Errors from Rayleigh–Jeans approximation in satellite microwave radiometer calibration systems

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The advanced technology microwave sounder (ATMS) onboard the Suomi National Polar-orbiting Partnership (SNPP) satellite is a total power radiometer and scans across the track within a range of $\pm 52.77°$ from nadir. It has 22 channels and measures the microwave radiation at either quasi-vertical or quasi-horizontal polarization from the Earth's atmosphere. The ATMS sensor data record algorithm employed a commonly used two-point calibration equation that derives the earth-view brightness temperature directly from the counts and temperatures of warm target and cold space, and the earth-scene count. This equation is only valid under Rayleigh–Jeans (RJ) approximation. Impacts of RJ approximation on ATMS calibration biases are evaluated in this study. It is shown that the RJ approximation used in ATMS radiometric calibration results in errors on the order of 1–2 K. The error is also scene count dependent and increases with frequency.

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1. Introduction

On October 28, 2011, the Suomi National Polar-orbiting Partnership (SNPP) satellite was successfully launched into a circular, near-polar, afternoon-configured (1:30 p.m.) orbit at an altitude of 824 km above the Earth and an inclination angle of 98.7° to the equator. The advanced technology microwave sounder (ATMS) onboard the SNPP satellite profiles atmospheric temperature and moisture in nearly all-weather conditions, and supports continuing advances in numerical weather prediction (NWP) for an improved short- to medium-range weather forecasting accuracy. ATMS calibration data, including raw radiometer counts, geolocation, telemetry, and house-keeping data, have been fully processed at the SNPP Interface Data and Processing Segment since November 7, 2011, when the ATMS instrument was turned on. The ATMS antenna temperature data records are now being distributed to the user community from NOAA's Comprehensive Large Array-Data Stewardship Systems for various applications. It was found that ATMS temperature sounding channels can depict more details of thermal structures in the lower troposphere and more details of cloud liquid water path for tropical cyclones than its predecessor advanced microwave sounding unit (AMSU-A) on NOAA satellites [1]. The ATMS brightness temperatures from its radiometric calibration and antenna pattern correction display small but systematic biases to the NWP simulations. One of the root causes for the ATMS data biases was found to be related to the spillover effect from ATMS antenna side lobes, which result in an angular-dependent bias for each channel [2]. However, another source of errors contributing to the ATMS data bias could come from the Rayleigh–Jeans (RJ) approximation used in ATMS radiometric calibration. The primary purpose of this study is to investigate the impacts of the calibration using the RJ approximation on the ATMS data biases.

2. Statement of the Problem

The ATMS sensor data record (SDR) algorithm employed a two-point calibration equation in terms of the earth scene view brightness temperature ($T_{b,s}$), the blackbody temperature ($T_{b,w}$), and the cold-space view temperature ($T_{b,c}$):

$$T_{b,s} = \delta_c(T_{b,w} - T_{b,c}) + T_{b,c}, \tag{1}$$

where

$$\delta_c = \frac{\bar{C}_s - \bar{C}_c}{\bar{C}_w - \bar{C}_c}. \tag{2}$$

The blackbody brightness temperature is determined from its physical temperature measured by the embedded platinum resistance thermometers (PRTs) with a possibly temperature-dependent bias correction; the cold-space view brightness temperature is estimated by taking into account a correction to the RJ approximation to cold space temperature, and $\bar{C}_c$ and $\bar{C}_w$ are the cold space and warm target counts averaged over a calibration cycle (i.e., up to four values).

In theory, a two-point calibration equation must be based on the electromagnetic energy received from antenna in radiance

$$R_s = \delta_c(R_w - R_c) + R_c. \tag{3}$$

In this study, problems associated with using the calibration equation (1) instead of Eq. (3) will be investigated.

3. Theoretical Derivations of ATMS Radiometric Calibration Errors

A. The Rayleigh–Jeans Approximation

Planck's law describes the amount of electromagnetic energy radiated by a blackbody in a thermal equilibrium as a function of its temperature (T) and wavenumber (υ)

$$R_\upsilon(T) = \frac{2hc^2\upsilon^3}{\exp\left(\frac{hc\upsilon}{kT}\right) - 1} \equiv \frac{C_1\upsilon^3}{\exp\left(\frac{C_2\upsilon}{T}\right) - 1}, \tag{4}$$

where k is the Boltzmann constant, h is the Planck constant, c is the speed of light, $C_1 = 2hc^2 = 1.1909 \times 10^{-8}\ \mathrm{W\,m^{-2}\,sr^{-1}\,cm^{-1}\,cm^3}$, and $C_2 = (hc/k) = 1.438786\ \mathrm{cm\,K^{-1}}$.

Assuming $(C_2\upsilon/T) \ll 1$, the exponential function in the Planck function can be expressed in Taylor series:

$$\exp\left(\frac{C_2\upsilon}{T}\right) = 1 + \frac{C_2\upsilon}{T} + \frac{1}{2}\left(\frac{C_2\upsilon}{T}\right)^2 + \cdots + \frac{1}{n!}\left(\frac{C_2\upsilon}{T}\right)^n + \cdots. \tag{5}$$

Substituting the first-order approximation of the above Taylor expansion into Eq. (4), one obtains the following linear relationship between the blackbody temperature (T) and radiance (R_ν):

$$R_\upsilon^{\mathrm{RJ}}(T) = \frac{C_1\upsilon^2}{C_2}T. \tag{6}$$

Equation (6) is called the RJ approximation. Since $0 < C_2\upsilon < 10$ K when $23.8\ \mathrm{GHz} \le f \le 190.3\ \mathrm{GHz}$, where $f = c\upsilon$ is frequency, Eq. (6) is valid when temperature is above 100 K.

The accuracy of the radiance calculated from Eq. (3) and the linear approximation in Eq. (6) varies with frequency and temperature. Figure 1 shows the relative and absolute variations of the accuracy of the first-order approximation of Planck function (e.g., $(T_{b,\nu}^{\mathrm{RJ}} - T_{b,\nu})/T_{b,\nu}$ and $(T_{b,\nu}^{\mathrm{RJ}} - T_{b,\nu})$) with temperature at four arbitrarily selected frequencies of 23.8, 53.6, 89.0, and 190.3 GHz. A direct use of brightness temperature instead of radiance in Eq. (1) could result in brightness temperature errors as shown in Fig. 1. At a fixed temperature, the higher the frequency, the larger the error is. Alternatively, at a fixed frequency, the lower the temperature, the larger the error is. At a high frequency near 190.3 GHz, there is a 4.5% error in brightness temperature.

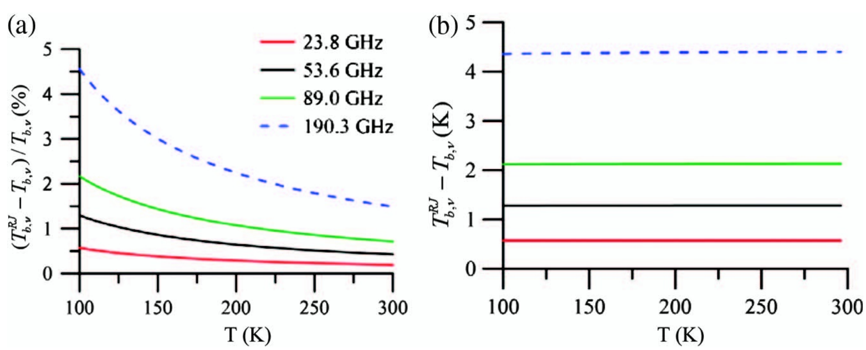

Fig. 1. (a) Relative and (b) absolute variations of the brightness temperature with blackbody temperature varying from 100 to 300 K at frequencies 23.8, 53.6, 89.0, and 190.3 GHz.

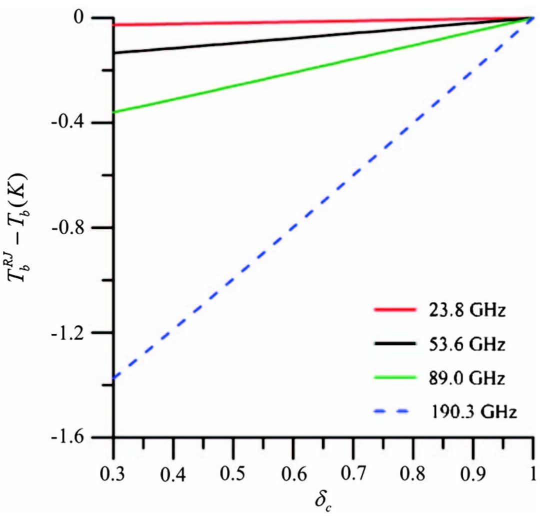

Fig. 2. Variations of calibration errors ($T_b^{\mathrm{RJ}} - T_b$) with count ratio (δ_c) introduced by the RJ approximation at 23.8 (red), 53.6 (black), 89.0 (green), and 190.3 GHz (blue). Here T_b^{RJ} is calculated by Eq. (1) and T_b is obtained by Eq. (2), with T_c and T_w set to 2.73 and 300 K, respectively.

The error decreases rapidly with an increase of temperature. The RJ approximation $T_{b,\nu}^{\mathrm{RJ}}$ is about 0.5, 1.25, 2.1, and 4.4 K warmer than the true value $T_{b,\nu}$ at 23.8, 53.6, 89.0, and 190.3 GHz, respectively. It is noted that calibration errors of a degree or more for high microwave frequency observations due to the RJ approximation may be tolerable since clouds and precipitation can produce scattering and emission, which result in large variability in brightness temperatures at high microwave frequencies.

Given that $T_{b,c} = 2.73$ K and $T_{b,w} = 300$ K, a set of $\Delta R_{\upsilon}^{\mathrm{RJ}} (= R^{\mathrm{RJ}} - R)$ values can be derived at different frequencies for a set of δ_c values using Eqs. (2) and (6). By applying the inverse Planck function to the differential radiance $\Delta R_{\upsilon}^{\mathrm{RJ}}$, the error introduced by the RJ approximation in terms of brightness temperature, i.e., $\Delta T_{b,\upsilon}^{\mathrm{RJ}}$, can be derived (see Fig. 2). It is found that the radiance errors are the largest when the counts are smallest. These calibration errors decrease linearly with the count ratio at a fixed frequency. The higher the frequency, the larger the calibration errors are. In the C-band, the calibration error due to the RJ approximation can be as large as 1 K when $\delta_c = 0.5$. Thus, in the microwave two-point calibration equation, the accurate Plank function should be used instead of the RJ approximation.

B. Inappropriateness of Calibration Using the RJ Approximation

Substituting Eq. (6) into Eq. (3), one obtains the following equation:

$$R^{\mathrm{RJ}} = \delta_c \left(\frac{C_1 \upsilon^2}{C_2} T_w - \frac{C_1 \upsilon^2}{C_2} T_c \right) + \frac{C_1 \upsilon^2}{C_2} T_c, \qquad (7)$$

where the subscript for wavenumber "υ" is omitted. It becomes clear that the two-point calibration used in Eq. (1) to derive the ATMS scene brightness temperature from the scene count ($\bar{C}_s$), the cold count ($\bar{C}_c$), and the warm count ($\bar{C}_w$) is a result of directly applying the RJ approximation [Eq. (6)] to the calibration equation [Eq. (3)] in radiance. However, the RJ approximation in Eq. (6) is only valid when $C_2 \upsilon / T \ll 1$, which is not the case at the cold space temperature T_c.

4. Verification of ATMS Calibration Errors Using NOAA-18 AMSU-A/MHS Data

In the ATMS calibration process, the brightness temperature is directly derived from Eq. (1) with some corrections to the cold space temperature at each channel. The original counts from its calibration targets and earth scenes are separated into different data streams called raw data record and SDR, respectively. Unlike ATMS, the AMSU-A and microwave humidity sounder (MHS) datasets on NOAA satellites include both calibration counts and brightness temperatures. Thus, AMSU-A/MHS data is used for verifying the calibration errors introduced by using Eq. (1). First, the gain δ_c is calculated from the observed scene count ($\bar{C}_s$), the cold count ($\bar{C}_c$), and the warm count ($\bar{C}_w$) according to Eq. (2), which is denoted as δ_c^{obs}. Then, brightness temperatures using the two-point radiance calibration in Eq. (3), to be denoted T_b^{obs}, are calculated from δ_c^{obs}, and the measured values of the blackbody brightness temperature ($T_{b,w}$) and the cold space view brightness temperature $T_{b,c}$. Similarly, brightness temperatures using the two-point calibration in Eq. (1), to be denoted $T_b^{\mathrm{obs,RJ}}$, are calculated from the same set of δ_c^{obs}, $T_{b,w}$, and $T_{b,c}$ values. Finally, calibration errors introduced by the RJ approximation, defined as $T_b^{\mathrm{obs,RJ}} - T_b^{\mathrm{obs}}$, are examined. Figure 3 provides scatter plots of calibration errors with respect to the observed count ratio (δ_c^{obs}) and brightness temperature T_b^{obs}. Data used in Fig. 3 include one-month AMSU-A/MHS data at 23.8, 53.6, 89.0, and 190.3 GHz in January 2010 from NOAA-18 within the following three small geographic areas: Sahara desert (D1: 5W-25E, 15N-30N), tropical ocean (D2: 55E-85E, 10S-5N), and Antarctic (D3: 90E-120E, 70S-85S). Here $T_b^{\mathrm{obs,RJ}}$ is calculated by Eq. (1) and T_b^{obs} is obtained by Eq. (2) and the inverse Planck function. It is seen that calibration errors are earth-scene dependent. The colder the temperature and the smaller the count ratio, the larger the calibration errors are. The calibration errors due to the RJ approximation are rather small (e.g., less than 0.1 K) for AMSU-A channels at 23.8 and 53.6 GHz. However, at 89 and 190 GHz, the use of the RJ approximation introduces a calibration error greater than 0.5 K.

Biases and standard deviations of calibration errors introduced by the RJ approximation (e.g., $T_b^{\mathrm{RJ,obs}} - T_b^{\mathrm{obs}}$) for all 20 AMSU-A/MHS channels are estimated in Fig. 4 using one-month data at nadir in January 2010 from NOAA-18 over the same three geographic areas as used in Fig. 3. Calibration errors are smallest over the Sahara desert, where

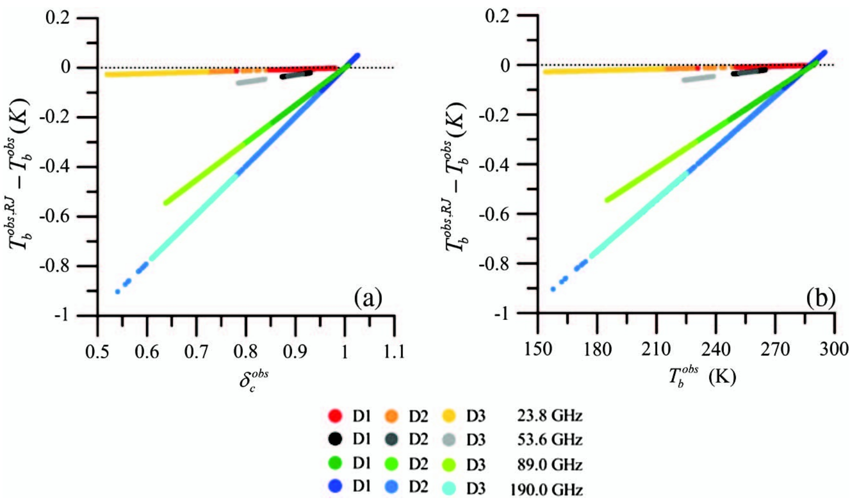

Fig. 3. Scatter plots of calibration errors introduced by the RJ approximation (e.g., $T_b^{\mathrm{obs,RJ}} - T_b^{\mathrm{obs}}$) with respect to (a) observed count ratio (δ_c^{obs}) and (b) brightness temperature (T_b^{obs}) at 23.8, 53.6, 89.0, and 190.3 GHz using one-month AMSU-A/MHS data at nadir in January 2010 from NOAA-18 within three small geographical areas: Sahara desert (D1: 5W-25E, 15N-30N), tropical ocean (D2: 55E-85E, 10S-5N), and Antarctic (D3: 90E-120E, 70S-85S).

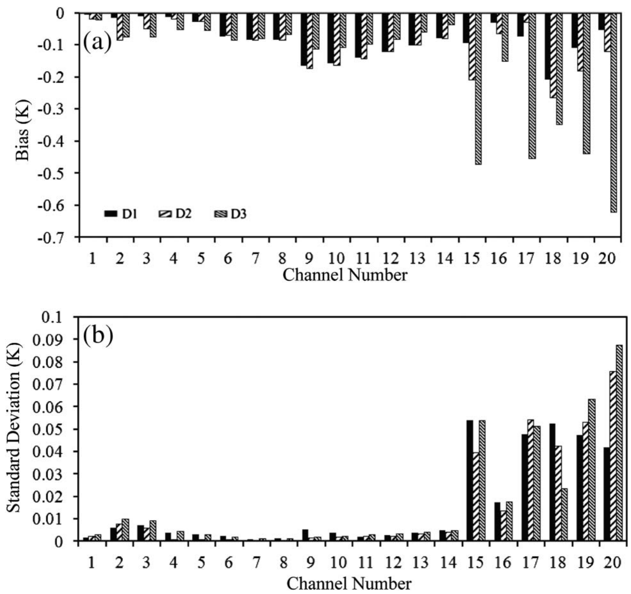

Fig. 4. (a) Biases and (b) standard deviations of calibration errors introduced by the RJ approximation (e.g., $T_b^{\mathrm{RJ,obs}} - T_b^{\mathrm{obs}}$) for 20 AMSU-A/MHS channels using one-month data at nadir in January 2010 from NOAA-18 over the same three small domains as in Fig. 3.

temperature is highest among the three selected small geographic areas. Calibration errors are of appreciable magnitudes for AMSU-A channel 15 and MHS channels 1–5, especially when the scene temperature is low.

Based on Eqs. (5) and (6), the radiance calibration errors due to the RJ approximation can be derived as follows:

$$\Delta R^{\mathrm{RJ}} \equiv R^{\mathrm{RJ}} - R = \delta_c(\Delta R_w - \Delta R_c) + \Delta R_c. \quad (8)$$

In the ATMS calibration, the PRT and the cold space temperature are directly used to derive the brightness temperature using Eq. (1). Only the cold space temperature is corrected to take into account the bias from the RJ approximation to the full Plank function. Based on Eq. (8), it is seen that the radiances from cold and warm target temperatures should be quantified and corrected, and the correction is earth-scene dependent. Estimation of the cold space and warm target biases, ΔR_c and ΔR_w, is extremely difficult.

5. Conclusions

This study emphasizes the importance of replacing the calibration Eq. (1) used in the ATMS SDR calibration algorithm with Eq. (3) to avoid complications to estimating the cold space and warm target biases ΔR_c and ΔR_w. Application of a two-point calibration equation directly to brightness temperatures introduces significant biases to the ATMS data, especially for channels with frequencies greater than or equal to 89 GHz. If Eq. (1) is not replaced by Eq. (3), it is suggested that the ATMS brightness temperatures must be corrected by incorporating a correction term [see Eq. (8)] into the ground calibration process.

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