RSB from the solar diffuser measurements. The determination of F for RSB resembles the case of IR bands as discussed in relation to Equation (32).

After determining the F factor from the solar diffuser measurements, the calibrated earth view at-aperture radiance for RSB is calculated using the calibration equation *i.e.*, Equation (40),

$$\overline{L}_{ap}\,(\theta_{ev},\ B) = \frac{F\,.\sum_{i=0}^{2} c_i\ .dn_{ev}^{i}}{\mathrm{RVS}\ (\ \theta_{ev},\ B)} \tag{43}$$

where $\overline{L}_{ap}\,(\theta_{ev},\ B)$, the band-averaged spectral radiance at the aperture for earth view scan angle θ_{ev}, $\overline{L}_{ap}\,(\theta_{ev},\ B)$, is the response *versus* scan function at earth view scan angle θ_{ev} for band B and $dn_{ev} = \ DN_{ev} - DN_{sv}$, the difference between total digital output for earth view angle θ_{ev} and digital counts for space view.

The spectral earth-view reflectance for VIIRS RSB can be written as discussed for MODIS sensor,

$$\rho_{ev}\ \ (\theta_{ev},\lambda) = \frac{\pi.\ L_{ap}\,(\theta_{ev},\lambda)}{\cos{(\theta_{sun\_earth})}\ .\ E_{sun}\,(\lambda,\ d_{se})} \tag{44}$$

Applying band-averaging for Equation (44) over spectral band "B" and using Equation (40) to substitute for $\overline{L}_{ap}\,(\theta_{ev},\ B)$, we obtain the band- averaged earth-view reflectance as

$$\overline{\rho}_{ev}\,(\theta_{ev},\ B) = \frac{\pi\ .\ F\ .\sum_{i=0}^{2} c_i\ .dn_{ev}^{i}}{\mathrm{RVS}\ (\ \theta_{ev},\ B)\ .\cos{(\theta_{sun\_earth})}\ .\ \overline{E_{sun}\,(\lambda,\ d_{se})}} \tag{45}$$

2.2.3. Analysis of the VIIRS Calibration Algorithm and SI Traceability

The VIIRS sensor was launched into orbit in October 2011 and much experience on its On-orbit performance is reported in literature. The calibration equations, Equation (39) for TEB and Equation (45) for RSB have been developed from first principles of Radiometry as shown in Section 1 of this paper. The calibration algorithm differs from the simplicity of MODIS due to new Cal factor "F" introduced as a scaling factor in the calibration equations as discussed in Sections 2.2.1 and 2.2.2 for monitoring on-orbit performance compared to the results of extensive pre-launch characterization and calibration of the sensor. The pre-launch test data was comprehensive over the full range of instrument operating conditions guided by stringent uncertainty requirements that provided LUTs for on-orbit data analysis. The F factor is evaluated at every scan, at every detector of every band, for every HAM mirror side which is a good practice to identify anomalies. However there is an intrinsic difficulty in determining the F factor for TEB due to the RVS variation with angle of incidence as can be seen in the Equations (37) and (39). The space view does not cancel the background because of the RVS difference between space view and the blackbody view. As such one needs accurate RVS data to evaluate F using the blackbody radiance as input in Equation (37). The other way out is to have RVS for blackbody view same as for the space view by design and provide an accurate measurement of this RVS in LUT. This will eliminate background contribution and F can be determined from Equation (37) without getting coupled to RVS and Equation (38) can be used for analyzing earth view radiances knowing the other parameters. However, at the time of this writing the long wave TEB radiances for Sea Surface Temperature (SST) Environmental data Record (EDR) for the blackbody Warm Up and Cool Down (WUCD) time periods showed anomalous values. David Moyer *et al.*, are analyzing the WUCD data to resolve the issue [20].

The radiometric performance and stability of VIIRS sensor TEB during normal operations is considered excellent compared to expectations [21]. The large degradation of the NIR and SWIR of the RSB bands soon after launch was addressed and resolved as caused by the tungsten contamination in the RTA mirror coatings. This degradation is currently reported to have considerably leveled off [22]. As part of good practice, spacecraft maneuvers are being performed to verify and update key parameters. At the beginning of the mission yaw maneuver was performed to validate and update the transmission of the SD and SDSM screen [23]. Roll maneuvers are performed on nearly monthly-basis for lunar observations for independent validation of RSB calibration using the SD and SDSM. Pitch maneuver was performed and the data validated the relative TEB RVS values [24]. However, a pitch maneuver coupled to WUCD may provide independent data to address the SST EDR anomaly. The pitch maneuver will point the earth view to another space view and thus provide another zero radiance reference. The path difference background signal can be analyzed independently as a function of the temperature of the HAM mirror and the angle dependent RVS. This independent experiment could validate the parameters evaluated by Reference [19] for SST anomaly resolution. If there are limitations of time for the complete WUCD cycle, even a part of the cycle during the useful time of the pitch maneuver may help to get TEB data for the anomaly resolution.

The SI traceability is addressed in the ATBD comprehensively as part of stringent uncertainty requirements [19]. The Reference [19] and published literature followed GUM to a large extent to determine uncertainty by using the calibration equations [23,25]. However, the usage of terminology of GUM such as "Standard uncertainty" for individual components and "Combined Standard uncertainty" for the total are yet to be introduced in to the common practice for VIIRS calibration.

3. Methods of Radiometric Calibration—Geostationary Satellite Sensors

3.1. GOES Imager

The current GOES imagers trace back to GOES-8 launched in 1994 as the start of 2nd generation GOES satellites (also called as the 3rd generation by Tim Schmit *et al.*, [26]. Currently GOES-13 (N) is covering the eastern part of the United States and GOES-15 (P) is covering the West. They belong to extended 2nd generation N-O-P satellite series (Tim Schmit *et al.*, called it as the 4th generation that is equipped with improved image navigation and registration performance [26]. All satellites in the series carried a five channel (one visible band (RSB) and four infrared bands (TEB)) imaging radiometer designed to sense the earth both in emitted and reflected energy and a warm blackbody for the calibration of the TEB. The space view served to provide zero radiance reference for calibration. There was no on-board visible reference standard to calibrate the visible band on-orbit and the pre-launch calibration provided the calibration coefficients. The radiometer had a two axis gimbaled scan mirror, a Cassegrain telescope to focus the energy into after telescope (aft) optics that separates the visible and four infrared bands through beam splitters and filters to produce the image by the detector array at each band [27]. The gimbaled scan mirror produces a bidirectional scan (East/West and North/South) of the earth scene and provides a space look at an extreme East West coordinate and a blackbody look when it is rotated in the N-S direction through an angle of approximately 180 degrees.

3.1.1. GOES TEB Radiometric Calibration

Weinreb *et al.* described in detail the operational calibration algorithm based on GOES-8 and GOES-9 on orbit observations [28]. This algorithm is being followed to date on all sensors in the series. The calibration equation for the TEB was given originally at launch by the vendor as

$$R = q\, X^2 + m\, X + b \tag{46}$$

where R is the radiance from the scene, X is the signal output for each band, q, m, and b are the coefficients [28]. The radiance R for a band and detector is the average of spectral radiance over the spectral response function as shown in Section 1 for the calculation of band average. The value of the nonlinear coefficient q was determined from the prelaunch measurements to account for instrument and detector operating temperature dependence. The slope m and the intercept b are given by the following equations:

$$m = \frac{\left[R_{\mathrm{bb}} - q\left(X_{\mathrm{bb}}^2 - X_{\mathrm{sp}}^2\right)\right]}{\left(X_{bb} - X_{sp}\right)} \tag{47}$$

$$b = -m\, X_{sp} - q\, X_{\mathrm{sp}}^2 \tag{48}$$

where the subscripts bb and sp refer to data taken from blackbody and space views respectively.

However, the above equations were found to be insufficient to describe the observed data as there was significant dependence of the radiance R on the emissivity of the scan mirror as a function of its east-west scan angle. Weinreb *et al.* modified Equation (46) as follows:

$$[1 - \epsilon(\theta)]\, R + \epsilon(\theta)\, R_M = q\, X^2 + m\, X + b \tag{49}$$

where $\epsilon(\theta)$ is the emissivity of the scan mirror as a function of its angle θ. The parameter R_M is the radiance of the scan mirror that can be computed from its monitored temperature using Planck's law and the spectral response function of the band. Weinreb *et al.* developed an algorithm to derive $\epsilon(\theta)$ using the laboratory data on all bands for the emissivity of witness samples of the scan mirror at 45°, $\epsilon(45)$ that corresponds to the viewing angle at the center of the east-west scan [28]. It is implemented through special data collection of the instrument's output during east-west scans of space across the entire east-west field of regard above and below the earth and is described in detail in Reference [28]. Knowing $\epsilon(\theta)$, Equation (49) can be solved for m and b using the two point calibration of blackbody-look and space-look instrument output, X_{bb} and X_{sp} respectively as given below.

$$m = \frac{\left[[1 - \epsilon(45)]\, R_{\mathrm{bb}} + [\epsilon(45) - \epsilon(\mathrm{sp})]\, R_{M,bb} - q\left(X_{\mathrm{bb}}^2 - X_{\mathrm{sp}}^2\right)\right]}{\left(X_{bb} - X_{sp}\right)} \tag{50}$$

$$b = -m\, X_{sp} - q\, X_{\mathrm{sp}}^2 + \epsilon(sp)\, R_{M,sp} \tag{51}$$

where $R_{M,bb}$ and $R_{M,sp}$ are the radiances of the scan mirror computed from its temperature at the time of blackbody-look and space-look respectively. So from the observed detector output X for the earth-view, the radiance R is computed for each band from Equation (49) using Equations (50) and (51) and the detector output X_{sp} collected for the space-look and interpolated as needed. The expression for R is given below.

$$R = \frac{\left[q\left[X^2 - X_{sp}^2\right] + m\left[X - X_{sp}\right] - \left[\epsilon\ (\theta) - \epsilon\,(sp)\right] R_{M,sp}\right]}{\left[1 - \epsilon\,(\theta)\right]} \tag{52}$$

3.1.2. GOES Visible Band (0.55–0.75 µm) Radiometric Calibration

Weinreb *et al.* showed the calibration equation for the visible band radiance expressed in two ways [28].

$$R = m\,X + b \tag{53}$$

$$R = m\ \left(X - X_{sp}\right) \tag{54}$$

where m and b are the calibration coefficients determined prelaunch, X and X_{sp} are the observed signals at the earth view and space view respectively and the radiance R is the band averaged radiance computed with the spectral response function. Their recommendation is to use Equation (54) as the b from prelaunch calibration in Equation (53) may not be valid on orbit because of drifts and noise spikes. However for GOES-8 and GOES-9 imagers, Equation (53) is used with $b = m\ X_0$ where X_0 is chosen to be 29.

The reflectance factor of the earth scene ρ is obtained from the radiance R as:

$$\rho = \frac{\pi\,R}{E_{sun}} \tag{55}$$

where E_{sun} is the band averaged solar spectral irradiance computed with the spectral response function of the visible band. The pre-launch calibration coefficients determined as above have been used post-launch until 2005. Since then those post launch coefficients are being updated monthly based on the collocated Terra MODIS cloud observations using GSICS inter comparison methodology [29].

3.1.3. Analysis of the GOES Calibration Algorithm and SI Traceability

The GOES Imager was in orbit prior to the LEO sensors discussed earlier and it provided a learning experience for the establishment of SI traceable observations from satellite sensors that followed as its main anomalies listed below for the TEB required critical examination of instrument design and assumptions of pre-launch characterization.

As discussed in Section 3.1.1 the calibration algorithm had to be modified on-orbit to account for the scan angle dependence of the reflectivity of the scan-mirror that was not observed until the launch of GOES-8.

In addition to the normal, expected diurnal variation of the calibration slope, m in Equation (50) (responsivity), caused primarily by the diurnal changes in background flux reaching the detectors, there was another effect occurring around midnight called the "midnight calibration anomaly". It was attributed to the extra heating of the instrument surfaces around midnight when the sun directly shines into the scan-mirror cavity in the front of the instrument. The emitted radiation from the rapidly heated surfaces gets reflected by the blackbody (emissivity < 1) and reaches the detector when the blackbody look is performed for calibration. This extra flux adding to the blackbody flux erroneously reduces the calculated slope during the heating phase, which leads to erroneously low measurements of the scene temperature. This effect is not noticed when the blackbody and the instrument cavity are close to the same temperature. In addition to this effect it was noticed that the space view gets contaminated with scattered solar flux during eclipse seasons resulting in a larger subtraction and increased slope. These effects were well studied and a correction algorithm was implemented [30]. The GSICS methodology based comparisons to well studied SI-traceable radiometers in LEO orbits, Aqua MODIS for visible band and Infrared Sounding Radiometer (IASI) on Metop-A for TEB were made to reduce the uncertainties in the corrections [31].

There were erroneous SRF induced scene dependent biases noticed in brightness temperature (T_b) in GOES series and the GSICS methodology based comparisons with Atmospheric Infrared Sounder (AIRS) and IASI allowed to correct the Spectral Response Functions of GOES TEB especially for Band 6 (13.3 μm) [32,33].

Various vicarious calibration methods were suggested and used based on Empirical Distribution Function (EDF) of earth view data, on measurements from stable earth target such as desert, on star observations, and on MODIS data [34]. As noted earlier Collocated Terra MODIS cloud observations are being used for operationally updating the calibration coefficients [29]. However, it is difficult to establish SI traceable uncertainty because of lack of quantitative measurements of environmental parameters and lack of sufficient validation of model assumptions to arrive at Top of the Atmosphere (TOA) reflected radiances. Based on the experience gained on the GOES Imager and other innovations in imaging technology, the ABI sensor is built as the next generation GEO sensor and will be discussed in the next section.

3.2. GOES-R Advanced Baseline Imager (ABI)

GOES-R forms the beginning of the 3rd generation series (also called as the 5th generation by Tim Schmit *et al.*, [26]) of geostationary satellites with the ABI instrument replacing the GOES Imager for weather, oceanographic, climate, and environmental applications. ABI is an advanced imager with sixteen spectral bands spanning visible to long wave infrared (0.45 μm–13.6 μm), three times more spectral information, four times the spatial resolution, and more than five times faster temporal coverage than the current GOES imager [35]. It has a unique 2-mirror scanner design with independent East/West and North/South scan mirrors allowing the system to be repositioned quickly while using less power. This design allows flexible, custom scanning configurable on orbit [36,37].

There are on-board SI traceable standards for radiometric calibration consisting of a three bounce cavity design blackbody with emissivity guaranteed to be better than 0.995 called the Internal Calibration Target (ICT) for TEB calibration and a Spectralon™ diffuser called the Solar Calibration Target (SCT) for the calibration of RSB. The ICT is observed at least every 15 min depending on the scan mode selected. The space look is collected every 30 s. The solar calibration can be scheduled as needed and ABI interrupts operational image collection and performs the solar calibration using SCT by opening the solar calibration cover (SCC) for reflecting sunlight by the diffuser in to the sensor through its solar viewing port. The SCC is closed the rest of the time to protect it from unnecessary exposure and degradation. The ABI can collect lunar images when the moon appears in its field of view for RSB calibration stability validation through intercomparison with the SD calibration

The GOES-R is yet to be launched and much of the ABI instrument specific measurements and calibration details are yet to be released to the public. However, the hardware configuration is similar to the Advanced Himawari Imager (AHI) in the geostationary meteorological satellite of the Japan Meteorological Agency (JMA), Himawari-8, that was launched in October 2014 and entered into operation in July 2015. The information for the review below is drawn from the JMA presentation [38] and presentations of ABI calibration scientists at technical meetings [39–41].

The general formulation of the calibration algorithm is same as of the GOES Imager except it is now adapted to the ABI optical setup. The radiance observed by GOES-R ABI viewing an object is determined from the measured counts (C) of the object view (ov) and the space view (sv) as follows

$$\Delta L = L^{ov} - L^{sv} = m\,\Delta C_{ov} + q\Delta C_{ov}^2 \tag{56}$$

where,

$$\Delta C_{ov} = C_{ov} - C_{sv} \tag{57}$$

The quantity m is determined pre-launch and up dated on orbit. The quantity q is derived from pre-launch measurements to account for any detector non linearity. Again the radiance L is used in

Equation (56) as a short hand and it represents the band averaged spectral radiance with the spectral response function of each band.

3.2.1. GOES-R ABI TEB Radiometric Calibration

As noted earlier the ABI instrument has two mirrors, North/South and the East/West. The North/South mirror projects the earth, the ICT and the space views to the East/West mirror which raster scans and reflects it to the telescope aperture. The angular dependence of the mirror reflectance and the emissivity of the mirrors are measured pre-launch and provided as LUTs for on-orbit radiometric data analysis to produce radiances. The mirror emission and reflection contribute to the total radiance observed. So these contributions are accounted and for convenience the following notation is used to represent their contributions as they are in the optical path to the telescope. The effective radiance L_x^{eff} at the telescope aperture from an object x is the product of its emissivity and its radiance with unity emissivity, and the reflectance of the North/South mirror, ρ_N^x and the East/West mirror, ρ_E^x at the angles they are set to view the object x.

$$L_x^{eff} = \varepsilon_x L^x \cdot \rho_N^x \rho_E^x \tag{58}$$

Similarly the effective radiance $L_{N@x}^{eff}$ of the North/South mirror while viewing the object x is represented as the product of its emitted radiance at its temperature T_N and the reflectance of the East/West mirror.

$$L_{N@x}^{eff} = \varepsilon_N^x L^{T_N,\, x}\, \rho_E^x \tag{59}$$

The effective radiance $L_{E@x}^{eff}$ of the East/West mirror while viewing the object x is simply its emitted radiance at its temperature because it is the final optical element in the optical path to the telescope.

$$L_{E@x}^{eff} = \varepsilon_E^x L^{T_E,\, x} \tag{60}$$

Using the above notation the radiance at the Telescope aperture, L^x by accounting for the radiance contributions of various optical elements in the beam path for the space view (sv), ICT view ($ICTv$) and the Scene on the earth view (ev) can be written as follows.

For the space view:

$$L^{sv} = L_{N@sv}^{eff} + L_{E@sv}^{eff} \tag{61}$$

In Equation (59) the terms in the right hand side are the radiance contributions from the North/South and East/West mirrors given by Equations (57) and (58) respectively and the radiance contribution of space is dropped off as the radiance of space is assumed to be zero for all practical purposes.

Similarly, we can write using Equation (56), the radiance for the ICT view,

$$L^{ICTv} = L_{N@ICT}^{eff} + L_{E@ICT}^{eff} + L_{ICT}^{eff} \tag{62}$$

and the radiance for the scene on the earth view,

$$L^{ev} = L_{N@ev}^{eff} + L_{E@ev}^{eff} + L_{ev}^{eff} \tag{63}$$

Using Equations (59) and (60) and the calibration equation; Equation (54) the linear calibration coefficient m can be determined from

$$m = \frac{L_{ICT}^{eff} - q\,\Delta C_{ICT}^2 + \left(L_{E@ICT}^{eff} + L_{N@ICT}^{eff}\right) - \left(L_{E@sv}^{eff} + L_{N@sv}^{eff}\right)}{\Delta C_{ICT}} \tag{64}$$

Therefore, m is updated on orbit at least viewing ICT every 15 min depending on the scan mode as is being done in AHI every 10 min [38]. The rest of the quantities are measured from the ICT view and the space view or deduced from measurements using the LUTs.

Using m obtained from Equation (64), the scene radiance on the earth view can be determined from the calibration Equation (56) and using Equations (63) and (58), as follows:

$$\langle L_{ev} \rangle = \frac{m\, \Delta C_{ev} + q\Delta C_{ev}^2 - \left(L_{N@ev}^{eff} - L_{N@sv}^{eff}\right) - \left(L_{E@ev}^{eff} - L_{E@sv}^{eff}\right)}{\rho_N^{ev} \rho_E^{ev}} \tag{65}$$

where $\langle L_{ev} \rangle$ is band averaged radiance of the earth scene, *i.e.*, mW/(m^2-sr-cm^{-1}) for each band that can be converted to corresponding brightness temperature using Planck's law (emissivity = 1). It should be noted that in Equation (64) any reflected radiation from the blackbody due to its finite emissivity is neglected as is the case for GOES sensor where as it is accounted in the calibration equations of MODIS and VIIRS sensors.

3.2.2. GOES-R ABI RSB Radiometric Calibration

The radiance observed for the RSB bands follows from Equation (65) except that the mirror contributions for radiance in this spectral region are negligible and the offset due to the radiance from mirrors is set to zero. However, the space view counts are still subtracted in determining ΔC_{ev} to eliminate any other background effect and biases for the RSB. Therefore, for RSB,

$$\langle L_{ev} \rangle = \frac{m\, \Delta C_{ev} + q\Delta C_{ev}^2}{\rho_N^{ev} \rho_E^{ev}} \tag{66}$$

where $\langle L_{ev} \rangle$ is the band-averaged spectral radiance for the scene in the earth view, *i.e.*, W/(m^2-sr-µm) for the RSB, m and q are the linear and quadratic coefficients, respectively. Again the quadratic coefficient q is determined pre-launch per band and per detector element as noted in Section 3.2. The linear coefficient m for RSB is determined on-orbit viewing the Solar Calibration Target (SCT), which is a solar diffuser. Essentially Equation (64) holds for determining m except the mirror radiance contributions drop off as noted earlier for RSB and

$$m = \frac{f_{int,ch}\, L_{SCT}^{eff} - q\, \Delta C_{SCT}^2}{\Delta C_{SCT}} \tag{67}$$

where $f_{int,ch}$ is the integration factor for each band for viewing SCT determined pre-launch. The integration factor accounts for the change in integration time to measure a higher signal in viewing the SCT. L_{SCT}^{eff} is the effective band average calibrated radiance defined for viewing SCT as

$$L_{SCT}^{eff} = \langle L_{SCT} \rangle\ \rho_N^{sct} \rho_E^{sct} \tag{68}$$

Here, ρ_E^{SCT} and ρ_N^{SCT} are the reflectance of the East/West and North/South scan mirrors respectively, when viewing SCT. In Equation (66), $\langle L_{SCT} \rangle$ is the SCT band-averaged on-orbit calibrator radiance and is computed from the equation

$$\langle L_{SCT} \rangle = K_{\beta_{eff}}^{detector\ row\#} cos\left(\theta_{sun}\right) \left[\pi \langle L_{100\%\alpha} \rangle \left(\frac{R_{sun}}{r_{sun}} \right)^2 \right] \tag{69}$$

In Equation (69), R_{sun} is the average radial distance from Earth to the Sun (*i.e.*, 1 AU) and r_{sun} is the actual distance between the Earth and the Sun at the time of the calibration. $\pi\langle L_{100\%\alpha} \rangle$ is the solar irradiance at 1 AU over a Lambertian surface with 100% albedo. The factor

$cos\,(\theta_{sun})\left[\pi\langle L_{100\%\alpha}\rangle\left(\frac{R_{sun}}{r_{sun}}\right)^2\right]$ is solar irradiance normal to the solar diffuser surface when the solar incident angle is θ_{sun} and earth-sun distance is r_{sun}. The factor $K_{\beta_{eff}}^{detector\ row\#}$ is related to the effective BRDF of the *SCT*. It is an instrument property parameter that is determined pre-launch.

3.2.3. Analysis of the GOES-R ABI Calibration Algorithm and SI Traceability

The ABI with its advanced imaging capabilities and on-board SI traceable standards built to meet stringent uncertainty requirements opens a new era of SI traceable radiometric observations from GEO. The calibration algorithm is transparent in describing all the terms considered for converting the scene signal into radiance. The reflection of background from the blackbody in the calibration is not considered in the calibration algorithm. One of the reasons to neglect this effect is that the emissivity of the blackbody is high. Also the instrument is designed to maintain the temperature of the blackbody at a constant temperature and the background is well controlled by thermal stabilization of the environment. However, including the term would have been better just in case to account for anomalies that may happen due to uncontrolled background as happened with GOES Imager.

There was extensive pre-launch calibration using transfer standards from NIST that adds solid support for pre-launch SI traceability. The vendor measured spectral response functions (SRF) were validated through additional band pass measurements at NIST on witness samples for the sensor geometry of incidence angles and operating temperature. The sensor was tested in a cryo-chamber at LN_2 background for validating the TEB radiance calibration algorithm with a blackbody called the External Calibration Target (ECT) and was found to meet the specifications [42]. The ECT was calibrated with the NIST Thermal IR transfer standard radiometer (TXR) for the radiance observed in its field of view and predicted from the ECT thermal model [43]. GOES-R ABI has large number of detectors (hundreds) per band and the SRF differences between detectors in each band are relatively small and met the sensor specifications. In order to maintain computational efficiency to meet the needs of operational processing in a timely manner, it is decided to use a band averaged single SRF for each band. However, the individual detector level SRFs are available for GOES-R project to reprocess on-orbit data for research and analysis. Studies are done on the impacts for on-orbit analyses of using simulated average of the SRFs of all detectors in each band *vs.* individual measured detector SRFs for TEB and the radiometric biases in the RSB in a simulated comparison between GOES-R ABI and VIIRS expected radiances from Sonoran Desert and White Sands National Monument desert sites. The knowledge base built in these studies helps assess uncertainties in the forthcoming GOES-R ABI on-orbit data analysis [40,41]. The size of the solar diffuser in GOES-R ABI chosen by design limitations only fills partially the full aperture of the telescope and as such the uncertainties estimated in prelaunch testing need to be validated post launch on orbit. Also, there is no solar diffuser stability monitor for RSB. So there is extensive post launch testing planned to monitor and validate the individual detector spectral responsivity uniformity band by band using the North/South mirror scanning a vicarious calibration scene of uniform radiance while the East/West scan mirror points to each band systematically. The GOES-R ABI CWG at NOAA, NASA program office and the Vendor have been working together in implementing such best practice guidelines for SI traceability [39]. Also the GOES-R ABI CWG and NIST researchers worked together and created methodology to translate the sensor radiometric requirements written in error analysis framework to the modern approach based on the GUM that allows implementation of the guideline for SI traceability [44]. It helps to adopt the best practice in analyzing and reporting ABI radiance results and comparisons to other sensors on-orbit in the GSICS frame-work.

4. Discussion—Comparison of the Spectral Bands and Their Calibration Features of the Four Sensors, MODIS, VIIRS, GOES and GOES-R ABI

4.1. Comparison of Spectral Bands

The spectral data on the bands of VIIRS and MODIS that are equivalent for their primary purpose are shown in Tables 1 and 2. Their horizontal spatial resolution (HSR) specification is also given in the tables. There are 22 bands in VIIRS. The calibration uncertainty specification in spectral reflectance for a scene at typical radiance of VIIRS RSB both M and I bands is less than 2%. The specifications on the absolute uncertainty of emissive M bands varied based on the scene temperature and typically for 270 K it is 0.7% for M12 and M13, 0.6% for M14 and 0.4% for M15 and M16.

The VIIRS imaging bands are compared with equivalent MODIS bands in Table 2 in the same way as Table 1. The absolute uncertainty on the VIIRS imaging TEB is 5% for I4 and 2.5% for I5. The polychromatic Day-Night Band (DNB) in VIIRS is a special addition and MODIS did not carry its equivalent. The DNB uncertainty requirement is based on its gain state in the range of 5% to 100%. More details on these specifications of all VIIRS bands can be found in Reference [19]. These specifications are currently being validated and reported [21,22].

There are 36 bands in MODIS in total 15 bands go beyond the VIIRS equivalent 21 bands. The full details on all the MODIS bands can be seen in Reference [13]. The uncertainty requirement for MODIS RSB bands was 2% in reflectance and 5% in radiance. The MODIS TEB uncertainty specification was 1% in radiance except 0.5% for bands 31 and 32 for SST measurements, 0.75% for Band 20 and 10% for band 21 for fire detection [45]. These specifications are being continuously validated operationally and reported [17,18].

Table 1. Visible Infrared Imaging Radiometer Suite (VIIRS) Spectral Bands (M) and Moderate Resolution Imaging Spectroradiometer (MODIS) Equivalent Bands (M for Moderate spatial resolution; HSR for Horizontal Spatial Resolution).

VIIRS Band	Central Wavelength (µm)	Wavelength Range (µm)	Nadir HSR (m)	Primary Use	MODIS Equal Band(s)	Central Wavelength (µm)	Wavelength Range (µm)	Nadir HSR (m)
M1	0.412	0.402–0.422	750	Ocean color Aerosals	8	0.4113	0.405–0.420	1000
M2	0.445	0.436–0.454	750	Ocean color Aerosals	9	0.442	0.438–0.448	1000
M3	0.488	0.478–0.488	750	Ocean color Aerosals	3 10	0.4656 0.4869	0.459–0.479 0.483–0.493	500 1000
M4	0.555	0.545–0.565	750	Ocean color Aerosals	4 12	0.5536 0.5468	0.545–0.565 0.546–0.556	500 1000
M5	0.672	0.662–0.682	750	Ocean color Aerosals	13 14	0.6655 0.6768	0.662–0.672 0.673–0.683	1000 1000
M6	0.746	0.739–0.754	750	Atmospheric Correction	15	0.7464	0.743–0.753	1000
M7	0.865	0.846–0.885	750	Ocean color Aerosals	16	0.8662	0.862–0.877	1000
M8	1.240	1.23–1.25	750	Cloud Particle size	5	1.2416	1.23–1.25	500
M9	1.378	1.371–1.386	750	Cirrus/Cloud Cover	26	1.38	1.36–1.39	1000
M10	1.61	1.58–1.64	750	Snow Fraction	6	1.629	1.628–1.652	500
M11	2.25	2.23–2.28	750	Clouds	7	2.114	2.105–2.155	500
M12	3.7	3.61–3.79	750	Sea Surface Temperature (SST)	20	3.79	3.66–3.84	1000
M13	4.05	3.97–4.13	750	SST/Fires	21 22 23	3.96 3.96 4.06	3.929–3.989 3.929–3.989 4.02–4.08	1000 1000 1000
M14	8.55	8.4–8.7	750	Cloud Top Properties	29	8.52	8.4–8.7	1000
M15	10.763	10.26–11.26	750	SST	31	11.02	10.78–11.28	1000
M16	12.013	11.54–12.49	750	SST	32	12.03	11.77–12.27	1000

Table 2. VIIRS Spectral Bands (I) and MODIS Equivalent Bands (I for Imaging).

VIIRS Band	Central Wavelength (μm)	Wavelength Range (μm)	Nadir HSR (m)	Primary Use	MODIS Equal Band (s)	Central Wavelength (μm)	Wavelength Range (μm)	Nadir HSR (m)
DNB	0.7	0.5–0.9	750 (across full scan)	Imagery				
I1	0.64	0.6–0.68	375	Imagery	1	0.6455	0.62–0.67	250
I2	0.865	0.85–0.88	375	NDVI	2	0.8565	0.841–0.876	250
I3	1.61	1.58–1.64	375	Binary Snow Map	6	1.6291	1.628–1.652	500
I4	3.74	3.55–3.93	375	Imagery of Clouds	20	3.79	3.66–3.84	1000
I5	11.45	10.5–12.4	375	Imagery of Clouds	31 32	11.02 12.03	10.78–11.28 11.77–12.27	1000 1000

The GOES-R ABI imager has 16 bands and their wavelength range, central wavelength, Instantaneous Geometric Field of View (IGFOV), primary use, comparable bands in MODIS, VIIRS and GOES are shown in Table 3 [35]. As noted earlier the GOES-R series carry only the imager ABI and do not have a sounder. However some of the bands of the GOES sounder are carried into the ABI as shown Table 3.

Table 3. Advanced Baseline Imager (ABI) Spectoral band data and equivalent bands in heritage instruments.

ABI Band	Wavelength Range (μm)	Central Wavelength (μm)	IGFOV (km)	Primary Use	Heritage Instrument (s)
1	0.45–0.49	0.47	1	Daytime aerosol land, coastal water mapping	MODIS B 3 and B 10; VIIRS M3
2	0.59–0.69	0.64	0.5	Daytime Clouds, fog, Insolation, winds	Current GOES Imager; Sounder
3	0.846–0.885	0.865	1	Vegetation/ burn scar and aerosol over water, winds	VIIRS I2; MODIS B 2
4	1.371–1.386	1.378	2	Daytime Cirrus Cloud	VIIRS M9; MODIS B 26
5	1.58–1.64	1.61	1	Daytime Cloud-top Phase and particle size, snow	VIIRS I3 and M10; MODIS B 6
6	2.225–2.275	2.25	2	Daytime land/cloud properties, particle size, vegetation, snow	VIIRS M11; MODIS B 7
7	3.80–4.00	3.9	2	Surface and Cloud, fog at night, fire and winds	Current GOES Imager
8	5.77–6.6	6.19	2	High-level atmospheric water vapor, winds, rainfall	Current GOES Imager
9	6.75–7.15	6.95	2	Mid-level atmospheric water vapor, winds and rainfall	Current GOES Sounder
10	7.24–7.44	7.34	2	Lower-level water vapor, winds, rainfall	Current GOES Sounder
11	8.3–8.7	8.5	2	Total water for stability, cloud phase, dust, SO_2	VIIRS M14; MODIS B 29
12	9.42–9.8	9.61	2	Total Ozone, Turbulence and winds	Current GOES Sounder
13	10.1–10.6	10.35	2	Surface and Cloud	VIIRS M15; MODIS B 31
14	10.8–11.6	11.2	2	Imagery, SST, Clouds and rainfall	Current GOES Sounder
15	11.8–12.8	12.3	2	Total water, ash, and SST	Current GOES Sounder
16	13.0–13.6	13.3	2	Air temperature, cloud heights and amounts; CO_2	Current GOES Imager; Current GOES Sounder

4.2. Comparison of Sensor Features for Calibration and On-Orbit Observations

In Table 4 below the scanning optics hardware of the four sensors is compared. The VIIRS design is an advancement based upon the experience from heritage sensors. The VIIRS has RTA that is chosen because of the need to have better scattered light control than MODIS because of VIIRS higher altitude orbit to cover the earth in a day. Also the HAM rotates at half the angle in VIIRS and reduces the scan angle effects on the sensor response compared to the paddle mirror in MODIS as discussed in Reference [19].

Table 4. Comparison of the radiometer optics.

MODIS	VIIRS	GOES Imager	GOES-R ABI
Passive Cross-track imaging radiometer	Passive Cross-track imaging radiometer	Passive staring imaging radiometer	Passive staring imaging radiometer
Two sided beryllium paddle wheel scan mirror continually rotates at 20.3 rpm (1.478 s for each mirror side).	Scanning telescope: RTA (Rotating telescope assembly) projecting on to a half angle mirror (HAM). The RTA continuously rotates at constant speed taking 1.7864 s per revolution and is synchronized with the HAM once per scan.	Scan mirror that alternately sweeps east to west and west to east perpendicular to a north south path to direct the beam to a Casegrain telescope. Full disk scan interval 30 min	N/S scanning mirror reflection scanned by E/W mirror to the fore-optics (Off-Axis Four Mirror Assembly (FMA) Telescope. Independent N/S and E/W scanners. E/W raster scan rate 1.4 degree/Section Full disk scan interval 5 min.

The GOES-R ABI has 2-mirror scanner design that is unique with its capability to scan many ways that is not possible in the GOES heritage sensor architecture. The major difference is GOES-R ABI uses a raster scan that allows collection of all data in one scan direction. The scan from one point to another point is called a swath and the image collection is swath based. The time interval across swath boundary is constant. The swaths can be chosen to cover the full disk or a commanded area to be observed (CONUS) or meso scale scene or other choices.

Tables 5 and 6 show the comparison of various other features of the sensor calibration algorithms of TEB and RSB respectively.

Table 5. Comparison of various features of Emissive band calibration of the four sensors.

Feature	MODIS	VIIRS	GOES Imager	GOES-R ABI
Instrumentation temperature dependency	Yes	Yes	No (Calibration algorithm). Yes (for corrections)	No
Scan mirror Radiance considered	Yes	Yes	Yes	Yes (Both East/West and North/South mirrors)
Scan mirror housing cavity	Yes	Yes	No	No
Telescope Radiance considered	No Need	Yes	No Need	No Need
Calibration function	Quadratic with offset	Quadratic with offset	Quadratic with offset (before space view subtraction)	Quadratic (Offset cancelled by space view)
On-orbit Calibration Coefficients updated	Linear coefficient (Offset and non-linear terms from LUTs updated from on orbit BB warm up and cool down cycles)	Scale Factor F to update calibration coefficients provided in the LUTs (Offset and non-linear terms from LUTs updated from on orbit BB warm up and cool down cycles)	Calibration coefficients determined on orbit	Linear Coefficient is updated and LUT provides quadratic coefficient and no offset

Table 5. *Cont.*

Feature	MODIS	VIIRS	GOES Imager	GOES-R ABI
Spectral Response Function (SRF)	Pre-launch	Pre-launch	Prelaunch (Corrections using GSICS LEO comparison [31,32]	Pre-launch
Band averaged spectral radiance	LUT generated using SRF	LUT generated using SRF	Approximate formulas generated using Planck and SRF.	LUT generated using SRF
Response *versus* mirror scan angle	Pre-launch Post-launch verification–Update once done for TERRA Deep Space maneuver)	Pre-launch and on-orbit verification (Pitch Maneuver)	Determined using on orbit space look data at various angles and laboratory witness sample data for 45° scan angle.	Pre-launch (potential on-orbit verification)
Calibration Interval	Scan-by scan	Scan-by-scan for single Gain bands. Dual gain M13 band Low gain LUT on-orbit update.	Blackbody 30 min; Space view 2.2 s, or 36.6 s	5–15 min

Table 6. Comparison of various features of RSB calibration of the four sensors.

Feature	MODIS	VIIRS	GOES Imager	GOES-R ABI
Instrumentation temperature dependency	Yes	Yes	No	No
Detector temperature dependency	Yes (detector temperatures are correlated with instrument temperatures)	Yes	No	No
Calibration function	Linear without offset	Quadratic with offset	Linear with offset	Quadratic (Offset cancelled by space view)
On-orbit Calibration Coefficient	Linear coefficient based on calibration by Solar Diffuser	Scale Factor F using Solar Diffuser calibration to update Calibration coefficients provided in the LUTs	Calibration coefficients are being updated monthly by vicarious calibration using collocated Terra MODIS cloud observations since 2005.	Linear Coefficient using solar Diffuser Calibration and also using LUT
Spectroradiometric Calibration assembly Sector (SRCA)	Yes	No	No	No
Spectral Response Function (SRF)	Pre-launch and on orbit verification using SRCA	Pre-launch	Prelaunch	Pre-launch
Response *versus* mirror scan angle	Post Launch on–orbit using moon or earth view	Pre-launch (Pitch maneuver—on-orbit verification)	No	Pre-launch (potential on-orbit verification)
Lunar Calibration	Yes	Yes	Yes	Yes
Solar Diffuser Stability Monitor (SDSM)	Yes	Yes	Not Applicable as No Solar Diffuser	No
Solar Diffuser (SD) Calibration Interval	Weekly to tri-weekly	Daily	No SD	Weekly to monthly
SD–Vignette Function (VF) of Partial Aperture (PA)	Averaged VF Pre-launch, and on-orbit verification	Band-dependent VF Pre-launch (Updated on orbit)	No SD	Partial Aperture Pre-launch
Solar Irradiance data	3 data sets; (0.4 to 0.8 µm [46]; 0.8 to 1.1 µm [47]; Above 1.1 µm [48].	MODTRAN 4.3 [49]	Bishop and Rossow [50]	4 data sets; 0.4 to 1.2 µm [47]), 033 to 1.25 µm [50]; 1.2 to 100 µm [51]; 0.2 to 10.1 µm, [52].

5. Conclusions

The review shows that the calibration algorithm harmonization facilitated by NOAA NCC, accounting for all the contributions to the radiometric signal based on SI traceable measurements from pre-launch to post launch is being implemented at NOAA/NESDIS/STAR following the best practice guidelines going from MODIS to VIIRS and GOES to GOES-R ABI. The new sensors VIIRS and GOES-R ABI have SI traceable standards for on-orbit radiometric calibration having the methodology evolved from lessons learned from the legacy sensors MODIS and GOES. However, it is an open question to see how the assumption made in neglecting the background reflection from the blackbody in GOES-R ABI holds on orbit.

The critical component that leads to uncertainty in on-orbit measurements is the scanning mirror temperature and its reflectance. In Terra MODIS the RVS (scan angle dependence of the scanning mirror reflectance) had to be measured on-orbit with a deep space maneuver of the spacecraft as discussed in Section 2.1.3. The follow up Aqua MODIS pre-launch characterization based on Terra experience was more thorough and the RVS problem was thus mitigated. Current S-NPP VIIRS SST data during WUCD of the on-board blackbody is being shown as anomalous compared to GSICS based comparisons to other sensors. The WUCD of the blackbody is carried out quarterly and the discrepancy noticed is consistent in the time series. Currently this issue is under investigation by the VIIRS SDR team. Lessons learned in resolving this issue could help the upcoming VIIRS operational sensor on Joint Polar Satellite System (JPSS) satellite missions JPSS -1 and JPSS-2 to eliminate the problem.

The GOES-R ABI optical setup has dual scanning mirrors with advanced scanning capabilities and their RVS was measured pre-launch to meet stringent requirements to provide reliable data as LUTs and should provide accurate data base to mitigate anomalies. The legacy experience of GOES sensor in this regard as discussed in Section 3.1.3 gave a solid base in the design of GOES-R ABI and its calibration algorithm. The blackbody temperature is controlled to one operating temperature and the scanning environment is effectively shielded from spurious reflections and heating effects, thus reducing the possibility of diurnal variation and midnight anomaly (Section 3.1.3) experienced in GOES. The limited data available from Himawari-8 AHI the equivalent of GOES-R ABI largely support the expected on-orbit performance of GOES-R ABI. However, including the possibility of background reflection from the blackbody in the calibration algorithm would have been better to start with for possible use if needed.

The best practice guidelines give equal importance to both pre-launch and post launch testing and monitoring of SI traceability of measurements. Both VIIRS and GOES-R ABI are following the best practice guidelines. For RSB, the VIIRS calibration algorithm is similar to MODIS and the VIIRS SD degradation issue was closely monitored using the MODIS data for inter comparison under GSICS methodology. There is no SDSM in GOES-R ABI and the calibration algorithm uses lunar observations for SD stability monitoring besides taking the precaution that the SD is exposed to Sun only during RSB calibration. The RSB observations of Himawari-8 AHI show thus far that the sensor is largely following expectations; although anomalies due to some scattered light issues are being discussed in private meetings.

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Appendix

The radiometric symbols, terminology and methodology in the calibration algorithms of sensors reviewed in this article mostly follow self explanatory common usage. However, Table A1 below shows a few specific exceptions.

Table A1. Few differences in symbols, terminology and methodology across sensors.

Terminology	Symbols			
	MODIS	**VIIRS**	**GOES/Imager**	**GOES-R ABI**
Radiance	L	L	R	L
Detector output (counts) used in the Calibration equation	The difference in counts between sensor view of an object and space view.	The difference in counts between sensor view of an object and space view.	Detector response in Counts.	The difference in counts between sensor view of an object and space view.
(*SV = Space View*)	$dn = \mathrm{DN} - \mathrm{DN}_{SV}$	$dn = DN - \overline{DN_{sv}}$	X	$\Delta C = C - C_{sv}$.

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