Solar Irradiance and Effective Brightness Temperature for SWIR Channels of AVHRR/NOAA and GOES Imagers

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ABSTRACT

Satellite observations in the shortwave infrared (SWIR) part of spectrum between 3.5 and 4.0 μm deliver critically important information for many applications. The satellite signal in this spectral band consists of solar-reflected radiation and thermal radiation emitted by surface, clouds, and atmosphere. Accurate retrievals require precise knowledge of solar irradiance values within a channel’s bandwidth. The magnitudes of solar irradiance for shortwave infrared channels (3.7–3.9 μm) for the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic and Atmospheric Administration-7 (NOAA-7) to NOAA-18 satellites and the Geostationary Operational Environmental Satellite-8 (GOES-8) to GOES-12 are considered in this paper. Four recent solar reference spectra [those of Kurucz, Gueymard, the American Society for Testing and Materials (ASTM), and Wehrli] are analyzed to determine uncertainties in the knowledge of solar irradiance values for SWIR channels of the listed sensors. Because thermal radiation is frequently converted to effective blackbody temperature for analysis, computations, and calibration purposes, it is proposed here to express band-limited solar irradiance values in terms of brightness temperature as well. It is shown that band-limited solar irradiance for AVHRR radiometers expressed in terms of blackbody equivalent brightness temperature correspond to the range 355–360 K, and vary around 345 K for the SWIR channels of the GOES imagers. The values of band-limited solar irradiance and brightness temperatures are provided for various reference solar spectra. The relative differences in band-limited solar irradiance computed for the considered reference solar spectra are between 0% and 2.5%. Differences expressed in terms of brightness temperatures may reach 0.8 K. The results for the ASTM and the Kurucz reference spectra agree within 0.1% relative difference. Parameters of linear fits relating effective brightness temperatures and spectral radiance equivalent temperatures are also determined for all sensors. They are required for precise radiance–temperature and temperature–radiance conversion through Planck’s functions in the case of the finite spectral response of real sensors.

1. Introduction

Satellite observations in the shortwave infrared (SWIR) spectral region between 3.5 and 4.0 μm are important for many applications, such as cloud retrievals, sea surface and land surface temperature determination, wildfire detection, albedo, emissivity, and land cover mapping among others (Cracknell 1997; Kidwell 1998; Cihlar et al. 2004). The radiative energy observed by a satellite sensor in this spectral band during daytime conditions consists of solar-reflected and thermal-emitted components with comparable magnitudes. For a particular frequency ν, the amount of reflected spectral radiative energy \( R(ν) \) is proportional to the pixel reflectance \( \rho(ν) \) and incoming solar radiation \( S_0(ν)\mu_0 \) at the top of the atmosphere (TOA). Variable \( \mu_0 \) denotes the cosine of the solar zenith angle (SZA). The outgoing emitted thermal radiation \( E(ν) \) is proportional to the pixel emissivity \( e(ν) \) and thermodynamic temperature \( T \) of the emitting surface. Thus, to derive a pixel reflective \( R(ν) \) or emitted radiative energy \( E(ν) \), one needs to separate these components in the total signal \( L(ν) \). Thus, the reflected solar radiative energy is given by

\[
R(ν) = L(ν) - E(ν).
\]

Due to the finite spectral response of the instrument, the monochromatic equation must be replaced by inte-
gration over the spectral interval of the spectral response function \( f(\nu) \) to derive in-band values:

\[
L = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu)L(\nu) \, d\nu,
\]

\[
R = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu)R(\nu) \, d\nu,
\]

and

\[
E = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu)E(\nu) \, d\nu,
\]

where \( \nu_{\text{min}} \) and \( \nu_{\text{max}} \) are the minimum and maximum wavenumbers, respectively, for the spectral response function. Equation (1) then becomes

\[
R = L - E. \tag{1'}
\]

It is a common practice to use brightness temperature for satellite measurements in the thermal infrared region. The standard units are reflectance or albedo for the satellite data in the wavelength region less than 2 \( \mu \text{m} \). Although the SWIR region from 3.5 to 4.0 \( \mu \text{m} \) encompasses a region where reflected and emitted components have similar magnitude, frequently the satellite measurements in this region are also converted into brightness temperatures without concern for the solar-reflected component. Another reason why it is convenient to use the brightness temperatures in the SWIR region from 3.5 to 4.0 \( \mu \text{m} \) is the onboard calibration, which is conducted by means of blackbody calibration targets of a known temperature (Cracknell 1997; Trishchenko and Li 2001; Trishchenko 2002; Trishchenko et al. 2002b).

While the use of brightness temperature in the SWIR regions became a common practice, there was little attempt of systematic analysis of solar irradiance values and their magnitude and uncertainty in terms of effective brightness temperature for operational satellite sensors in this spectral region. Published results are fragmentary and not always consistent (Roger and Vermote 1998).

An attempt is made in this paper to fill this gap and to provide recommendations on how to parameterize the solar component in the SWIR region in terms of brightness temperature. This parameterization makes analysis and computations easier and physically more justified because similar physical terms or parameter units are compared for both solar-reflected and thermal-emitted components.

The finite width of the spectral response function of real sensors requires careful consideration to achieve precise results in temperature–radiance conversion using the monochromatic Planck’s equation. The relationship between effective blackbody brightness temperature and spectral radiance equivalent blackbody brightness temperature is considered and analytical parameterizations for the difference between these temperatures are provided for a number of operational satellite sensors in the SWIR spectral region. This analysis updates the National Atmospheric and Oceanic Administration (NOAA) recommendations for radiance–temperature conversion for Advanced Very High Resolution Radiometer (AVHRR)/3 SWIR channels and introduces this technique for AVHRR/2 and AVHRR/1 types of sensors. The NOAA recommendations are available from the NOAA Polar Orbiter User’s Guide (Kidwell 1998; Goodrum et al. 2000).

The paper is structured as follows. Section 2 contains a general discussion about solar and thermal spectra. Section 3 analyzes the definition of effective brightness temperature and spectral radiance equivalent brightness temperature for monochromatic and nonmonochromatic (finite spectral response function) cases. Section 4 considers spectral response function features of SWIR channels of AVHRR for NOAA and Geostationary Operational Environmental Satellite (GOES) imagers. Section 5 discusses how to separate thermal and solar components in total SW signal. Section 6 presents an analysis of solar irradiance values and equivalent brightness temperatures for AVHRR and GOES imager SW channels. Section 7 analyzes the effect of solar zenith angle and pixel albedo on the magnitude of brightness temperature of the solar-reflected component. Section 8 presents an analysis of the quantitative relationship between effective blackbody brightness temperature and spectral radiance equivalent brightness temperatures and provides the coefficients of a linear regression of the difference between these two temperatures.

### 2. Solar spectrum

Detailed knowledge of the solar spectrum is required to obtain the band-limited solar irradiance \( S_0 \) and equivalent brightness temperatures \( T_S \) of the radiation reaching the top of the atmosphere (TOA). There are several solar spectra currently in use. The Calibration and Validation (CALVAL) Working Group of the Committee on Earth Observation Satellites (CEOS) (Ungar and Desnos 2004) has recently recommended the solar spectrum of Thullier et al. (2003). This spectrum, however, does not cover the spectral region beyond 2.4 \( \mu \text{m} \). Four spectra that cover the entire range up to 4.0 \( \mu \text{m} \) are those by Wehrli (1985), Kurucz (2005), the American Society for Testing and Materials (ASTM 2000), and the recently published spectrum described by Gueymard (2004). The Kurucz spectrum is
widely used by the atmospheric radiation modeling community through the MODTRAN atmospheric radiative transfer model. The Kurucz spectrum employed in our study was taken from the MODTRAN 4 package (Berk et al. 1998). There are also some older solar spectra published prior to 1985 that cover the wavelength range greater than 2.5 \(\mu\)m such as Labs and Neckel (1968), Neckel and Labs (1984), Thekaekara (1974), and others. However, we will not use them here assuming that the recent data are of better accuracy.

Comprehensive intercomparisons of many spectra have been conducted by Thuillier et al. (2004) and Gueymard (2004). These analyses indicated that the commonly accepted value of the total solar irradiance (TSI) is 1366.1 W m\(^{-2}\) (Gueymard 2004; Fröhlich 2004), although there are still differences of a few percent level between various reference spectra at various wavenumbers. Since the Kurucz solar spectrum from MODTRAN 4 has slightly larger TSI value by \(-0.1\%\), it was normalized in this paper by applying a constant factor at each wavelength to get a TSI of 1366.1 W m\(^{-2}\). The recent measurements reported by the Solar Radiation and Climate Experiment (SORCE) satellite project team for TSI (Kopp 2005) indicate somewhat lower TSI values than mentioned by Gueymard (2004) and Fröhlich (2004).

Table 1 provides a summary of solar irradiance for several typical wide spectral bands computed from five solar reference spectra. Spectral bands of 1-\(\mu\)m width beyond the \(\lambda > 1\ \mu\)m region were considered. In the wavelength region \(\lambda < 1\ \mu\)m, three spectral bands were selected: 0.2–0.4, 0.4–0.7 (photosynthetically active radiation, PAR), and 0.7–1 \(\mu\)m. Two broadband intervals, total shortwave (SW) (0.2–5.0 \(\mu\)m) and total (shortwave + longwave) (<100 \(\mu\)m), were also included. The relative difference for each spectral band is plotted in Fig. 1 for four reference spectra: Gueymard (2004), ASTM (2000), Wehrli (1985), and Thuillier et al. (2003). The comparison for the last spectrum is limited to the range of 0.2–2 \(\mu\)m. Relative differences are defined with respect to the MODTRAN 4 Kurucz solar spectrum (Kurucz 2005) normalized as described above. In the shortwave region, relative differences between the five spectra vary from -6\% to +2.5\%. In the

TABLE 1. Comparison of the total solar energy in several bands for different reference spectra.

<table>
<thead>
<tr>
<th>Spectral band ((\mu)m)</th>
<th>Kurucz* W (W m(^{-2}))</th>
<th>Gueymard W (W m(^{-2}))</th>
<th>ASTM W (W m(^{-2}))</th>
<th>Wehrli W (W m(^{-2}))</th>
<th>Thuillier et al. W (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2–0.4</td>
<td>112.48</td>
<td>110.77</td>
<td>106.51</td>
<td>107.79</td>
<td>111.37</td>
</tr>
<tr>
<td>PAR (0.4–0.7)</td>
<td>532.10</td>
<td>534.64</td>
<td>530.12</td>
<td>530.84</td>
<td>529.14</td>
</tr>
<tr>
<td>0.7–1.0</td>
<td>308.22</td>
<td>308.60</td>
<td>311.18</td>
<td>308.74</td>
<td>307.79</td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>328.51</td>
<td>328.90</td>
<td>333.62</td>
<td>337.57</td>
<td>332.84</td>
</tr>
<tr>
<td>2.0–3.0</td>
<td>57.45</td>
<td>56.93</td>
<td>57.36</td>
<td>54.38</td>
<td>—</td>
</tr>
<tr>
<td>3.0–4.0</td>
<td>15.46</td>
<td>15.19</td>
<td>15.46</td>
<td>14.96</td>
<td>—</td>
</tr>
<tr>
<td>4.0–5.0</td>
<td>5.60</td>
<td>5.25</td>
<td>5.63</td>
<td>5.55</td>
<td>—</td>
</tr>
<tr>
<td>SW (0.2–5.0)</td>
<td>1359.8</td>
<td>1360.3</td>
<td>1359.9</td>
<td>1359.8</td>
<td>—</td>
</tr>
<tr>
<td>5.0–6.0</td>
<td>2.56</td>
<td>2.35</td>
<td>2.50</td>
<td>2.46</td>
<td>—</td>
</tr>
<tr>
<td>6.0–7.0</td>
<td>1.35</td>
<td>1.23</td>
<td>1.30</td>
<td>1.28</td>
<td>—</td>
</tr>
<tr>
<td>7.0–8.0</td>
<td>0.77</td>
<td>0.70</td>
<td>0.75</td>
<td>0.73</td>
<td>—</td>
</tr>
<tr>
<td>8.0–9.0</td>
<td>0.47</td>
<td>0.43</td>
<td>0.45</td>
<td>0.44</td>
<td>—</td>
</tr>
<tr>
<td>9.0–10.0</td>
<td>0.31</td>
<td>0.28</td>
<td>0.30</td>
<td>0.29</td>
<td>—</td>
</tr>
<tr>
<td>&gt;10.0</td>
<td>0.83</td>
<td>0.75</td>
<td>0.79</td>
<td>0.84</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td>1366.1</td>
<td>1366.1</td>
<td>1366.1</td>
<td>1366.0</td>
<td>—</td>
</tr>
</tbody>
</table>

* The original Kurucz spectrum was normalized to get TSI 1366.1 W m\(^{-2}\).
3–4-μm spectral region, the ASTM and Kurucz spectra are very close to each other. The Gueymard spectrum is on average ~1.75% lower, and the Wehri spectrum about 3.2% lower than the Kurucz one. The relative differences in the λ > 5 μm region are from nearly −10% to +12%. Although they look quite large, due to the overall small magnitude of the solar-reflected component relative to the terrestrial thermal emitted component in the spectral region above 5 μm, this discrepancy is of less concern. The differences in the 0.2–0.4-, 1–2-, and 2–3-μm spectral regions are of much greater concern. These relative differences range from −1% to −5.3% in the 0.2–0.4-μm spectral band. The relative differences in the PAR spectral band are within ±0.5%. In the 0.7–1-μm region, the differences are from −0.1% to +1%. Relative differences vary from +1.3% to 2.8% in the 1–2-μm region and from −0.1% to −5.3% in the 2–3-μm region. Such a large disagreement between reference solar spectra may have quite important consequences for many remote sensing applications related to aerosol, cloud, and land parameter retrievals.

3. Effective brightness temperature of the solar radiation

Another way of assessing the amount of energy in the solar spectrum is to convert the spectral radiance into equivalent brightness temperatures. For monochromatic radiation, this is achieved by the simple inversion of Planck’s formula:

\[ B(\nu, T) = \frac{c_1 \nu^3}{\exp\left(\frac{c_2 \nu}{T}\right) - 1} \]

where \( c_1 = 1.191 \, 042 \, 7 \times 10^{-8} \) (W m\(^{-2}\) sr\(^{-1}\) cm\(^{-4}\)) is the first radiation constant for spectral radiance, and \( c_2 = 1.438 \, 775 \, 2 \) (cm K\(^{-1}\)) is the second radiation constant for spectral radiance.

By inverting this formula, the temperature \( T \) can be easily obtained as

\[ T = B^{-1}(\nu, E) = \frac{c_2 \nu}{\ln\left(\frac{1 + c_1 \nu^3}{E}\right)} \]

where \( E \) is the spectral radiance.

The solar spectrum in terms of brightness temperature is shown in Fig. 2. Results are shown for the Kurucz solar spectrum normalized to 1366.1 W m\(^{-2}\) as explained in section 2 of the text. Black curves correspond to the sun’s brightness temperature at the TOA. Red curves correspond to the brightness temperatures of the sun’s surface computed as

\[ T = B^{-1}(\nu, E) = \frac{c_2 \nu}{\ln\left(\frac{1 + c_1 \nu^3}{E}\right)} \]

where \( r_s \) is the radius of the sun, equal to 6.96 \times 10^5 km, and \( R_{\text{E-S}} \) is the average distance between the earth and the sun, that is, 1 astronomical unit (AU) equal to 1.495 9787 \times 10^8 km. Figure 2a shows the entire spectral range. Figure 2b shows the details in the SWIR part of the solar spectrum from 2.75 to 4.5 μm. The temperatures computed using Eq. (5) are between 5000 and 6000 K. The typical brightness temperatures in the vicinity of 3.75 μm at the TOA level are around 350–360 K.

Fig. 2. Effective brightness temperature of the solar radiation at the TOA (black) and the sun’s surface (red): (a) the entire solar spectrum in SW and thermal regions and (b) the SWIR interval (2.75–4.5 μm). Scale plotted in black is for black lines; scale plotted in red is for red lines. Results are shown for the Kurucz solar spectrum normalized to 1366.1 W m\(^{-2}\) as explained in section 2 of the text.
The relationship between radiance and brightness temperature for the nonmonochromatic case with an arbitrary spectral distribution of the radiance \( L(\nu) \) and spectral response function \( f(\nu) \) is defined by the following expression:

\[
L = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu) L(\nu) \, d\nu = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu) B(\nu, T_{\text{eff}}) \, d\nu,
\]

where \( T_{\text{eff}} \) is the effective brightness temperature of the blackbody radiance field. For the entire unfiltered spectrum [i.e., \( f(\nu) = 1 \)] expression (5) is reduced to Stefan–Boltzmann’s law:

\[
L = \sigma T_{\text{eff}}^4,
\]

where \( \sigma = 5.6703 \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\).

The values of the effective brightness temperature for the spectral bands listed above are given in Table 2. Table 2 contains the same spectral bands as Table 1 and provides effective brightness temperatures at the TOA and the sun’s surface computed according to Eq. (6) with a rectangular spectral response function. The effective brightness temperature for the entire solar spectrum at the sun’s surface is around 5778 K. However, effective temperatures at the TOA are significantly different. Effective temperatures decrease from about 2230 K in the 0.2–0.4-μm region to around 300 K at 5 μm and as low as 65 K at 10 μm. One can see that the TOA solar brightness temperatures in the SWIR region are of the order of magnitude as the temperature for typical terrestrial scenes.

Equation (6) for band-integrated irradiances can be transformed into an equation for band-average spectral irradiances by simple normalization:

\[
L = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu) L(\nu) \, d\nu = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu) B(\nu, T_{\text{eff}}) \, d\nu = \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu) \, d\nu
\]

Therefore, the effective brightness temperature \( T_{\text{eff}} \) is the temperature of a blackbody that emits an equivalent amount of radiant energy within a spectral band characterized by the spectral response function \( f(\nu) \). In the case of the average spectral radiance \( \bar{L} \) described by Eq. (8), one needs to specify the central wavenumber value \( \nu_c \) and temperature \( T^* \) to compute this quantity from Planck’s equation. One possible approach to solving Eq. (6) or Eq. (8) is to assume that

\[
T^* = T_{\text{eff}}.
\]

Using Eq. (9), one can derive the value for \( \nu_c \) from Eqs. (4) and (8). This approach ensures that the same temperature value is used in Planck’s function in all parts of Eq. (8). However, this definition depends on the spectrum \( L(\nu) \) and may lead to different \( \nu_c \) for different spectra.

It is, therefore, more convenient to define a constant central wavenumber \( \nu_c \) in a traditional sense as the first moment:

\[
\bar{\nu} = \frac{\int_{\nu_{\text{min}}}^{\nu_{\text{max}}} \nu f(\nu) \, d\nu}{\int_{\nu_{\text{min}}}^{\nu_{\text{max}}} f(\nu) \, d\nu}
\]
With this definition, the central wavenumber is defined by the shape and location of the spectral response function and is an instrument-related parameter. However, it is not guaranteed that $T^*$ is equal to $T_{eff}$. This issue will be discussed later in this paper.

4. Spectral response functions for SWIR channels of AVHRR and GOES imagers

Although spectral response functions for the same instrument type (AVHRR or GOES imager) are similar, they are not identical. Each sensor’s spectral response needs to be treated separately, similar to optical channels (Trishchenko et al. 2002a). The instrument spectral response functions of the sensors analyzed in this study are shown in Fig. 3. We considered several AVHRRs on board NOAA satellites NOAA-7 to -18 and imagers on GOES-8 to -12. The SWIR channels for the AVHRR/1 and AVHRR/2 types of sensors (i.e., prior to NOAA-15) are called channel 3. The SWIR channels of the AVHRR/3-type instrument (NOAA-15 and follow-on platforms) are called channel 3B, as there is a satellite programming option to receive channel 3A (1.6 μm) or 3B (3.75 μm) data. The term 3B is used here on for all AVHRR 3.7-μm channels for consistency.

The tables of spectral response functions used in this paper were taken from several NOAA Web sites (http://www2.ncdc.noaa.gov/docs/podug/html/c1/sec1-4.htm, http://www2.ncdc.noaa.gov/docs/klm/html/d/app-d.htm, and http://www.oso.noaa.gov/goes/goes-calibration/goes-imager-srfs.htm) and the International Satellite Cloud Climatology Project (ISCCP) Web site (http://isccp.giss.nasa.gov/docs/response.html). The AVHRR instruments typically have a wider spectral response than the GOES imagers. On average, spectral response functions for the GOES imager SWIR channels are shifted toward longer wavelengths. Altogether, there are four groups among SWIR channel of the AVHRR sensors (AVHRR/NOAA-7, -9, -10, -11; AVHRR/NOAA-8, -12, -14; AVHRR/NOAA-15 and -16; and AVHRR/NOAA-17 and -18). All SWIR channels for GOES imagers fall under the same generic group. The differences between central wavelengths of AVHRR instruments are small, although there are some differences between shapes of the spectral response functions. The central wavelengths for the AVHRR sensors are around 3.70–3.75 μm, while GOES imagers have central wavelengths around 3.90 μm.

The central wavenumbers $\nu_c$ computed in this paper according to Eq. (10) are given in the Table 3. To compute $\nu_c$ we interpolated the spectral response function $f(\nu)$ to a regular grid in wavenumber space at a spectral resolution of 1 cm$^{-1}$ and calculated the integrals as simple sums:

$$\nu_c = \frac{\int_{\nu_{min}}^{\nu_{max}} f(\nu) \nu \, d\nu}{\int_{\nu_{min}}^{\nu_{max}} f(\nu) \, d\nu}.$$  \hspace{1cm} (10)

The differences between central wavelengths of AVHRR instruments are small, although there are some differences between shapes of the spectral response functions. The central wavelengths for the

$$\int_{\nu_{min}}^{\nu_{max}} f(\nu)F(\nu) \, d\nu = \sum_{k=k_{min}}^{k_{max}} f(k)F(k).$$  \hspace{1cm} (11)
Note that the central wavenumbers computed according to Eqs. (10)–(11) and listed in Table 3 are not the same as those provided by NOAA for calibration and conversion between radiance and brightness temperature. We provide values computed as the first-order central moments for parameters the first-order central moments for AVHRR/NOAA (3B) and GOES imagers.

5. Separating solar and thermal components in SWIR channels

The general expression for radiance at the TOA level measured by a satellite sensor in the SWIR for the monochromatic case can be written as follows:

\[ L(\nu) = \rho(\nu) \left( \frac{R_{\text{AL}}}{R_{\text{ES}}} \right)^2 S_{\odot}(\nu) \mu_0 + e(\nu)B(\nu, T), \]

where \( \rho(\nu) \) is the pixel reflectance, \( S_{\odot}(\nu) \) is the solar irradiance, \( \mu_0 \) is the cosine of the solar zenith angle.
is the distance between the earth and the sun in Eq. (12) is the average distance between the earth and the sun, where $R_{\text{AU}}$ is the average distance between the earth and the sun, equal to 1 AU, and $R_{E-S}$ is the distance between the earth and the sun at any particular moment. It is assumed in Eq. (12) that the solar irradiance $S_0(v)$ is provided for the nominal distance of 1 AU.

Assuming a radiative equilibrium for a particular pixel, one can relate reflectance and emissivity as

$$\varepsilon(v) + \rho(v) = 1. \quad (13)$$

For the nonmonochromatic case, the integration of Eqs. (12) and (13) over a finite spectral interval is required:

$$\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) L(v) \, dv = \int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \left( \rho(v) \left[ \frac{R_{\text{AU}}}{R_{E-S}} \right]^2 S_0(v) \mu_0 + \varepsilon(v) B(v, T) \right) \, dv \quad (12')$$

$$\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) (\varepsilon(v) + \rho(v)) \, dv = \int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \, dv. \quad (13')$$

The normalization by $\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \, dv$ reduces the above equations to expressions for band-average quantities:

$$\bar{L} = \overline{\rho} \left[ \frac{R_{\text{AU}}}{R_{E-S}} \right]^2 S_0 \mu_0 + \overline{\varepsilon} \overline{B}(T) \quad \text{and} \quad (12')$$

$$\overline{\varepsilon} + \overline{\rho} = 1. \quad (13')$$

where

$$\overline{S_0} = \frac{\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) S(v) \, dv}{\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \, dv}, \quad (14)$$

and we assume that $\rho(v)$ and $\varepsilon(v)$ vary slowly so that

$$\rho(v) \approx \text{const} = \overline{\rho} \quad \text{and} \quad (15)$$

$$\varepsilon(v) \approx \text{const} = \overline{\varepsilon}. \quad (16)$$

The average value for the blackbody function $\overline{B}(T)$ is defined as

$$\overline{B}(T) = \frac{\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) B(v, T) \, dv}{\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \, dv}. \quad (16)$$

If $\rho(v)$ and $\varepsilon(v)$ vary significantly over the spectral response function interval, we then assume that

$$\overline{\rho} = \frac{\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \rho(v) S_0(v) \, dv}{\overline{S}_0} \quad \text{and} \quad (15')$$

$$\overline{\varepsilon} = \frac{\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \varepsilon(v) \, dv}{\int_{v_{\text{min}}}^{v_{\text{max}}} f(v) \, dv}, \quad (19')$$

and a similar expression for emissivity can be derived with the solar spectrum replaced by Planck’s function.

For the convenience and effectiveness of computations, all variables $\overline{L}$ and $\overline{S}_0$ in Eq. (12’) can be expressed through Planck’s function at the specified wavenumber $\nu_c$ as

$$\overline{L} = B(\nu_c, T^\nu) = \overline{\rho} \left[ \frac{R_{\text{AU}}}{R_{E-S}} \right]^2 S_0 \mu_0 + \overline{\varepsilon} B(\nu_c, T) \quad (17)$$

The solar irradiance in Eq. (17) is replaced by its parameterization through Planck’s function at temperature $T^\nu_\text{sun}$. Temperature $T^\nu_\text{pix}$ is derived by inversion

$$T^\nu_\text{pix} = B^{-1}(\nu_c, \overline{B}(T)). \quad (18)$$

The temperature $T^\nu_\text{pix}$ is defined as the thermodynamic temperature of a pixel and can be approximated by the temperature $T_{\text{IR}}$ observed in the IR window’s 11–12-μm region. The temperature $T^\nu$ is a pixel spectral equivalent brightness temperature at $\nu_c$ derived from instruments counts as a result of the calibration procedure and Eq. (8). By substituting Eq. (13’) into Eq. (17), the expressions for pixel reflectance and emissivity can be derived as

$$\overline{\rho} = \left( \frac{B(\nu_c, T^\nu) - B(\nu_c, T^\nu_\text{pix})}{\left[ \frac{R_{\text{AU}}}{R_{E-S}} \right]^2 \mu_0 B(\nu_c, T^\nu_\text{sun}) - B(\nu_c, T^\nu_\text{pix})} \right) \quad (19)$$

$$\overline{\varepsilon} = \left( \frac{B(\nu_c, T^\nu) - \left[ \frac{R_{\text{AU}}}{R_{E-S}} \right]^2 \mu_0 B(\nu_c, T^\nu_\text{sun})}{B(\nu_c, T^\nu_\text{pix}) - \left[ \frac{R_{\text{AU}}}{R_{E-S}} \right]^2 \mu_0 B(\nu_c, T^\nu_\text{sun})} \right). \quad (19')$$

Equations (19) and (19’) employ only blackbody functions, thus making analysis and interpretation of the
relative contribution of solar and thermal components more expedient.

6. Solar irradiance and effective brightness temperature for SWIR channels of AVHRR and GOES imagers

The values of solar irradiance and brightness temperatures required in Eqs. (19) and (20) are provided in Table 3 for channel 3B of AVHRR/NOAA-7 to -18 and SWIR channels of GOES-8 to GOES-12 imagers. Computations were performed for several solar spectra: Kurucz (Kurucz 2005; Berk et al. 1998), Gueymard (2004), ASTM (2000), and Wehrli (1985). For each spectrum, Table 3 contains five parameters: central wavenumber $\nu_c$ (in cm$^{-1}$), band-average spectral solar irradiance $S_0$ [in W m$^{-2}$ (cm)$^{-1}$], effective solar brightness temperature $T_{\text{TOA}}^{\text{eff}}$ (in K) computed according to Eq. (6), equivalent solar brightness temperature $T^{*}$ (in K) computed according to Eq. (8), and effective brightness temperature at 1 AU $T_{\text{AU}}^{\text{eff}}$ (in K) computed according to Eqs. (5) and (6). The difference between various reference spectra reflects the current level of uncertainty in the knowledge of the solar spectrum.

The absolute values and relative differences between solar irradiance values computed with different reference spectra are shown in Figs. 4a and 4b, where Fig. 4a shows absolute values and Fig. 4b shows relative differences computed with respect to Kurucz spectrum results. The results for the ASTM spectrum are very close to those of the Kurucz spectrum for all sensors considered. The relative differences between these two spectra are less than 0.1%. Two other spectra show quite substantial relative differences between each other and with respect to the Kurucz and ASTM spectra. For the AVHRR channels, both spectra show close results and relative differences with respect to the Kurucz spectrum results varying from −1.5% to almost −2%. The Gueymard spectrum shows larger differences for GOES imager SWIR channels (up to −2.5%) relative to the Kurucz spectrum results. The Wehrli spectrum reveals the relative difference with respect to the Kurucz spectrum to be −1.2%.

Figure 5 shows solar irradiance values expressed in terms of brightness temperatures $T_{\text{TOA}}^{\text{eff}}$ computed according to Eq. (6). Figure 5a displays absolute values of temperature. The temperatures for AVHRR channel 3B vary from about 354 K to values slightly greater than 360 K. Temperatures for GOES imager SWIR channels are smaller. They are in the range of 342–345 K, that is, by 10–15 K smaller than temperatures for AVHRR channel 3B. The differences in brightness temperatures computed for different reference spectra taken with respect to the Kurucz data are presented in Fig. 5b. The spread ranges from near 0 K to almost −0.8 K. The biggest difference is between the Kurucz and Gueymard spectra. This difference ranges from −0.6 to −0.8 K. The results for the Wehrli reference spectrum are close to those for the Gueymard spectrum for AVHRR channel 3B. The difference between the Wehrli and Kurucz reference spectra for the GOES imager SWIR channels are 0.2 K smaller (−0.4 K instead of −0.6 K). The Gueymard reference spectrum shows the largest differences for GOES SWIR channels (between −0.7 and −0.8 K). The Kurucz and ASTM spectra provide very similar results (within 0.01 K) for all sensors considered.

7. Solar zenith angle and pixel reflectance effect on the magnitude of the brightness temperature

It is interesting to assess the effect of solar zenith angle and pixel reflectance on the magnitude of the effective brightness temperature of the solar-reflected component. Equation (4) has to be modified as
The temperature $T$ of the solar-reflected component is now a function of the cosine of the solar zenith angle $\mu_0$ and pixel reflectance $\rho$.

Figure 6 shows the dependence described by Eq. (4') for two sensors: Fig. 6a AVHRR/NOAA-16 channel 3B and Fig. 6b the GOES-10 SWIR imager channel. These two sensors represent maximum and minimum temperatures and cover the entire range of variability for all sensors considered. Results for seven pixel reflectance levels are shown: 100%, 50%, 20%, 10%, 5%, 1%, and 0.1%. Due to the logarithmic relationship between energy and temperature described by Eq. (4'), the brightness temperature of the solar-reflected component is quite high even for small $\rho$ and large solar zenith angles (low sun elevation). The brightness temperatures for the case of normal incidence and 100% reflection are between 360 and 300 K for SZA up to $85^\circ$. The brightness temperature of the solar-reflected component is larger than 240 K for most sensors up to $70^\circ$–$80^\circ$ of the SZA even for pixel reflectances as small as 1%. The results presented in Fig. 6 indicate that the solar-reflected component in Eq. (1) and Eqs. (12) and (12') is potentially important for all observational conditions. The brightness temperature of the solar-reflected component exceeds or is comparable to typical terrestrial and cloud temperatures for pixel albedo as low as 1% and almost the entire range of the solar zenith angles ($80^\circ$–$85^\circ$).

8. Relationship between blackbody temperature $T_{eff}$ and radiance equivalent temperature $T^*$

For computation purposes, it is easier to use Planck’s equation to compute pixel radiance from pixel bright-
ness temperature or from the blackbody thermodynamic temperature in the case of data calibration than to perform numerical integration according to Eq. (6). However, this convenience comes at a price. The relationship between band-integrated radiance and band-average spectral radiance described by Eq. (8) introduces a new radiance equivalent brightness temperature \( T^* \), which is in general not equal to the effective blackbody brightness temperature \( T_{\text{eff}} \). This temperature also depends on the central wavenumber \( \nu_c \).

The NOAA manuals for AVHRR data processing (Goodrum et al. 2000; Kidwell 1998) for the sensors prior to AVHRR/NOAA-15 recommend using a variable central wavenumber depending on the brightness temperature range and assume an equivalence between \( T_{\text{eff}} \) and \( T^* \). For AVHRR/3 sensors on board NOAA-15 and higher, the NOAA Polar Orbiter User’s Guide recommends a simple linear relationship between the above temperatures and uses a constant central wavenumber across the entire range of temperatures (Goodrum et al. 2000). To take advantage of this latter approach, which provides a simple yet accurate analytic expression for data calibration and radiance-temperature conversion, we applied this method for all sensors considered in this paper. Due to differences in the definition of central wavenumber \( \nu_c \), our coefficients may differ from those provided in the NOAA manuals.

To find the relationship between temperatures \( T_{\text{eff}} \) and \( T^* \), Eq. (8) was solved numerically at 1-K steps for the range of blackbody temperatures \( T_{\text{eff}} \) from 150 to 375 K. The tables of \( T_{\text{eff}}, T^* \), and \( \Delta T = T_{\text{eff}} - T^* \) were then used to derive the fitting parameters \( a \) and \( b \) as

\[
\Delta T = T_{\text{eff}} - T^* = a + bT_{\text{eff}}.
\]  

Examples of fitting results for GOES and AVHRR SWIR channels are presented in Fig. 7. Fitting accuracy is better than 0.01 K for all sensors with the exception of AVHRR/NOAA-16 (Fig. 7c). There is a strong nonlinearity in this case due to a spectral leak at 4.25 \( \mu \)m, mentioned earlier. Linear fitting for AVHRR/NOAA-16 channel 3B provides accuracy within 0.1 K. To achieve better results, a third-degree polynomial is recommended. Parameters \( a \) and \( b \) of the linear fit for all sensors are given in Table 4. A special approximation for AVHRR/NOAA-16 as a third-degree polynomial is also given in Table 4. The difference \( \Delta T \) for this special case is expressed as a function of \( T_{\text{eff}} \) and \( T^* \) for convenience in the radiance to temperature direct and inverse conversion. The differences \( \Delta T \) are negative for all cases; that is, the radiance equivalent temperature \( T^* \) is greater than the effective blackbody temperature \( T_{\text{eff}} \).

9. Summary

Satellite observations in the SWIR part of the spectrum (3–4 \( \mu \)m) are important for many applications related to remote sensing of the surface, atmosphere, and cloudiness. The electromagnetic radiation detected in this part of the spectrum consists of two components: reflected radiation coming from the sun and radiation emitted by the earth atmosphere, clouds, and surface. Due to the different natures of these components, they need to be separated from each other to retrieve information pertinent to specific physical processes in the earth climate system. To separate these components and to carry out accurate retrievals, one needs to know precisely the spectrum of the incoming solar radiation. This paper analyses information about the SWIR solar spectrum and its representation in terms of equivalent brightness temperature in detail. Representation of the
Table 4. Coefficients of linear fit for temperature correction \( \Delta T = T_{\text{eff}} - T^s = a + b \ T_{\text{eff}}. \)

<table>
<thead>
<tr>
<th>Sensors</th>
<th>( a ) (K)</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVHRR/NOAA-7</td>
<td>-1.962 37</td>
<td>0.002 61</td>
</tr>
<tr>
<td>AVHRR/NOAA-8</td>
<td>-1.769 76</td>
<td>0.002 42</td>
</tr>
<tr>
<td>AVHRR/NOAA-9</td>
<td>-1.902 03</td>
<td>0.002 51</td>
</tr>
<tr>
<td>AVHRR/NOAA-10</td>
<td>-1.816 48</td>
<td>0.002 43</td>
</tr>
<tr>
<td>AVHRR/NOAA-11</td>
<td>-1.817 75</td>
<td>0.002 39</td>
</tr>
<tr>
<td>AVHRR/NOAA-12</td>
<td>-1.936 14</td>
<td>0.002 57</td>
</tr>
<tr>
<td>AVHRR/NOAA-14</td>
<td>-2.030 23</td>
<td>0.002 67</td>
</tr>
<tr>
<td>AVHRR/NOAA-15</td>
<td>-1.636 03</td>
<td>0.002 32</td>
</tr>
<tr>
<td>AVHRR/NOAA-16</td>
<td>-2.292 04</td>
<td>0.003 66</td>
</tr>
<tr>
<td>AVHRR/NOAA-17</td>
<td>-1.721 94</td>
<td>0.002 27</td>
</tr>
<tr>
<td>AVHRR/NOAA-18</td>
<td>-1.747 67</td>
<td>0.002 28</td>
</tr>
<tr>
<td>GOES-8</td>
<td>-0.635 44</td>
<td>8.9023E-4</td>
</tr>
<tr>
<td>GOES-9</td>
<td>-0.589 16</td>
<td>8.363 25E-4</td>
</tr>
<tr>
<td>GOES-10</td>
<td>-0.625 81</td>
<td>8.877 43E-4</td>
</tr>
<tr>
<td>GOES-11</td>
<td>-0.631 31</td>
<td>8.991 83E-4</td>
</tr>
<tr>
<td>GOES-12</td>
<td>-0.695 39</td>
<td>9.7593E-4</td>
</tr>
</tbody>
</table>

* Correction is nonlinear due to a spectral leak near 4.25 \( \mu \text{m} \) for channel 3B of AVHRR/NOAA-16. Linear fit provides accuracy within 0.1 K. Third-degree polynomial is recommended to achieve better-fitting accuracy: \( \Delta T(\ T_{\text{eff}}) = -3.3430 \ 54 + 0.015 \ 66T_{\text{eff}} - 3.928 \ 16 \times 10^{-3}T_{\text{eff}}^2 + 4.021 \ 98 \times 10^{-5}T_{\text{eff}}^3 \) and \( \Delta T(T^s) = -3.4737 + 0.015 \ 98 \ T^s - 4.010 \ 54 \times 10^{-3}(T^s)^2 + 4.094 \ 38 \times 10^{-5}(T^s)^3. \)

solar spectrum in terms of brightness temperature makes the analysis of emitted and reflected components more efficient and convenient.

Several recent solar reference spectra have been analyzed to determine the range of uncertainty in the knowledge of solar irradiance for the satellite SWIR channels for AVHRR/NOAA-7 to -18 and imagers on GOES-8 to -12. Solar irradiance values, effective brightness temperatures, and spectral radiance equivalent temperatures are provided for these sensors. The sensor band average spectral irradiances vary from approximately \( 1.60 \times 10^{-2} \ \text{W m}^{-2} \ (\text{cm})^{-1} \) to approximately \( 1.41 \times 10^{-2} \ \text{W m}^{-2} \ (\text{cm})^{-1} \) depending on the sensor spectral response function and the solar reference spectrum. While there is a commonly accepted value of the total solar irradiance (1366.1 \( \text{W m}^{-2} \)), the difference between various solar reference spectra might be quite significant for selected spectral bands. For the SWIR channel, this uncertainty amounts to approximately 2.5%. In terms of brightness temperature, this difference can be as large as 0.8 K. Among four solar reference spectra considered in this paper, the Kurucz and ASTM spectra are similar to each other within 0.1% relative difference. The Wehrli and Gueymard spectra give smaller solar irradiances (from -1.2% to approximately -2.5%) than the Kurucz and ASTM spectra.

The analysis of the relative contribution of solar-reflected component to the total TOA signal proves that during daytime conditions this component is important for almost the entire solar zenith angle range (up to 85° or more) and pixel reflectances as small as 1% where the signal is comparable to thermal emission from cold clouds.

To perform a precise direct and inverse radiance to temperature conversion using Planck’s blackbody function at a single wavenumber for a finite spectral response range, it is necessary to define the relationship between effective blackbody brightness temperature and spectral equivalent brightness temperature. It is shown that the difference between these temperatures can be efficiently parameterized as a linear function of either temperature. Coefficients of the linear functions are provided for all of the above sensors. The accuracy of the linear fit is better than 0.01 K except for AVHRR/NOAA-16 where it is within 0.1 K. The larger error occurs due to a spectral leak at 4.25 \( \mu \text{m} \) for AVHRR/NOAA-16 channel 3B. The third-degree polynomials are derived for the case of AVHRR/NOAA-16 to provide accuracy better than 0.01 K.

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